TECHNICAL REPORT

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Space systems - Debris mitigation design and operation manual for launch vehicle orbital stages

Systèmes spatiaux - Conception pour l'attenuation des débris et manuel d'utilisation à étages orbitaux pour les véhicules de lancement

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Foreword

The International Organization for Standardization (ISO) is a worldwide federation of national standards bodies (ISO member bodies). International Standards are generally prepared by ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to represent that committee. International organizations, both 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 (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 (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 on the meaning of ISO specific terms and expressions related to the conformity assessment, as well as information about ISO's adherence to the World Trade Organization (WTO) principles in the Technical Barriers to Trade (TBT).

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

Introduction

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

ISO 24113 "Space debris mitigation requirements," and other ISO documents, introduced in Clause 4, were developed to encourage debris mitigation. Table 1 shows those requirements together with the recommendations in the United Nations Space Debris Mitigation Guidelines and the Inter-Agency Space Debris Coordination Committee (IADC) Space debris guidelines referred to in the United Nations (UN) guidelines.

Table 1 lists the main debris mitigation requirements defined in the standards and compares them to equivalent recommendations published by the UN and the IADC.

In Clause 5, the main space debris mitigation requirements are reported and analyzed.

In Clause 6, the guidance for life-cycle implementation of space debris mitigation related activities are 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.

In this document, where the content is not directly required by existing ISO Standards but considered relevant to launch vehicle orbital stages operations or design and debris mitigation, it is labelled as "[Information]."

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

	Measures		ISO Standards (or Technical Reports)	UN Guidelines	IADC Guidelines
Limiting debris generation	**Released objects**	General measures for avoiding the release of objects	**ISO 24113, 6.1.1**	Recommendation-1	5.1
		Slag from solid motors	**ISO 24113, 6.1.2.2, 6.1.2.3**	--	--
		Combustion products from pyrotechnics	**ISO 24113, 6.1.2.1** (Combustion Products < 1 mm)	--	--
	On-orbital break-ups	Intentional destruction	**ISO 24113, 6.2.1**	Recommendation-4	5.2.3
		Accidental break-ups during operation	**ISO 24113, 6.2.2** (Probability < 10^{-3})	Recommendation-2	5.2.2 (Monitoring)
		Post-mission break-up (Passivation, etc.)	**ISO 24113, 6.2.2.3** (Detailed in ISO 16127)	Recommendation-5	5.2.1
Disposal at end-of-operations	**GEO**	Reorbit at end of operation	**ISO 24113, 6.3.2** (Detailed in ISO 26872) 6.3.2.1: General Requirement 6.3.2.2: 235 km+ (1 000•Cr•A/m), e < 0,003 6.3.1: Success Probability > 0,9	Recommendation-7 (No quantitative requirements) Note: ITU-R S.1003-1 recommends; 235 km + 1,000 *Cr*A/M* Here, A[m^2], M[kg], Cr[-]	5.3.1 235 km+ (1 000•Cr•A/m), e < 0,003
	LEO	Reduction of orbital lifetime	**ISO 24113, 6.3.3** (Detailed in ISO 16164, 16699) 6.3.3.1: Orbital lifetime after end of operation < 25 years 6.3.1: Success Probability > 0,9	Recommendation-6 (No quantitative requirements)	5.3.2 (Recommend 25 years)
		Transfer to out of protected region	**ISO 24113, 6.3.3.2 (f)** (Guarantee 100 years of non-interference)	Mentioned in Recommendation-6	5.3.2
		Other options	**ISO 24113, 6.3.3.2 (a) ~ (e)**	--	5.3.2
Re-entry		Avoidance of ground casualties	**ISO 24113, 6.3.4** (Detailed in ISO 27875)	Included in Recommendation-6	5.3.2
Collision avoidance for large debris			**ISO/TR-16158** (for assessment only)	Recommendation-3	5.4
Protection from the impact of micro-debris			**ISO 16126** (for assessment only)	--	5.4

Space systems - Debris mitigation design and operation manual for launch vehicle orbital stages

1 Scope

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

This document can be used to guide engineers in the application of the family of space debris mitigation standards (see 4.2) to reduce the growth of space debris by ensuring that launch vehicle orbital stages are designed, operated, and disposed of in a manner that prevents them from generating debris throughout their orbital lifetime.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

There are no normative references in this document.

