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

Systèmes spatiaux — Conception de réduction des débris spatiaux et manuel d'utilisation pour les engins spatiaux

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Foreword

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

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

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

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

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

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

This second edition cancels and replaces the second edition (ISO/TR 18146:2015), which has been technically revised.

The main changes compared to the previous edition are as follows:

— text has been updated to be aligned with ISO 24113:2019[1];

— information has been added that the ejection of slag debris from solid rocket motors is limited newly in low Earth orbit in addition to GEO previously;

— information relating to collision avoidance against catalogued space objects has been improved;

— information of the intention of the new requirement avoiding fragmentation caused by impact of space debris and meteoroid, and typical assessment procedure in the world space agencies has been added;

— corresponding to the new requirement limiting the total probability of successful disposal to be at least 0,9, the state of the art to confirm the compliance with that taken in the world space industries and national agencies has been added;

— other information relating to the changes in ISO 24113 has been added.

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

Introduction

Coping with debris is essential to preventing the deterioration of the orbital environment and ensuring the sustainability of space activities. Effective actions are also 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 is taken to prevent damage due to the impact. Collision avoidance manoeuvres are taken to avoid large debris (larger than 10 cm, for example), which can be observed from the ground. Spacecraft design protects against micro-debris (even smaller than 1 mm) that can cause critical damage to vulnerable components.

ISO 24113:2019[1] and other ISO documents, introduced in Bibliography, were developed to encourage debris mitigation activities.

In Clause 5, the major space debris mitigation requirements are informed.

In Clause 6, the information of life-cycle implementation of space debris mitigation related activities is provided.

In Clause 7, the system level aspects stemming from the space debris mitigation requirements are highlighted; while in Clause 8, the impacts at subsystem and component levels are detailed.

This document provides comprehensive information on what ISO requires to do for the design and operation of the launch vehicles, and where such requirements and recommendations are registered in a set of ISO documents.

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

1 Scope

This document contains information on the design and operational practices for launch vehicle orbital stages for mitigating space debris.

This document provides information to engineers on what are required or recommended in the family of space debris mitigation standards to reduce the growth of space debris by ensuring that spacecraft is designed, operated, and disposed of in a manner that prevents them from generating debris throughout their orbital lifetime.

2 Normative reference

There are no normative references in this document.

3 Terms and definitions

No terms and definitions are listed in this document.

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

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

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

4 Symbols and abbreviated terms

A/M	area-to-mass
AOCS	attitude and orbit control system
CDR	critical design review
CFRP	carbon-fibre-reinforced plastic
CNES	Centre National d'Etudes Spatiales
CSpOC	Combined Space Operations Center (USA)
DAS	debris assessment software (NASA)
COTS	commercial off-the-shelf
DRAMA	debris risk assessment and mitigation analysis (ESA)
EOMDP	end-of-mission (operation) disposal plan
ESA	European Space Agency
FDIR	failure detection, isolation and recovery

FMEA	failure mode and effect analysis
GEO	geosynchronous Earth orbit
GPSR	global positioning system receiver
IADC	Inter-Agency Space Debris Coordination Committee
IRU	inertial reference unit
LEO	low Earth orbit
MASTER	meteoroid and space debris terrestrial environment reference
MIDAS	MASTER (-based) impact flux and damage assessment software
NOTAM	notice to airmen and notice to mariners
OLI	operation time limited item
ORDEM	orbital debris engineering model
PDR	preliminary design review
PNF	probability of no failures
QA	quality assurance
QR	qualification review
RCS	reaction control system
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
TLE	two-line element set
TT&C	telemetry tracking and command
UN	United Nations

5 System-level activities

5.1 General

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

a) Identify debris-related requirements, recommendations and best practices.

b) Determine how to comply with these requirements, recommendations, and best practices.

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

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

e) Apply appropriate procedures during operation/utilisation and disposal to implement proper space debris mitigation and protection.

This subclause provides information useful 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:

— limiting the release of objects in protected orbital regions;

— preventing fragmentation in orbit (including intentional break-ups, and accidental break-ups caused by collision with trackable objects, impact of tiny debris, and stored energy);

— proper disposal at the end of operation;

— minimization of hazard on the ground from re-entering debris;

— quality, safety and reliability assurance.

5.2 Design for limiting the release of objects

5.2.1 Intents of requirements in ISO 24113:2019[1]

ISO 24113:2019[1], 6.1 requires avoiding the intentional release of space debris into Earth orbit during normal operations, including general objects such as fasteners, fragments from pyrotechnics, slag from solid rocket motors, etc.

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

a) objects released as directed by mission requirements (not directory indicated in ISO 24113:2019[1], 6.1.1.1, though);

b) mission-related objects, such as fasteners, apogee motor cases, etc. (ISO 24113:2019[1], 6.1.1.1);

c) fragments and combustion products from pyrotechnic devices (ISO 24113:2019[1], 6.1.2.1);

d) slag ejected from solid motors (ISO 24113:2019[1], 6.1.2.2).

It implies that if objects are unavoidably released despite requirements in ISO 24113:2019[1], 6.1.1.1, the orbital lifetime of such objects in LEO and interference with GEO is limited as described in ISO 24113:2019[1], 6.1.1.3.

5.2.2 Work breakdown

Table 1 shows the work breakdown for the actions required to prevent the releasing of debris.

Table 1 — Work breakdown for preventing the release of objects

Process	Subjects	Major work
Preventive measures	Identification of released objects and design measures	a) In the mission, which releases objects required by mission objectives, the effect on the orbital environment and the expected benefit for the mission will be assessed." b) Take preventive design to avoid releasing objects turning into space debris (ISO 24113:2019[1], 6.1). c) If objects might be released unintentionally, designers will investigate design problems and take appropriate action during design phase (e.g. insulators). d) If release is unavoidable, designers will estimate the orbital lifetime of released objects and check compliance with ISO 24113:2019[1], 6.1.1.3. e) When applying the solid motors, the possible generation of slag and its risk posed to space activities will be assessed.
Risk detection	Monitoring during operation	a) Confirm that the orbiting characteristics of released parts are as estimated, if needed. b) 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.

5.2.3 Identification of released objects and design measures

Identify the parts designed is released, estimate their orbital lifetimes, and determine the propriety of their release.

a) 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:

1) 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. NASA, JSC, Orbital Debris Quarterly News, Volume 17[2] reported that *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.*

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

b) Mission-related objects

Release of the following objects are avoided by appropriate mission and spacecraft design (ISO 24113:2019[1], 6.1.1):

1) fasteners for deploying and holding devices for panels or antennas;

2) nozzle closures and igniters of solid motors;

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

NOTE The structural elements which support upper spacecraft used in the multi-payloads launching missions can be released due to their unavoidability. Disposal orbit of these elements are complied with ISO 24113:2019[1], 6.1.1.2. (These elements usually belong to the launch vehicle, not the spacecraft.)

c) Fragments and combustion products from pyrotechnic devices

Devices are selected and/or designed to avoid the production and release of the fragments of parts or the combustion by-products. Employing vehicle components that trap all fragments and combustion products inside for segregation (ISO 24113:2019[1], 6.1.2.1).

d) Combustion products from solid motors

Solid motors are designed not to generate slag in both GEO and LEO protected regions (higher than the manned orbit [≒approximately 400 km]). (ISO 24113:2019[1], 6.1.2.2)

5.2.4 Design measures

In general, only devices that do not release parts into the space environment are selected.

CSpOC sometimes detects released cases of the apogee kick motors. The solid motors are not used for the apogee kick motors if they generate slag. Furthermore, it is refrained from disposing the motor cases into the orbit crossing the GEO protected region.

If parts would be released due to unavoidable reasons, the orbital lifetime of the parts and the risk of impact on another spacecraft are assessed. The orbital lifetime can be assessed according to ISO 27852:2016[3]. ISO 27852:2016[3] does not designate a specific analysis tool but rather expects that the users employ their reliable techniques depending upon orbit regime, so that designers can select any tool(s) which adhere to ISO 27852:2016[3] approved techniques. Available simplified tools that can be used to estimate the long term orbital lifetime are, for instance: NASA DAS (https://orbitaldebris.jsc.nasa.gov/mitigation/debris-assessment-software.html), ESA DRAMA (after creating an account at https://sdup.esoc.esa.int/ one can obtain a license before downloading), or CNES STELA (https://logiciels.cnes.fr/content/stela?language=en).

5.2.5 Monitoring during operation

The released objects, if they are larger than 10 cm, are confirmed with 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 the CSpOC provides a good reference.

5.2.6 Preventing failure

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

5.3 Prevention of break-up

5.3.1 General

ISO 24113:2019[1], 6.2 requires the prevention of break-ups caused by intentional behaviour, stored energy, collision with catalogued objects, and impact of debris or meteoroid. In 5.3.2, the first two subjects are discussed. The collision with catalogued objects is addressed in 5.3.3, and the impact of debris and meteoroid in 5.3.4.

ISO 16127:2014[4] provides more detailed requirements and procedures for complying with them.

5.3.2 Break-up caused by intentional behaviour, or stored energy

5.3.2.1 Work breakdown for preventing orbital break-up caused by stored energy

Table 2 shows the work breakdown for preventing orbital break-up caused by stored energy.

Table 2 — Work breakdown for preventing orbital break-ups caused by stored energy

Process	Subjects	Major work
Preventive measures	Mission assessment	Mission which involves the intentional break-up will be assessed to justify its intention is essential for peaceful use of space, and its effect on the environment can be controllable.
	Identification of sources of breakup	Identify components that may cause fragmentation during or after operation.
	Design measures	a) Missions that involve intentional break-ups are not designed. b) Take preventive design to limit the probability of accidental break-up. Confirm it in FMEA. c) Provide functions for to prevent break-ups after disposal.
Risk detection	Monitoring during operation	a) Provide functions to monitor symptoms of break-up. b) Monitor the critical parameters periodically. c) Take immediate actions if the symptom of a malfunction that can lead to a breakup is detected.
Countermeasures	Preventive measures for break-up	Perform the disposal operations to eliminate the risk of break-ups.

5.3.2.2 Identification of the sources of break-up

For post-operation break-ups, ISO 16127:2014[4] identifies the following components as the most likely causes of the break-up of spacecraft:

a) batteries in the electrical subsystem;

b) propulsion mechanisms and associated components (such as engines, thrusters, etc.);

c) pressurized components (such as tanks or bottles in the propulsion subsystems, or pneumatic control system, and heat pipes);

d) rotating mechanisms.

5.3.2.3 Design measures

a) 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 *Space Debris Mitigation Guidelines*[5] state that it is conducted at sufficiently low altitudes so that orbital fragments are short-lived.

b) Accidental break-up during operation

According to ISO 24113:2019[1], *the probability of accidental break-up is no greater than* 10^{-3} *until its end of life.* The causes of break-ups are identified in FMEA, and preventive measures are incorporated in the design. Causes of break-ups are typically controlled by FDIR concept in system-safety management. More detailed assessment procedures are presented in ISO 16127:2014[4], Annex A. For engineers wondering how to cope with rotating mechanism or complicated subsystems such as apogee engines, ISO 16127:2014[4], Annex A provides good instruction.

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

c) Break-ups that occur after the end of operation

Many break-ups have occurred long after the end of operation life (e.g. 10 years after disposal). ISO 24113:2019[1] and ISO 16127:2014[4] 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, separating propellant tank design combined fuel and oxygen tanks only by a common bulkhead in a way caused many explosions.

5.3.2.4 Monitoring during operations

ISO 24113:2019[1], 6.2.2.5 and ISO 16127:2014[4], 4.3.1 requires monitoring of critical parameters to detect the symptoms that can lead to a) break-up, b) loss of mission capability, or c) the loss of orbit and attitude control function, and requires immediate action when any symptoms are detected.

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

5.3.2.5 Disposal operations

Sources of break-ups listed in 5.3.2.2 are mitigated (vented or operated in safe mode) according to ISO 16127:2014[4], 4.4.

5.3.3 Break-up caused by a collision with catalogued objects

5.3.3.1 Intents or requirements in ISO 24113:2019[1]

ISO 24113:2019[1], 6.2.3.1 to 6.2.3.3 require collision avoidance to prevent from generating fragments. (Fragmentation caused by impact with orbital objects is mentioned in ISO 24113:2019[1], 6.2.3.4 and explained in 5.3.4.)

Collision with a large object (observable from the ground; typically, larger than approximately 10 cm) causes critical damage to spacecraft and poses great risk to other intact spacecraft when thousands of fragments are dispersed within a range of a thousand of kilometres. Therefore, the UN Space Debris Mitigation Guidelines[6] recommend conducting the collision avoidance. ISO/TR 16158:2019[7] addresses best practices to evaluate and avoid collisions among orbital objects.

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

a) 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.);

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

c) criteria for notification (conjunction distance, probability of collision, etc.);

d) criteria for conducting avoidance manoeuvres (conjunction distance, features of approaching objects, etc.);

e) method of estimating the number of manoeuvres, amount of propellant for avoidance and returning manoeuvres, and how to ensure the propellant;

f) a sequence for avoidance and returning manoeuvre (methods of avoidance, concepts for avoidance by altitude change or phase shift);

g) how to access contact points to plan coordinated avoidance manoeuvres, data exchanging rules, etc.

5.3.3.2 General information

ISO/TR 16158:2019[7] 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.

5.3.3.3 Work breakdown

Table 3 shows the work breakdown for avoiding collisions with catalogued objects.

Table 3 — Work breakdown for avoiding collision with catalogued objects

Process	Subjects	Major work
Preventive measures	Estimation of probability	Estimate collision probability by debris population models.
	Design measures	a) If the collision probability cannot be ignored, the function to avoid collision is incorporated in design. b) 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	The criteria of collision avoidance and the standard procedure for collision avoidance is documented.
Risk detection	Receipt of warning from the collision avoidance services	a) If warning of close approach comes from USSTRATCOM/CSpOC, check the conjunction risk and identify the approaching object in detail. Reconfirm that the up-to-date, authoritative orbit ephemerides are provided to CSpOC for re-analysis. b) Operators can also use commercial services (e.g. the Space Data Association's conjunction assessment process) or one provided by other agencies. c) 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.
Counter-measures	Avoidance and returning manoeuvres	a) Decide to conduct avoidance manoeuvres, if necessary. b) Ahead of time, develop an avoidance manoeuvre plan (include return plan, if needed). c) Communicate avoidance manoeuvre plan to collision avoidance service and if any to the operator of the approaching spacecraft. d) Develop the avoidance manoeuvre plan (include returning manoeuvre, if needed) coordinating with them. e) Confirm conjunction probability during avoidance and returning manoeuvres. f) Execute avoidance and returning manoeuvres.

5.3.3.4 Estimation of collision probability

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

a) information on in-orbit objects from the "Space-Track" website posted by the United States (https://www.space-track.org/auth/login);

b) ESA-MASTER provides statistical debris population (an account at; https://www.esa.int/ESA_Multimedia/Images/2013/04/ESA_s_MASTER_software_tool);

c) NASA-ORDEM provides statistical debris population; the point of contact can be known from the user's guide available at: https://www.orbitaldebris.jsc.nasa.gov/modeling/engrmodeling.html;

d) ESA-DRAMA has dedicated routines based on MASTER to assess statistically the number of expected collision / avoidance manoeuvres (an account at https://sdup.esoc.esa.int/).

NOTE 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 16158:2019[7], Clause 8.

5.3.3.5 Design measures

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

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

If the spacecraft has an enough 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.

5.3.3.6 Procedures for collision avoidance

The criteria of collision avoidance and the standard procedure for collision avoidance are documented. It will include

a) criteria of warning for conjunction;

b) criteria to conduct re-analysis with up-to-dated authoritative orbit ephemerides;

c) criteria to decide the collision manoeuvre;

d) standard collision manoeuvre planning.

Procedures will be facilitated timely avoidance manoeuvres.

5.3.3.7 Detection of risk

5.3.3.7.1 Receipt of warning from the collision avoidance services

The CSpOC provides ready access to a conjunction warning service. When conjunctions involve actively-manoeuvring satellites (particularly in GEO), an approach such as the SDA's, which incorporates authoritative operator data (planned manoeuvres, momentum dumps, high-fidelity 3 degrees of freedom and 6 degrees of freedom attitude and orbit propagation, and active transponder ranging across the orbital arc) is more actionable and credible. Both CSpOC and SDA sides recommend 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), are submitted for re-analysis.

ISO/TR 16158:2019[7], Clause 12 specifies the minimum content of warning information.

5.3.3.7.2 Internal conjunction analysis

To determine the orbital characteristics for an operator's own satellites, see the procedures defined in ISO/TR 11233:2014.

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

NOTE Orbital data for other satellites and debris can be obtained via public sources (e.g. CSpOC's TLEs and Conjunction Data Messages) or the services providers such as the SDA which aggregates actionable operator ephemerides to provide the most actionable and timely analyses for operator-on-operator spacecraft conjunctions.

5.3.3.8 Avoidance and return manoeuvres

5.3.3.8.1 Determine if avoidance manoeuvres are necessary

Operators 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 16158:2019[7], Clause 9 lists points that are 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.

5.3.3.8.2 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.

5.3.3.8.3 Communication with the operator of the approaching spacecraft

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

a) the owner of the approaching object and the owner's contact information;

b) the operational status (under operation or disposed of) of the objects and the manoeuvrability of the objects;

c) the feasibility of coordinated mutual avoidance manoeuvres;

d) 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.unoosa.org/oosa/osoindex/search-ng.jspx?lf_id=).

5.3.3.8.4 Collision-avoidance plan

ISO/TR 16158:2019[7], Clause 12 addresses the development of an avoidance plan. This avoidance manoeuvre plan includes a return manoeuvre plan. It is 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.

NOTE A variety of methods and services exist for detecting and monitoring upcoming conjunction events. But in any cases, 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.

5.3.4 Break-up caused by the impact of debris or meteoroid

5.3.4.1 Contents of requirements in ISO 24113:2019[1]

ISO 24113:2019[1], 6.2.3.4 requires assessment for the risk that a space debris or meteoroid impact will cause the spacecraft to break-up before its end of life.

Also, ISO 24113:2019[1], 6.3.1.2 requires assessing the risk that a space debris or meteoroid impact will prevent the successful disposal". See 5.4.12.

5.3.4.2 Concept of the requirements

The term of "break-up" is defined in ISO 24113:2019[1], 3.2 as an "event that completely or partially destroys an object and generates space debris". In such meaning, the requirement in ISO24113:2019[1], 6.2.3.4 looks to require assessing the probability that even a millimetre-size debris impact on every part of spacecraft, since most the elements of spacecraft can't help to generate a fragment if a small debris or meteoroid impact on the spacecraft. However, this requirement would not pose so strict requirement. The intention of the requirement of ISO24113:2019[1], 6.2.3.4 is to assess the risk of the following two catastrophic fragmentations.

a) Fragmentation of spacecraft or its large deployment devices

   At the early phase of development of spacecraft and its large elements (e.g. conceptual design phase), when the operation orbit, cross-sectional area, etc. of spacecraft would be defined, the probability of fragmentation due to the kinetic energy of impact of debris or meteoroid is assessed to compare the different solutions to improve design against impacts. For this level of analysis, a relatively crude EMR (energy-to-mass ratio) threshold is often applied in the calculation.

b) Fragmentation of high energy storage equipment

   The probability of fragmentation of a high energy storage equipment item, such as a propellant tank or high-pressure vessel, due to the impact of debris or meteoroid is assessed to evaluate the needs to relocate behind the rigid element, or to protect by shielding.

5.3.4.3 General information

There is no ISO standard defining the detailed procedure to avoid the fragmentation due to the impact of debris.

ISO 16126:2014[8] 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, and it is not corresponding to the catastrophic fragmentations. However, as far as assessment for the energy storage vessels is concerned, since they are critical both to conducting disposal actions and to causing catastrophic fragmentation, both assessments will be done corporately for better efficiency.