3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 10795:2011 and the other standards listed in 4.2, 4.3, and 4.4 apply.

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

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

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

4 Related documents and abbreviated terms and symbols

4.1 Overview of ISO debris-related standards

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

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

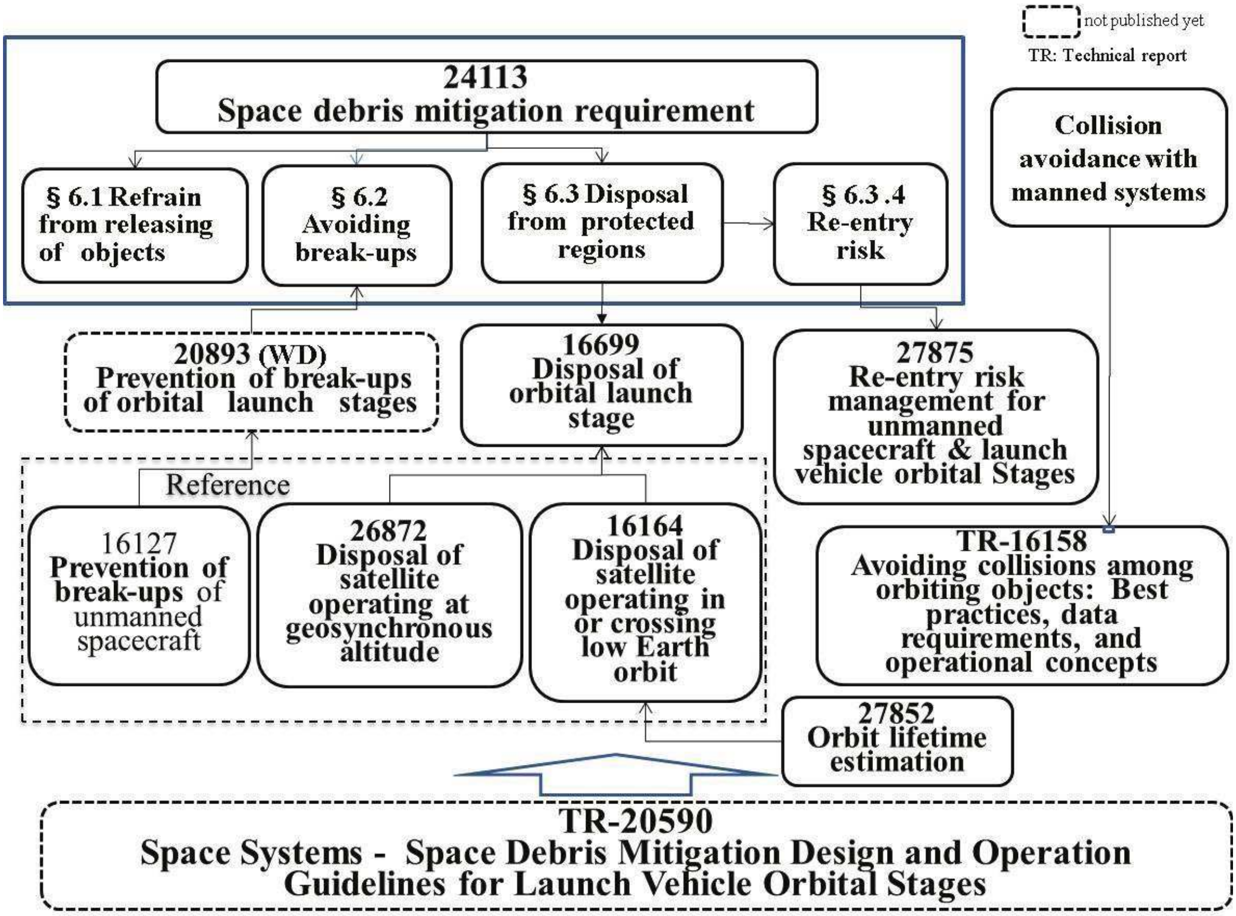

Figure 1 — Structure of major debris related standards for orbital stages

4.2 ISO debris-related standards for launch vehicles as of 2016

The following ISO Standards have been developed to address space debris mitigation. Readers are expected to confirm the most up to date list of ISO standards (available at http://www.iso.org/iso/store.htm. Also for 4.3 – 4.5).

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

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

(3) ISO 16699:2015, *Space systems — Disposal of orbital launch stages*

(4) ISO 20893, *Space systems — Prevention of break-up of orbital launch stages*

4.3 Spacecraft related ISO standards

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

(2) ISO 16164:2015, *Space systems — Disposal of satellites operating in or crossing LEO*

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

4.4 Other ISO standards

The following ISO Standards are not specific to space debris mitigation. However, they are considered pertinent:

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

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

(3) ISO 14300-2:2011, *Space systems — Product assurance — Policy and principles*

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

(5) ISO 27025:2010, *Programme management —Quality assurance requirements*

(6) ISO 10795:2011, *Space systems – Programme management and quality –Vocabulary*

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

4.5 Other documents

The following documents are referenced to understand the background of the ISO documents:

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

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