ISO 14200:2012[9] provides 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 exist, sometimes with different predictions of debris fluxes versus size distributions. Since each model will be revised every several years, the designers need to confirm the latest revision of those models.

IADC provides the "IADC Protection Manual"[10] and "Spacecraft Component Vulnerability for Space Debris Impact"[11].

ESA provides ESSB-HB-U-002[12] "ESA Space Debris Mitigation Compliance Verification Guidelines".

5.3.4.4 Work breakdown

Table 4 shows the work breakdown for protection design against debris and meteoroid.

Table 4 — Work breakdown for avoiding fragmentation caused by impact of orbital objects

Process	Subjects	Major work
Preventive measures	Definition of requirements	a) Minimize the risk of system-level fragmentation. b) Minimize the risk of break-up of large element. c) Minimize the risk of fragmentation of high energy storage equipment d) Minimize the risk of loss of function for disposal actions. Define the EMR for a) and b) above. Define the requirement for impact survivability, as a form of PNF for c) and d) above.
	Assessment of the risk	a) Calculate the threshold of debris size corresponding to EMR on the condition of mass, orbit characteristics of spacecraft, A/M of debris. And assess the probability of impact. b) Same as above using physical characteristic of large elements and their location. c) For component analysis: 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 is greater than requirements.
	Design improvement	a) Improve the configuration in the conceptual design level. b) Improve the basic design of the large elements. c) For elements that require protective design, apply proper countermeasures, i.e. re-allocation behind the hard elements, adding redundant elements, putting shielding in front of vulnerable components, and other measures.

5.3.4.5 System-level fragmentation

This analysis is conducted in early phase in the development lifecycle when the operation orbit, system concept, shape and size has not been fixed. In such concept design phase, the crowded orbital region may be avoided, the shape and area may be tuned for less probability of impact, the member of structures element may be reinforced, etc.

A world known analysis method is a concept of the energy-to-mass ratio (EMR), as introduced in ESSB-HB-U-002 “ESA Space Debris Mitigation Compliance Verification Guidelines”[12]:

$$r_{EMR} = \frac{\frac{1}{2} M_p V_{imp}^2}{M_t}$$

where

r_{EMR} is the EMR;

M_p is the projectile mass (i.e. an orbiting and uncontrolled debris);

V_{imp} is the impact velocity (i.e. relative velocity between the projectile and target);

M_t is the target mass (i.e. the spacecraft or launch vehicle stage).

The threshold for a catastrophic collision $r_{(EMR)cc}$ is known as:

$$r_{EMR} \geq r_{(EMR)cc} = 40 \text{ J/g}$$

Applying above method, on the condition of the target spacecraft (mass: 1,000 kg, altitude: 1,000 km, cross-sectional area of front side: 10 m^2), relative velocity (10 km/sec), EMR (40 J/g), then the threshold size of debris is calculated roughly 10 cm in diameter, and the probability of impact is 10^{-4} times/year, as the flux is 10^{-5} times/year/m^2.

In the case of such 10 cm class debris, usually, since it can be tracked and collision avoidance is possible, the fragmentation, in this category, can be avoidable in the operation phase to some extent. However, the risk of impact with non-catalogued debris or meteoroid can’t be reduced.

5.3.4.6 Fragmentation of high energy storage equipment caused by the impact of tiny object

5.3.4.6.1 General assessment flow

Concerning to the assessment of effect of the impact of tiny object, ISO 16126:2014[8] describes the 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 16126:2014[8] also describes two impact risk analysis procedures that can be used to satisfy the requirements.

The procedure described in the above standard is also available to assess the risk of break-up caused by the impact of tiny object with changing the definition of “critical component” from the “component whose failure would prevent the completion of an essential function” to “component whose damage would cause the Fragmentation” and “lethal collision” from “collision leading to the loss of a critical component on a spacecraft” to “collision leading to the fragmentation”, etc.

The threshold of allowable probability of fragmentation is 0,001 (compatible value to the allowable probability of break-up caused by internal source of break-up energy) as the sum of the probability of that of all the critical components. (See 5.3.4.6.2.)

The following break-up modes are assessed.

a) rupture of the high-pressure gas vessels caused by the perforation under a certain condition which exceeds the threshold defined by the relation of the “impact energy” and the “ratio of hoop stress and the break strength of the vessel’s wall”;

b) other break-up modes caused by components that contain the physical or chemical energy as the potential source of break-up energy. Rupture of the high-pressure liquid containers such as heat pipe, etc.

There are some analysis tools in the several countries and a few of them are being distributed to the world as ESA/DRAMA/MIDAS. These tools enable the flux and damage analysis, and the probability of perforation can be assessed, but the probability of explosion or rupturing can't be assessed.

5.3.4.6.2 High pressure gas vessels which causes rupture under a certain condition

When the debris would impact on the high-pressure gas vessels, whether the effect would be limited to the generation of a simple hole or developed to a rupture is a matter of discussion. TIADC protection Manual[10] introduces the result of experiments conducted to find the threshold of rupture for vessels made of Aluminium alloy (Al 5754, Al 2219) and Titanium alloy (Ti 99,6 %). The vessels were cylindrical vessels and defined by 150 mm in diameter, 350 mm in length, and 1 mm in wall thickness. The threshold is shown as a curve defined by the relation between "ratio of hoop stress and break strength" and "impact energy".

If the operational pressure of high-pressure vessels would be assumed to be 25 % of the break strength, the threshold size of debris is 0,6 mm for the Aluminium alloy tank (Al 5754, Al 2219), and 2 mm for Titanium alloy tank (Ti 99,6 %).

However, generally, the high-pressure vessels are not exposed to the outer space, and sometimes a structural panel covers the vessels. "IADC Spacecraft Component Vulnerability for Space Debris Impact"[11] introduces the result of hyper velocity impact test. This experiment revealed that the pressure vessels (wall thickness: 3 mm CFRP and 1 mm Al alloy, inner pressure 9 MPa), which were shielded by a panel, were caused to break-up by the impact of debris whose size is 5,0 mm to 6,0 mm in diameter, at the impact velocity of 6,5 km/s. The threshold would depend on inner pressure, materials and thickness of tank, etc.

In the practical situation, it is hard for manufactures to prepare such a chart for every tank, in terms of facilities (e.g. hypervelocity impact test facility, with large chamber accepting the tank and safety measures against the break-up event is required) and the number of tanks as specimens.

ISO 16126:2014[8] is expected to provide a standard procedure for simple procedures to assess those risk.

Practically, since such high-pressure vessels are essential for disposal action, and its criticality will be assessed by the perforation no matter if a rupture would occur or not. See 5.4.12.

5.3.4.6.3 Other break-up modes caused by the physical or chemical energy

There is another type of components as the potential source of break-up energy, high-pressure liquid containers such as heat pipe, etc. Those components are assessed considering the characteristics specific to them.

5.4 Disposal after the end of mission to minimize interference with the protected regions

5.4.1 Intents of requirements in ISO 24113:2019[1]

ISO 24113:2019[1], 6.3 requires removing a spacecraft or launch vehicle in orbital stage from the protected regions after end-of-mission, and requires the probability of successful disposal (PSD) to be larger than 0,9. This requirement is based on the research conducted by IADC that, to keep the LEO environment stable (or not so heavy change), LEO spacecraft is removed from the LEO protected orbital region within 25 years, on the condition that the 90 % of the LEO spacecraft are disposed properly.

The probability is evaluated based on mainly the inherent reliabilities of disposal function. However, since the probability is depending on the several other factors (listed below) which are identified in ISO 24113:2019[1], and that some of them are unmeasurable factors, there is no method to demonstrate perfectly the compliance quantitively. Rather the compliance will be assessed with comprehensive design and operation measures and procedures as shown in ISO 24113:2019[1], from 5.4.6 to 5.4.14.

a) the uncertainties in the availability of resources, such as propellant,

b) the inherent reliabilities of subsystems, monitoring of those subsystems, and operational remediation of any observed subsystem degradation or failure, and

c) the risk that a space debris or meteoroid impact which prevent the disposal (not mandatory).

In the world normal design, the controlling of lifetime-limited items is very important to assure long-time operation. A lifetime-limited item is those that have useful life duration or operating cycles limitation, prone to wear out, drift or degradation below the minimum required performance in less than the storage and mission time. Among the series of ISO standards for program management, even ISO 23460:2011[13] doesn't mention these items clearly, though, in the world dependability assurance concept, they are usually identified as critical items and controlled severely. It is particularly important when determining the life extension of operation of spacecraft. So, it is better to understand that the following factors are included in b) above.

— the operation lifetime limited items that cause degradation or wear-out during operation, and

— the health conditions of the critical devices are monitored periodically.

For the matter of reliability, it is hard for the industry to guarantee higher than 0,9 without a very accurate data source for failure rate of components particularly for design life longer than 18 years or so. It will take time for industrial companies currently applying MIL-HDBK-217F[14] to introduce the advanced accurate data sources (e.g. FIDES) into their production procedure. One of the reasons is such an advanced database requires input for various factors or coefficients to evaluate the failure rate. As an example, in the case of FIDES, failure rate consists of the physical failure rate, the various coefficients relating to the parts manufacturing process, and the quality and technical management process. That means it requires the input of mission profile, process qualification, grade of the parts, and the results of the audit of quality control process, etc. So far ISO 24113:2019[1] doesn't require necessarily to demonstrate the reliability of disposal function is larger than 0,9. ISO 24113:2019[1] allows to consider remediating measures in the operation phase such as monitoring the system, and immediate contingency actions against the failure or degradations once they are detected. So that, even if the reliability would be lower than 0,9, operational remediation can compensate the gap with 0,9.

5.4.2 Work breakdown

Table 5 shows the work breakdown for assuring the PSD, and for disposal manoeuvre. Figure 1 shows the workflow to assure the PSD, which is based on the concept applied in the world space agencies:

Table 5 — Work breakdown for preservation of protective orbital regions

Process	Subjects	Major work
Design Phase	Operation plan	a) "Procedure for Determination of Mission Extension or Termination" is developed. It defines the specific criteria to initiate disposal action, etc.
	Disposal plan	a) Disposal plan is developed to give a baseline to design the disposal function. b) Estimation of the orbital lifetime is made.
	Design measures	a) Design the functions to remove spacecraft from the protected orbital region, or controlled re-entry, etc. b) Assure resources for disposal manoeuvre (allocate the resources for disposal manoeuvre with considering various uncertainties). c) Design the reliability of disposal function. The probability is assessed coupled with the reliability of disposal function and following design and operational remediation measures. d) Design and verify the OLIs to ensure the proper function. e) Develop the health assessment procedure for the critical items to conduct disposal operation (ISO 24113:2019[1], 6.3.1.3). f) Facilitate the monitoring system to watch the health of the critical items and detect symptom of abnormal conditions (ISO 24113:2019[1], 6.3.1.4). g) Develop a contingency plan including an off-nominal procedure for emergent actions is taken in case an abnormal condition would be detected (ISO 24113:2019[1], 6.3.1.5). h) Assess the risk that the impact of micro-debris or meteoroid would damage the disposal function and apply the protective design to protect against such impact (ISO 24113:2019[1], 6.3.1.2, ISO 16126:2014[8]).
Operation phase	Operational measures / Risk detection	a) Monitor periodically the critical parameters to detect symptoms that can lead to the loss of the disposal function (ISO 24113:2019[1], 6.3.1.4). b) Control the accumulated operation time or cycles of the OLIs to ensure the proper function. c) Estimate the residual propellants and re-allocate the propellant to assure the required quantity for disposal, if necessary. d) If an anomaly is detected, the actions specified in the Contingency Plan will be executed (ISO 24113:2019[1], 6.3.1.5). e) Determine the termination or extension of mission operation by the end of design life. In the case of extension, confirm the followings (ISO 24113:2019[1], 6.3.1.6): 1) Confirm that the "useful life limited items" have been verified to assure further operation during the new life. 2) Make an health assessment based on the monitoring survey indicates the possibility to extend the mission. 3) Confirm that the failures have been analysed and no adverse effects on further operation are not anticipated. 4) Revise the disposal plan corresponding to the change of disposal timing considering the change of orbit, the solar activities, degradation of performances, etc., and guarantee that the required amount of propellant is assured.

Table 5 *(continued)*

Process	Subjects	Major work
Follow-on	Disposal sequence	Disposal operations are executed in the proper sequence according to the pre-planned disposal plan. The disposal manoeuvre and passivation are monitored from the ground. The foreign tracking or observation facilities can be coordinated to support the complete disposal actions.
	Registration	Notify the United Nations of the end of operation or removal from orbit as early as possible.

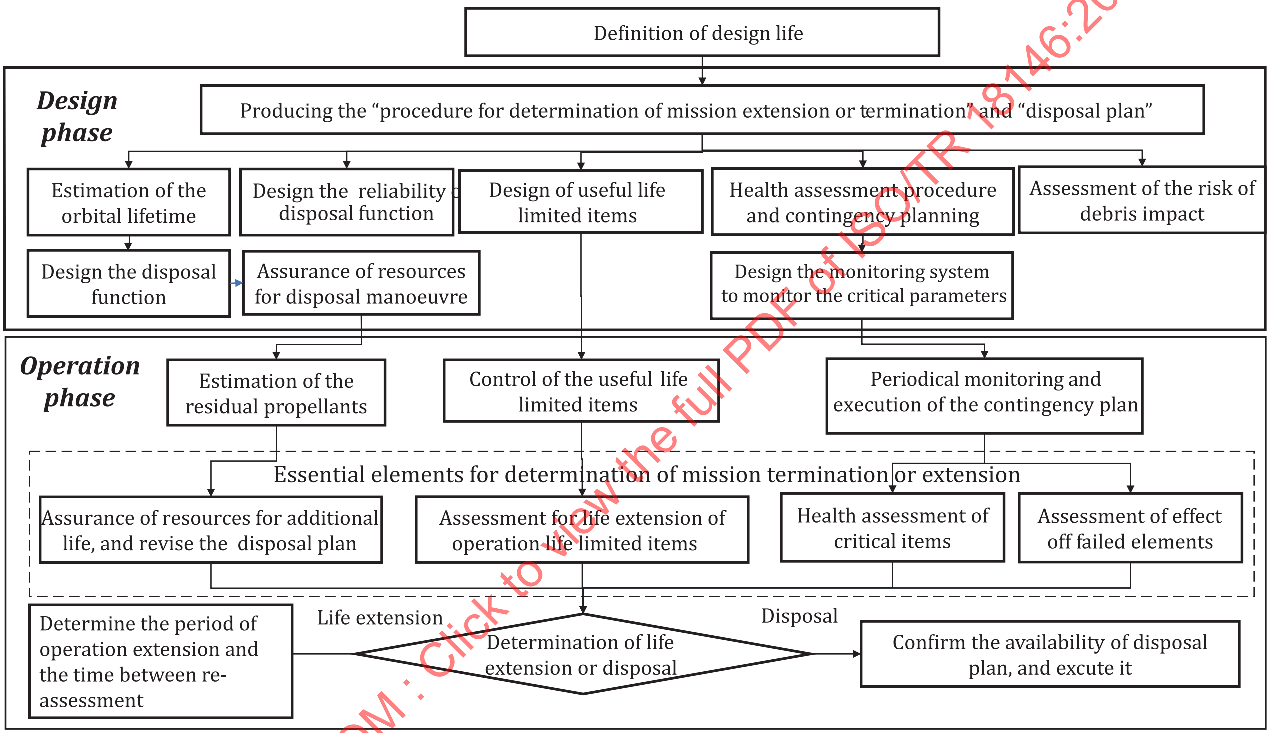

Figure 1 — Design and operation to guarantee the probability of successful disposal

5.4.3 Procedure for determination of mission extension or termination

For the proper decision to extend or terminate the mission operation at the end of spacecraft design life (or service life planned at the mission definition phase) complying with the required probability of successful disposal, a "procedure for determination of mission extension or termination" is developed. The procedure will prevent extending the operation period beyond the limit of the availability of the hardware or the resources, or causing sudden death during operation, etc. In many cases, the limit of the maximum extension of the operation period is tentatively defined, and the "operation life limited items" and "storage life limited items" are designed and verified in the ground test. The limit may be revised during operation with evaluating the status of the items considering the difference of the ground test and the actual orbital operation mode, etc.

The decision is affected with the following characteristics.

a) demand from the mission data users and stakeholders;

b) orbital characteristics (GEO, densely populated region, low altitude enough to decay soon, etc.);

c) existence of back-up spacecraft, redundant spacecraft, etc.;

d) the limit of operation time or cycles of applicable OLIs (see 5.4.9);

e) adverse effect on the orbital or ground environment in case of sudden death:

— risk of collision (large deployment device, mature of protection design, densely populated orbital region, etc.);

— risk of break-up (on-board explosive devices, common bulkhead in a propellant tank, etc.);

— risk of re-entry (expected casualties, etc.).

A “model for procedure for determination of mission extension or termination” is shown below.

A model procedure for determination of mission extension or termination

1 General

Declare the principle idea to determine of the extend or terminate mission operation, considering the orbital characteristics, mission characteristics, strength of the demand toward mission continuation, importance of successful disposal, etc.

The following are considered;

a) demand from the mission data users and stakeholders;

b) orbital characteristics;

c) existence of back-up spacecraft, redundant spacecraft, etc.;

d) the limit of operation time or cycles of applicable OLIs (see 5.4.9);

e) adverse effect on the orbital or ground environment in case of sudden death.

2 Responsible organization and person for the decision of mission extension or termination

The responsible organization and person will be appointed for proper review and decision for mission extension or termination.

3 Operation period

The planned operation period (= spacecraft design life) and tentative expected extendable operation period will be defined. (the extendable operation period will be revised during operation with monitoring and assessment for degradation, reduction of performance, residual resources, etc.)

4 Operation control

4.1 Forced termination

Define the criteria for decision of the forced termination. Examples are;

a) loss of mission function;

b) depletion of resources essential for disposal operation;

c) Critical redundancy can’t be sustained, etc.

4.2 Assessment of the residual life of the operation life limited items and storage life limited items

Identify the useful life (= “operation life” and “storage life”) and define the extendable operation period within the useful life.

4.3 Assessment of the residual resources essential for disposal operation

Define the procedure to control the residual resources for disposal operation, including planned disposal manoeuvres, required resources, etc.

The procedure includes the effect of the change of solar activities, degradation of propulsion devices, reduction of pressure gas, etc, according to the operation extension.

4.4 Health assessment of the critical items

Define the health assessment procedure for the critical items including assessment procedure and threshold for warning.

5 Assessment and reviewing of the extension or termination of the operation

The following activities are written, as examples;

a) Before the end of spacecraft design life (planned operation period), various assessment described in section 4 will be conducted, and be reviewed and endorsed to extend operation period.

b) After the initiation of the extended operation, once the abnormal symptom is detected, the status is analysed, and the adequacy of the decision to extend operation is reviewed.

c) Without any abnormal symptom, the adequacy to keep the operation will be assessed and reviewed periodically, once a year for example.

d) The adequacy to keep operation will be reviewed at every occasion that the circumstance is changed by the loss of demand for mission continuity, successful launch of successor, etc.

5.4.4 Disposal plan

A methodology for disposal manoeuvres requires the specific set of components, such as chemical thrusters, electric propulsion systems, aerodynamic drag enhancement devices, control systems for targeted re-entry or on-ground retrieval, etc. So that a disposal plan is developed in the early phase of development lifecycle before the conceptual design has not been completed.

A disposal plan includes a sequence of events (e.g. Table 6), such as disposal maneuverer, passivation, final confirmation of disposal works. In the case of controlled re-entry or on-ground retrieval, a more complex sequence is needed.

Table 6 — Disposal plan

	Sequence of Event	Work
1	Determination of disposal procedure	Select the methodology is complied with requirements written in ISO 24113:2019[1], 6.3.2 for the case of GEO mission, or ISO 24113:2019[1], 6.3.3 for LEO mission.
2	Determination of disposal maneuverer plan	Determine the disposal orbit (or re-entry trajectory) and disposal maneuverer plan considering the mass of spacecraft at the end of mission, solar activities at the end of mission, and their estimation errors. The reaction of venting fluid is taken into the maneuverer plan. If the foreign facilities and support work, such as the tracking station, command links, or observation of the re-entering are essential, its support plan is also needed.

Table 6 *(continued)*

	Sequence of Event	Work
3	Allocation of resources for disposal maneuverer (See 7.3)	a) Allocate the propellants or electric resource for disposal maneuverer (or re-entry maneuverer). b) If the aerodynamic enhancement devices are applied, allocate the resource for deployment and maintain the situation. c) Guarantee the electric resource to complete the passivation.
4	Mission termination, disposal maneuverer passivation	a) Terminate the mission operation, b) Conduct the disposal maneuverer, and confirm the final orbit, c) Conduct the break-up prevention operation (venting fluid, shut-off charging lines, etc.) d) Stop the solar paddle drivers, shut-off sensors, actuators, etc. [See Table 9 Typical sequence of disposal actions]
5	Confirmation of RF termination	a) LEO mission — Confirmation of RF termination on the ground relative to the expected time of passage. — Confirmation of no signal by RF search. b) GEO mission — Confirmation of no signal by RF search.

5.4.5 Estimation of the orbital lifetime

For LEO missions, ISO 16164:2015[15], 7.3.1 shows the steps for disposal manoeuvres. ISO 27852:2016[3] 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 the analysis which is not adequate to use in the early phase when the exact operation plan has not been fixed. Tools are selected during the design phase considering the certainty of planned orbit and disposal timing. When the spacecraft design life would be reduced or extended during the operation, the disposal plan is revised reflecting the solar activities, etc.

There are several tools available to calculate the orbital lifetime, for instance:

a) ISO 27852:2016[3] introduces STELA available via the CNES freeware server. At the June 2020, the latest version is 3.3, and can be downloaded from; https://logiciels.cnes.fr/content/stela?language=en.

b) NASA freely provides DAS (at Jun 2020, latest version is 3.0.1), which has functions to analyse various aspects of debris comprehensively, including orbital lifetime analysis (https://orbitaldebris.jsc.nasa.gov/mitigation/debris-assessment-software.html).

c) ESA provides DRAMA tool (after creating an account at https://sdup.esoc.esa.int/ one can obtain a license before downloading).

d) Other viable COTS tool kits exist to determine orbit lifetime as well.

5.4.6 Design of the function to remove spacecraft from the protected regions

If the spacecraft has an AOCS function, a simple way to transfer the spacecraft to a disposal orbit is to allocate additional propellant for the disposal manoeuvre. ISO 16164:2015[15], 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 manoeuvre.

Consider the merits that AOCS provides for not only the improvement mission quality but also for station keeping, collision avoidance, etc, it is strongly encouraged to have the AOCS function. In case that it is impossible to do so, another way is the augmenting decay by deployable device(s), refer ISO 16164:2015[15], 7.3.3.2 presenting the related requirements.

5.4.7 Assurance of resources for disposal manoeuvre

Note 1 to the definition of the "probability of successful disposal" in ISO 24113:2019[1], 3.20 indicates that "The calculation of this probability includes consideration of uncertainties in the availability of resources". So, the amount of propellant is defined not only for planned disposal manoeuvre, but also considering with the degradation of thruster performance, the precision of residual propellant measuring system, error in estimation of orbital lifetime, etc. Those uncertainty is counted as a part of the probability of successful disposal.

The monitoring system, corresponding to selected method to measure the residual propellant, is designed. See ISO 23339:2010[16].

5.4.8 Reliability of disposal function up to the design life

The reliability is assessed in the design phase based on the spacecraft design life (in other word "planned service life"). It will demonstrate potential reliability to pursue the mission conductance. At this moment, there is no requirement to re-assess the reliability after the extension of the operation period beyond the design life. Assurance of quality and availability after passing the design life is controlled by the ordinal quality and availability assurance activities with the monitoring, detection of symptom of abnormal situation, failure analyses, and contingency action, etc. Those works are out of the reliability control.

It is mentioned that the two conditions for reliability analysis. Namely the temperature for analysis and the component failure rate data sources.

a) Temperature

   The analysis condition of temperature is usually defined by the average temperature between the maximum and minimum expected design temperatures. Depending on the entities, this definition is not common. There are several formulae to get an average temperature. Also, one applies the design temperature, but others may take the temperature demonstrated by testing. There is no agreement for a common method. The relatively serious problem is that a certain entity may apply the highest temperature to take a conservative side. But a majority of entities applied the average temperature. This difference effect on the reliability to some extent. As the reliability analysis is mainly used to get a best solution for circuit design, this is not a problem. But once ISO requires the absolute value, such variation can't be ignored. In spite of such a problem, ISO standards don't designate the specific condition. It is up to the entities to select one among them. Especially for the spacecraft whose design life exceeds 15 years, this matter can't be ignored.

b) Failure rate data sources

   There is no specific requirement for the method for calculation of reliability, as long as a method known to the world is applied.

   The most widely used methodology by industry for reliability prediction is MIL-HDBK-217F[14]. But this source was developed in 1995 and has not been revised since then. Many engineers think this source has become out-dated and has limitations due to the obsolescence of its failure rate prediction models and the database incompleteness. Moreover, current prediction models are mostly addressing random failures while a significant number of in-orbit anomalies are not due to random failures and thus are not covered in current methods.

   To cover those subjects, this document introduce a model procedure to assure:

1) for electric and electronic components, the reliability analysis is applied;

2) for items that cause degradation or ware-out, identify as operation life limited items and control from on-ground operation to end of orbital operation (see 5.4.9);

3) for other critical items and EE parts suffered from radiation effects, periodical health check (see 5.4.10).

As a reference, if the reliability is calculated based on the average design temperature, it is usually larger than 0,85 for just the functions needed for disposal actions. That means, analysis is conducted for bus-part, and limiting to the function relating to disposal action. The data acquisition and storage devices can be clearly rejected, as an example. There is no standard for detailed methodology relating to the data source for failure rate of parts, such as MIL-HDBK-217F[14], or the correction factors for them. They are within the range of discretion of each entity.

5.4.9 Useful life limited items

There are items whose useful life is limited by degradation. They are called "useful life limited items" in this document. Among those items, some devices, mainly the mechanical devices such as wheels, are degraded along the operation time or cycles. They are called "operational life limited items" in this document. Others are degraded along the time. They are called "storage life limited items" in this document. They include thermal control material, coating material, cable shielding material, lubricant and other organic materials, solar battery cells, parts degraded by total dose, etc.

In the design of the spacecraft, "operational time limited items" are designed or selected to have enough margin comparing to the spacecraft design life. So are the "storage life limited items". If the operation period would be extended, the total operation period does not exceeded the "useful life" (or "limited operational life" and "limited storage life"). It is not often the case that some spacecraft are kept operation far beyond the double operation period. In such case, it is expected to declare the estimated operation life, and select or design such "useful life limited items".

In a normal case, for some "operational life limited items", the spacecraft manufactures record the accumulated operation time or cycles during the ground operation to assure enough residual life for the operation in orbit. They will transfer such record to operators to ensure enough margin of operation time or cycles for the planed operation period at the delivery time of spacecraft.

When the extension of operation time is planned, the operators of spacecraft designate "operational life limited items" to control more strictly and prepare the procedures for monitoring and keeping record of operation log in the design phase. Also, they confirm the "storage life limited items" are available during the expected operation period.

NOTE The following standards are published or being developed for materials having "storage life".

— ISO 16691.2019[17];

— ISO 23129[24];

— ISO 23230[25].

5.4.10 Health assessment procedure and contingency planning

A health assessment procedure is developed for each critical component. Examples are the following parameters of the critical devices to assess their health.

a) Electric power
   1) Bus voltage at power distribution box
   2) Battery voltage / Cell voltage
b) Instrumentation
   1) Power consumption at power distribution box
c) Solar paddle
   1) Generated power
   2) Drive voltage at the paddle driving mechanism
d) Propulsion
   1) Power consumption in valve driving circuit
   2) Temperature of catalyst bed
   3) Pressure in the propellant tank
   4) Temperature in combustion chamber of apogee engine / thrusters
   5) Pressure of pressure gas / propellant
e) TT&C
   1) Power consumption in telemetry (TLM) and command (CMD) devices
   2) Power consumption TLM/CMD repeaters
   3) TLM transmitter; power consumption, output power, transmission frequency
   4) CMD receiver: power consumption, receive power
   5) AGC telemetry voltage (MTP)
f) Attitude and orbit controller
   1) power consumption in AOC electronics, star tracker, GPSR
   2) IRU motor current, friction torque in RW

In addition, for electronic and electric parts, the total dose and single event failures are also monitored and taken adequate actions to prevent failures. Just for the reference, many ISO standards have been published to identify the space environment.

The health assessment procedure will help to know the symptoms of failures and prevent from sudden loss of function. ISO has published ISO/TR 20891:2020[18] for Li-ion batteries.

Such procedures will induce the specific criteria for initiating disposal.

The monitoring procedures will be developed including the monitoring parameters, identification of normal / abnormal range of each parameter, off-nominal procedures for the case of violating the normal range.

A contingency plan will be developed for each serious off-nominal case to assure the immediate actions.

5.4.11 Design the monitoring system to monitor the critical parameters

The monitoring system will be designed according to the specifications induced from the health assessment procedure for OLIs and critical components. For each monitoring parameters, off-nominal procedures are developed by manufactures and transferred to the operators. It also helps for the proper decision-making to terminate operation with knowing the limit of resources for disposal actions.

A monitoring system for the disposal function and for estimating residual propellant is required in ISO 16164:2015[15], 7.4 (also in ISO 16127:2014[4], 5.3).

Calculation of propellant reserves are discussed in ISO 23339:2010[16].

5.4.12 Assessment of the risk of debris impact

Generally, in the case of large LEO spacecraft, the impact of micro-debris or meteoroid will not be ignored to preserve the disposal function. The requirement to assessing of the risk that a space debris or meteoroid impact will prevent the disposal is duplicated in both ISO-24113:2019[1], 3.20, Note 3 to entry and 6.3.1.2. It is written that this is not mandatory in ISO-24113:2019[1], 3.20, Note 3 to entry. The risk assessment may be conducted together with the risk assessment for break-up caused by debris impact. See 5.3.4.6.

To complete the assessment according to ISO 16126:2014[8], the specifications for mission operation and hardware design of spacecraft, material data including ballistic limit curves, and applicable analysis codes and models are prepared.

The risk assessment procedure is defined in ISO 16126:2014[8] and consists of:

a) confirmation of spacecraft orbital parameters and design architecture;

b) identification of vulnerable components as critical components, which contribute to the post operation disposal, and those that can be potentially damaged by impact to lose their functions (see ISO 16126:2014[8], 7.3); the IADC Protection Manual[10], which is referred to by ISO 16126:2014[8] in the bibliography provides the information about components to consider;

c) 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 16126:2014[8], Annex C will support it;

d) conduct failure probability analysis with selecting impact risk analysis codes, and the space debris and meteoroid environment models; ISO 14200:2012[9] provides guidance on the selection of space debris and meteoroid environment models;

e) 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}).

If design improvement would be planned, the IADC Protection Manual[10] provides the examples of measures.

5.4.13 Operational remediations

5.4.13.1 General

The following activities are useful as operational remediations to improve the probability of successful disposal.

5.4.13.2 Periodical monitoring

As mentioned in 5.4.11, critical parameters are monitored.

5.4.13.3 Control of the operation life limited items

The spacecraft operators periodically monitor and calculate the accumulation of operation time or cycles, and the lifetime analysis is conducted to know the residual life. When the extension of operation is determined, the additional operation time is endorsed by the residual life of useful life.

In the case that the operation period is extended, as mentioned in 5.4.9, keep recording the operation log of the operation life limited items, and analyse the residual life.

5.4.13.4 Estimation of the residual propellants

The residual propellants are evaluated during operation. See ISO 23339:2010[16].

If there were events which required extra expenditure of propellant (such events as collision avoidance and return to original orbit, safe-mode operation and back to normal operation, leakage of propellants, etc.), the allocation of propellant is revised during operation.

The termination of the operation is determined before the moment that the necessary amount of propellant can't be guaranteed any longer.

The necessary amount of propellant is changed according to the extension of the operation period. It will be changed due to the solar activities, degradation of the performance of thrusters, pressure drop of gas tank, changing the mass of spacecraft, changing of the final disposal orbit, etc. Then the necessary amount of propellant is re-estimated at every epoch of extension of the operation period.

5.4.13.5 Execution of the contingency plan

If any symptoms for failures would be detected, the adequate actions would be executed, according to the off-nominal procedures or the contingency plan.

The failures occurred during operation are analysed to determine if the adequate actions to continue the operation can be taken, or if the operation is terminated to proceed with the disposal action.

5.4.14 Decision-making to extend or terminate the mission

The decision of operation period extension will be done on the conditions mentioned in from 5.4.5 to 5.4.13.

a) All the useful life limited items have enough margin for planned extended operation period (see 5.4.9 and 5.4.13.3).

b) The health condition of the critical devices is within the acceptable range to extend the mission (see 5.4.10 and 5.4.11).

c) Failures occurred during operation have been analysed and no adverse effects on further operation are anticipated (see 5.4.13.5).

d) Resources can be allocated for the extended operation period, considering the degradation of performance, the change of the solar activity, possible changes of disposal manoeuvres, etc. (see 5.4.13.4).

e) The mission objective is worth extending.

The period of operation extension, and the time between re-assessment to confirm the termination or extension are determined.

The decision to terminate operation will be done by the time that the propellant for disposal can be assured, and other criteria will be satisfied to guarantee the successful disposal (ISO 16164:2015[15], 7.4).

When directed to terminate operations, mission users and other stakeholders will be notified.

5.4.15 Disposal

In the case that mission termination is decided, the disposal actions will be conducted according to the disposal plan (see. 5.4.4). Detailed sequence is introduced in 6.9.

5.4.16 Registration of objects launched into outer space complying with the UN treaty

Operators are 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 includes "any change of status in operations (e.g. when a space object is no longer functional)". Operators (or the national governments which control the operators) 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.

5.4.17 Specific subjects for GEO mission

ISO 24113:2019[1], 6.3.2 requires removing a GEO spacecraft or launch vehicle orbital stage from the GEO protected regions after end-of-mission.

Detailed requirements and procedures are defined in ISO 26872:2019[19], Clause 8. It requires disposal planning and the development of an EOMDP.

5.4.18 Specific subjects for LEO mission

ISO 24113:2019[1], 6.3.3.2 requires removing a LEO spacecraft or launch vehicle in orbital stage from the protected regions after the end-of-mission, including the definition of "starting time to count 25 years", and several options for disposal manners:

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 a high altitude 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.

5.4.19 High elliptical orbit mission

In the case of the "high elliptical orbit mission", if it would be left in the operating orbit, it may pose a risk to both GEO and LEO protected regions.

It is desirable to place the perigee altitude as low as possible to limit orbital lifetime to shorter than 25 years. However, as explained in ISO 27852:2016[3], 5.6, since it is difficult to estimate the lifetime in a high elliptical orbit with a specific value, the maximum lifetime corresponds to the planned perigee altitude with an indication of its probability (e.g., if the perigee will be sent to 200 km, the lifetime will be shorter than 25 years, with a probability of 0,9).

Since it is unavoidable to induce such a probabilistic method, this probability can be excluded from the probability of successful disposal (>0,9) mentioned in ISO 27852:2016[3], 6.3.1.1.

5.5 Ground safety from re-entering objects

5.5.1 Intents of requirements in ISO 24113:2019[1]

ISO 27875:2019[20] 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 27875:2019[20] doesn't specify quantitative criteria for the expected number of casualties; these criteria are defined by appropriate regulatory bodies. But ISO 24113:2019[1], 6.3.4.2, NOTE 2 introduces that several existing guidelines and regulations use 10^{-4} as the threshold for the expected number of casualties. But there are no standard method, tool or analysis conditions agreed in the world.

5.5.2 Work breakdown

ISO 27875:2019[20] specifies the risk assessment procedure.

Table 7 shows the work breakdown for assuring ground safety from re-entry.

Table 7 — 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 is 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 can reach the ground, fragment fall back footprint size and its estimated falling location, etc.)
	Design measures	a) Design for demise is incorporated (see 5.5.5.1). b) Prevent the environmental pollution on the ground. c) If the expected number of casualties is larger than requirement, the controlled re-entry is planned.
Risk detection	Notification of impact	For controlled re-entry, notifications are sent to all countries that may be affected or sent through the NOTAM system.
Countermeasures	Conduct controlled r-entry and Monitoring	a) Conduct controlled re-entry as planned. b) Monitor the re-entry procedure and take adequate action in abnormal situations.

5.5.3 Identification of requirements

The first step is identification of re-entry safety requirements imposed contractually, voluntarily, or by national or international authorities.

ISO 27875:2019[20] provides procedures for assessing, reducing, and controlling the potential risks that the re-entering spacecraft and launch vehicle orbital stages pose to people and the environment, but does not show quantitative criteria even for the risk of expected number of casualties (Ec), which is defined by appropriate regulatory bodies. ISO 24113:2019[1], 6.3.4.2, NOTE 2 introduces the quantitative threshold as 10^{-4} in very soft way.

NOTE ISO 24113:2019[1], 6.3.4 mentions “casualty risk”, but, as ISO 27875:2019[20] mentions, there are other risks including environmental pollutions. Therefore “re-entry risk” is understood as comprehensive risk defined by approving agents.

ISO 27875:2019[20] adds the requirement for controlled re-entry concerning the planning, risk assessment, notification, post re-entry activities.

5.5.4 Hazards analysis

According to ISO 27875:2019[20], Clause 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 can 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, the impact area will be controlled according to ISO 27875:2019[20], Clause 6. Because the system concept may be affected significantly depending on whether the re-entry is controlled or not, decisions are made by the preliminary design review when the "system technical specifications" will be approved. In either case, hazards analysis is performed both to uncontrolled and controlled re-entry.

NOTE 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 formulae 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 provided by NASA as a very simple tool, available at https://orbitaldebris.jsc.nasa.gov/mitigation/debris-assessment-software.html,

b) SARA(Survival and Risk Analysis) in DRAMA tool is provide by ESA, (an account at https://sdup.esoc.esa.int/), and

c) DEBRISK tool by CNES (needs an agreement of CNES to download).

5.5.5 Design measures

5.5.5.1 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 taken in the design phase:

a) Selection of materials

Whenever possible, materials with a high melting temperature, specific heat, and heat of fusion, such as titanium or beryllium, are 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.

b) 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.

c) 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 can 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 is designed with adequate materials and is separated into multiple layers, instead of one thick, solid mass.

d) 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.

5.5.5.2 Prevention of environmental pollution on the ground

Efforts are made to avoid polluting the environment with toxic substances (including radioactive materials) as required in ISO 27875:2019[20], 5.6. However, few problems are anticipated, unless nuclear reactors are installed on-board.

5.5.6 Specific design for controlled re-entry in subsystem level

Corresponding to the system level requirement to controlled re-entry mentioned in ISO 27875:2019[20], Clause 7, subsystem engineers 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 is made in an early phase of planning, prior to defining the system.

a) 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 is designed.

b) Attitude and orbit control subsystem

To support controlled re-entry (in addition to the functions and performance required for normal space operation), the AOCS includes functions to determine and control orbit, attitude, and position in low altitude through the final burn (as stated in 8.4.2.2).

c) TT&C subsystem

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

d) 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.

5.5.7 Notification

ISO 27875:2019[20], 7.5 requires notification in the case of the planned re-entry event.

5.5.8 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.

5.6 Quality and reliability assurance

It is important to ensure enough quality and reliability for the bus subsystem. ISO 16127:2014[4], 5.1 contains the requirements for reliability and quality control to prevent failures that can lead to a break-up event.

The methodology for assessing break-up probability and the probability of successful disposal are provided in ISO 24113:2019[1], 6.2.2 and 6.3.1. A big event in terms of the quality and reliability control in ISO 24113:2019[1] is that the quantitative requirement for the probability of successful disposal which largely depends on the reliability of disposal function was added. In the current situation that there are no quantitative requirements on the reliability in other ISO standards relating to the programme management, it was a big challenge. This document aims to find the way to show the compliance with such requirement as seen in 5.4.

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 is noted that spacecraft of low quality may become debris immediately after injection into orbit and can pose a risk to other space operators.

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 27025:2016[21] provides the quality assurance system, and wider scope consists of product assurance, quality assurance, and ISO 23460:2011[13] provides dependability assurance.

6 Debris-related work in the development cycle

6.1 General

A typical phased planning of development lifecycle can be illustrated, as in Figure 2, according to ISO 14300-1:2017[22].

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

6.2 Concept of debris-related work in phased planning

The following debris-related activities will be considered in each phase (see Table 8):

a) 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 for the feasibility phase, as defined in ISO 14300-1:2017[22], 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 are identified as a part of requirements, such as design requirements and regulatory constraints.

b) The feasibility phase (phase A) consists of exploring the various possible concepts to meet the defined objectives (performance, cost and schedules), as defined in ISO 14300-1:2017[22], 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 reliability of disposal function, which affect system design and cost.

c) 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 14300-1:2017[22], 8.2.4. All the major debris mitigation and protection concepts that impact functions, performance, allocation of resources, reliability, and so on are reflected in the system level technical specification.

d) 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 14300-1:2017[22], 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.

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

f) 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.

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

Through all above 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 5; subsystem and component-level information is in Clause 6.

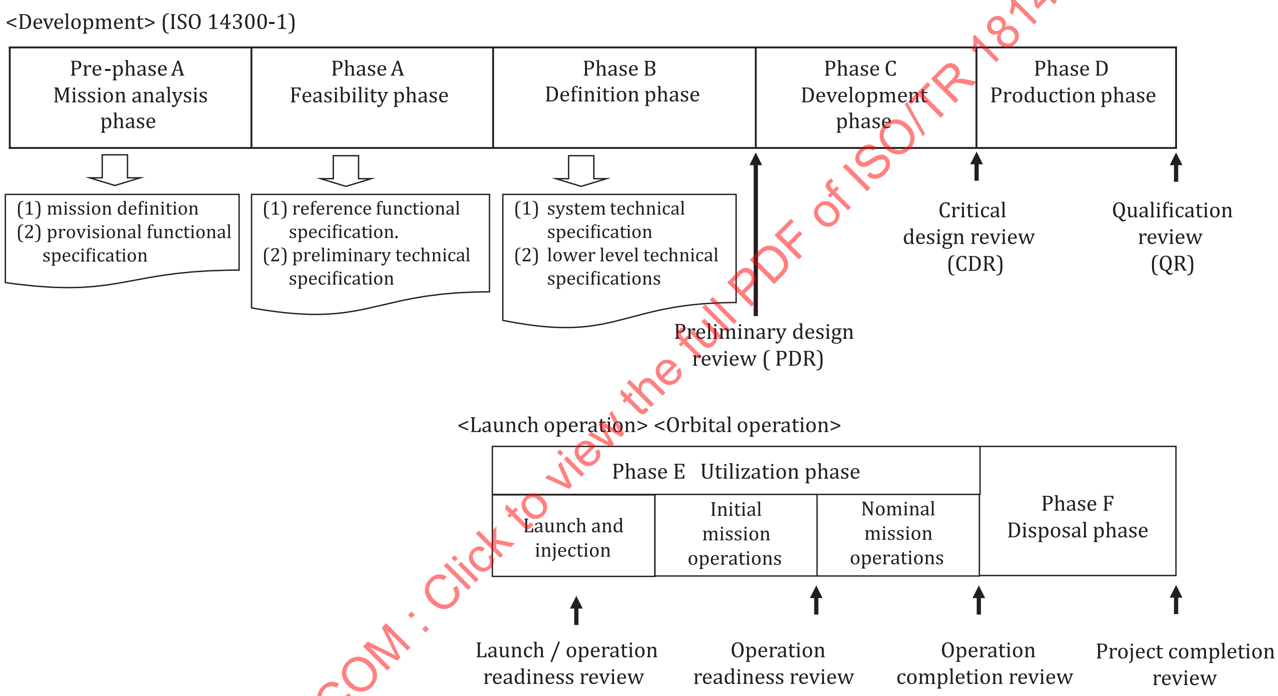

Figure 2 — Typical phased planning of development lifecycle

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**
System-level work	a) Input debris related requirements. b) Fix the debris mitigation philosophy and reflect on the "functional specification" and "preliminary system technical specification".	a) Produce a "procedure for determination of mission extension or termination" and a "disposal plan". b) Propellant allocation (including the disposal manoeuvre, collision avoidance, controlled re-entry, etc.). c) Mass allocation (including protection shields, etc.).	Transfer debris-mitigation plan to operators.	Final determination for disposal action (including disposal manoeuvre, break-up prevention, controlled re-entry).
Quality assurance	a) Clarify QA design philosophy. b) Define QA program including parts program.	Confirm that the probabilities for successful disposal and non-break-up, and other probability required in launching state, or the mission requirements.	Identify a disposal action for use in case of failure.	Ensure that the probability of successful disposal is complied with requirement.
Limiting debris generation (ISO 24113:2019[1], 6.1)	Clarify debris-mitigation design philosophy.	a) Fix the design to prevent the releasing objects, limit their orbital lifetime, etc. b) Identify the energy sources of break-up, and design to prevent them.	Monitor critical parameters to check symptoms of critical malfunctions that lead to break-ups or prevent disposal actions.	a) Vent residual energy. b) Terminate operation in the proper sequence.
Disposal (ISO 24113:2019[1], 6.3)	a) Clarify disposal concept. b) Estimate propellant for disposal.	a) Define a "procedure for determination of mission extension or termination" and a "disposal plan". b) Design a propulsion system for the disposal manoeuvre.	Monitor the residual propellant and decide to terminate operation timely.	Remove spacecraft to avoid interference with protected regions.
Re-entry safety (ISO 24113:2019[1], 6.3.4)	a) Clarify re-entry safety concept. b) Define the analysis method. c) Determination for controlled re-entry.	a) Define an operational procedure for the safe re-entry. b) Design a propulsion subsystem and attitude control system for controlled re-entry, if needed.	—	Conduct controlled re-entry.

Table 8 *(continued)*

	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**
Collision avoidance	a) Clarify avoidance concepts. b) Define debris population model to estimate the frequency of the collision avoidance manoeuvre.	a) Define an operational procedure for collision avoidance and return to original orbit. b) Design a propulsion subsystem for collision avoidance. c) Allocate an amount of propellant for avoidance manoeuvres.	Perform periodic conjunction analysis, and determine the avoidance manoeuvres, if needed.	—
Impact protection	a) Clarify protection design philosophy. b) Define the debris population model and ballistic limit equations. c) Estimate mass for shielding.	a) Protection design for vulnerable components to guarantee disposal function at least.	—	—

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

6.3.1 General

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

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

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

c) 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 16404:2020[23]. Traditionally, the following aspects are considered in requirement analysis:

— requirements from mission users;

— constraints of the launching system;

— constraints of the spacecraft bus system;

— constraints of the ground facility;

— legal regulations.

Although ISO 16404:2020[23] doesn't address the issue of debris, this document suggests paying attention to the following debris mitigation measures during the work of "definition of mission requirements":

— reduction of risk caused by the impact of micro-debris and collisions with orbital objects;

— safety on ground from re-entry.

6.3.2 Debris-related work

a) Identification of debris-related requirements

Debris-mitigation requirements are identified in ISO 24113:2019[1]. If there are other applicable debris-related regional and national regulations, they are also considered, and the final set of requirements is identified.

b) 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.

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, consideration will be made. Some recommendations will be provided to the users for preservation of the orbital environment upon demand.

6.4 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 considered.

Due to limited required resources (e.g., mass, quantity of propellant, electric power, communication capacity), allocation is coordinated among the mission equipment and bus elements in the later phases. Regarding 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..

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.

a) reorganization of debris-mitigation requirements in accordance with ISO 24113:2019[1] and other debris related documents,

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

c) plan for collision avoidance,

d) plan for protection design, and

e) quality assurance to comply with the debris mitigation requirements, and to contribute on the sustainability of space activities.

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

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

6.5 Definition phase (phase B)

6.5.1 Work in phase B

In this phase, the system requirements are defined in a system technical specification as specified in ISO 14300-1:2017[22].

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 are fixed during this phase at the latest.

The plan for complying with ISO 24113:2019[1] is defined in an SDMP as defined in ISO 24113:2019[1], 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 SDR.

6.5.2 Work procedure

a) 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 developed.

Design architecture will be determined considering the debris issues, including the survivability in the debris environment. The probability of breakup due to the impact of space objects will be assessed based on the requirement in ISO 24113:2019[1], 6.2.3.4. The result of the assessment will support to determine the operation orbit region and design architecture of the spacecraft to minimize the risk of impact.

b) Debris mitigation measures in system design

1) In the allocation of propellant, the propellant for disposal manoeuvres, controlled re-entry manoeuvres, and collision avoidance manoeuvres will be considered.

2) In the allocation of mass, beside the propellant mass mentioned above, the mass increase for protection shields (if any) will be considered.

3) 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.

4) 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, beryllium, etc. are minimized if 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.

6.6 Development phase (phase C)

6.6.1 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 SDMP.

During the above procedure, the following are considered:

a) 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 another spacecraft operating in orbit. (ISO 16127:2014[4], 5.1)

b) Break-up prevention and safety control

1) 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 16127:2014[4])

2) In order to detect malfunctions that may induce break-up, and to conduct disposal actions before the complete loss of operation functions, a spacecraft is designed to enable monitoring of critical parameters during operation. (ISO 16127:2014[4], 5.3.1)

c) Prevention of releasing parts

According to ISO 24113:2019[1], 6.1, spacecraft is 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.

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

Assess the risk of impact of micro-debris according to ISO 16126:2014[8]. If the risk can't be ignored, protective measures are 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.

e) Collision avoidance manoeuvre

To avoid collision from orbital objects observable from the ground, procedures for conjunction analysis are developed and criteria for the choice of avoidance manoeuvres are identified, and avoidance manoeuvre sequences are designed. The required ground infrastructure, analysis tools, communication lines with relevant organizations, and the decision-making process for conducting avoidance manoeuvres are also identified. (ISO/TR 16158:2019[7])

The passive tracking means (e.g., radar, optical and passive RF) attached on a space system will realize the reliable tracking from the ground. Space systems with limited observability, or those lose function of communications, will be helped by features that enhance visibility (e.g., laser retroreflectors and/or radar-cross-section enhancements). Getting the cooperation of the global network of the International Laser Ranging Service (ILRS) the variability of this reflectors will be increasing.

f) 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 23339:2010[13])

g) Safety assurance from ground impact after re-entry

1) According to ISO 27875:2019[20], the expected number of casualties will be estimated, and the safety on the ground is assured.

2) 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, enough 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 27875:2019[20])

6.6.2 Conditions

The following are completed before the design phase initiation:

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

b) 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.).

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

6.7 Production phase (phase D)

6.7.1 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.

6.7.2 Qualification review

Prior to qualification review, the final design and manufacturing procedure is confirmed to meet the requirements specified in the SDMP. The following are reviewed:

a) list of parts that are designed to separate or release;

b) list of sources of break-up energy, and disposal procedures for removing them after the end of operation;

c) a monitoring system for detecting critical malfunctions that may cause break-up or prevent disposal operations;

d) a disposal operation plan and data that are transferred to the operation phase, including procedures for determining when to terminate the mission, the disposal operation plan, etc.;

e) ground casualty expectations, if the spacecraft will be disposed of by decaying its orbit;

f) review of the operation plan, if controlled re-entry is planned;

g) plan for notifying air traffic and maritime traffic authorities, in the case of controlled re-entry;

h) protection and collision avoidance measures against the impact of debris.

6.8 Utilization phase (phase E)

6.8.1 Launch preparation

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

Before proceeding to the nominal operation phase, the following is confirmed:

a) SDMP and the related status;

b) list of parts that will be released into orbit, as designed;

c) 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.;

d) a precise description of a monitoring system for critical parameters, and a monitoring procedure and contingency plan for the case of detecting malfunction;

e) a decision-making process in case a malfunction is detected that can lead to fragmentation, loss of operation function, or a lack of propellant for disposal manoeuvres;

f) a procedure for a conjunction assessment and collision avoidance manoeuvres;

g) status of the protection of components against the impact of micro-debris;

h) procedure and criteria for deciding to terminate of operation:

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

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

   3) re-entry control plan.

6.8.2 Lift-off time

Lift-off time may be coordinated to ensure that neither orbital stages nor payloads will risk 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.

6.8.3 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 considering the propellant required for collision avoidance manoeuvres and disposal manoeuvres.

Design information related to debris mitigation is transferred to the operation team. Specifically, the followings are confirmed:

a) 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;

b) criteria for the choice of collision avoidance manoeuvres, and practical procedures for avoiding collision;

c) periodical monitoring of critical parameters, and contingency planning for the case of failure detection;

d) target disposal orbit.

6.8.4 Normal operation

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

a) critical parameters for detecting symptoms of malfunctions that may lead to fragmentation or loss of mission function, so that immediate action can be taken;

b) 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;

c) residual propellant, to ensure that enough propellant remains to complete planned disposal manoeuvres.

In addition, the following environmental changes are monitored, so that action can be taken regarding attitude control or a change to a safe mode of operation:

— meteor showers;

— the generation of debris clouds due to fragmentation.

6.8.5 Decision to terminate or extension of operations

The decision to terminate or extension of operation is conducted according to the "procedure for determination of mission extension or termination" mentioned in 5.4.3.

6.9 Disposal phase (phase F)

Disposal actions will be conducted as follows in accordance with ISO 16164:2015[15] or ISO 26872:2019[19]:

a) At the end of operation, a planned disposal manoeuvres defined in the SDMP is conducted.

NOTE 1 The conjunction analysis is conducted for the targeted disposal orbit. Although, under the condition that the amount of residual propellant cannot be measured precisely, the disposal orbit can't be estimated precisely, and the conjunction analysis also can't be conducted precisely, the disposal manoeuvres will be done as far as possible.

b) 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.

c) 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 2 The United Nation's "Convention on Registration of Objects Launched into Outer Space" also needs information of the termination of operations.

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: Re-orbit at a higher orbit. b) LEO: Reduce orbital lifetime below 25 years or take other measures described in ISO 24113:2019[1], 6.3.3. 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.

Table 9 *(continued)*

	Event	Actions
6	Confirmation of the termination of communication lines	a) Confirm the termination of communications systems using a ground station.

7 System-level information

7.1 Mission design

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

a) 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. The operation orbit is selected is less affected by debris and is lower altitude for shorter orbital lifetime.

b) 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.

7.2 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
a) Debris mitigation 1) Limiting the release of objects	i) mass of bolt catchers and other devices to hold fragments of fastener, etc.
2) Prevention of fragmentation	i) mass of monitoring systems to detect critical failures ii) mass of the venting mechanism, shut-off relay for battery charging lines, etc.
3) Prevention of slag ejection	i) mass of the additional solid propellant if metal free low performance propellant will be applied ii) mass of vehicle structure will be increased if the submerged nozzle is not applied to avoid generation of slag
b) Collision avoidance	i) additional propellant for avoidance manoeuvres, although it can be almost negligible usually
c) Protection against impact of micro-debris	i) mass of the protection shields or bumpers ii) additional redundant devices, fuses for short circuits, etc. iii) shift of the centre of gravity due to re-allocation of critical components behind structures
d) Disposal manoeuvre	i) additional propellant for disposal manoeuvres
e) Re-entry safety	i) additional propellant for controlled re-entry

7.3 Propellant allocation

For spacecraft in LEO, the quantity of propellant will be chosen with following aspects:

a) compensation for orbit-injection error caused by the launch vehicle;

b) orbit and attitude control during mission operations;

c) disposal operations (shorter orbital lifetime or transfer to outside of the protected orbit regions);

d) orbit change manoeuvres and following targeted re-entry for a controlled re-entry;

e) collision avoidance manoeuvres (estimated with the expected number of avoidance manoeuvres);

f) recovery from safe mode (estimated based on the expected annual number of safe mode operations);

g) estimated margin of error for propellant (6 % to 10 %);

h) safety margin.

7.4 Power allocation

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 enough margin in the design of the power supply.

8 Subsystem/component design and operation

8.1 General

During the design phase, the requirements defined in ISO 24113:2019[1] 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.

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

Clause 5 introduced system-level design concepts. This clause 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.

Especially, ISO 24113:2019[1], 6.2.3 requires having a recurrent manoeuvre capability to actively manage collision risk.

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				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						

8.3 Propulsion subsystem

8.3.1 General

This subclause applies to the apogee engine, and the thrusters for the AOCS, as listed below.

a) hydrazine thrusters;

b) bi-propellant engine and thrusters;

c) solid motor.

However, ISO 24113:2019[1], 6.1.2.2 requires not to release the slag from solid motors in both LEO and GEO protected regions, which practically means to prohibit use of solid motors for apogee kick motors for both GEO and LEO missions.

8.3.2 Debris-related design

The items considered in design or operation are shown in Table 12.

Table 12 — Debris-related measures in the propulsion subsystem, including 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 (For LES)	Yes		Yes		
Re-entry control (For LES)	Yes	Yes	Yes		
Collision avoidance	Yes	Yes	Yes		
Protection from the impact of micro-debris	Yes		Yes	Yes	

8.3.3 Information of propulsion subsystems

8.3.3.1 Prevention of the release of objects

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

a) slag from solid motors, disposal-type igniters and nozzle closures (see 8.3.4.1);

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

8.3.3.2 Break-up prevention

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

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

a) failures of solid motor;

b) an explosion due to malfunctioning of the engine and/or thruster during operation;

c) an explosion due to the mixing of a homogeneous set of fuel and oxidizer;

d) the rupture of a high-pressure vessel, such as the gas reservoir and propellant tank;

e) 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 is presented in 8.3.4:

— The reliability of components that may cause break-up is designed to limit the probability to less than 0,001 for the total spacecraft system.

— A liquid propulsion subsystem is designed to vent residual propellant and other fluids when they are no longer needed or, at the end of operation.

— Because critical parameters are monitored according to ISO 16127:2014[4], sensors are installed to detect and avoid failures by providing data to FDIR systems.

8.3.3.3 Disposal manoeuvres

A propulsion subsystem is designed to ensure successful disposal manoeuvres (see 8.3.4.3 and 8.3.4.4).

The required velocity and propellant consumption will be estimated according to ISO 16164:2015[15], Clause 8 and ISO 23339:2010[16].

NOTE 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 is confirmed by ISO 26872:2019[19].

8.3.3.4 Ground safety from re-entry

8.3.3.4.1 General

ISO 27875:2019[20], Clause 6 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 8.3.4.4).

8.3.3.4.2 Controlled re-entry

Consistent with ISO 27875:2019[20], 6.2, if the expected number of casualties would be larger than required, controlled re-entry into a safe area is 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 8.3.4.2 and 8.3.4.4).

8.3.3.5 Collision-avoidance manoeuvres

The thrusters for AOCS 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 are estimated based on the probability of a collision. See 5.3.3.4 for an estimation of number of collisions.

8.3.3.6 Protection from the impact of micro-debris

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