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

4.6 Abbreviated terms

A/m	Area-to-Mass Ratio
CDR	Critical Design Review
CFRP	Carbon-Fiber-Reinforced Plastic
CNES	Centre National d'Etudes Spatiales
COPUOS:	Committee on the Peaceful Uses of Outer Space
Cr	Solar Radiation Pressure Coefficient
DAS	Debris Assessment Software (NASA)
DRAMA	Debris Risk Assessment and Mitigation Analysis (ESA)
e	Eccentricity
Ec	Expected number of casualties
EOMDP	End-of-Mission (Operation) Disposal Plan
EOL	End-of-Life

ESA	European Space Agency
FMEA	Failure Mode and Effect Analysis
GEO	Geosynchronous Earth Orbit
GTO	Geosynchronous Transfer Orbit
IADC	Inter-Agency Space Debris Coordination Committee
ISO	International Organization for Standardization
JAXA	Japan Aerospace Exploration Agency
JSpOC	Joint Space Operations Center (USA)
LEGEND	LEO-to-GEO Environment Debris model
LEO	Low Earth Orbit
MASTER	Meteoroid and Space Debris Terrestrial Environment Reference
MEO	Medium Earth Orbit
MMOD	Micro-Meteoroid Orbital Debris
NOTAM	Notice To Airmen
NM	Notice to Mariners
NSS	NASA Safety Standard
ORDEM	Orbital Debris Engineering Model
PDR	Preliminary Design Review
QA	Quality Assurance
QR	Qualification Review
S/C	Spacecraft
SDR	System Definition Review
SDMP	Space-Debris-Mitigation Plan
STELA	Semi-analytic Tool for End of Life Analysis (CNES)
STSC	Scientific and Technical Subcommittee (UNCOPUOS)
USSTRATCOM	United States Strategic Command
TR	Technical Report (a type of ISO document)
UN	United Nations

5 Requirements in ISO Standards and system-level methodologies for complying with the requirements

5.1 General

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

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

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

(3) Applying debris mitigation measures early and throughout development and manufacturing to assure sound debris mitigation capability in the final product.

(4) Applying appropriate QA and qualification programs to ensure compliance with debris mitigation requirements.

This clause provides methodologies for taking comprehensive action at the system level. More detailed information for action at the subsystem and component levels is provided in Clause 8. The following specific subjects are emphasized:

(1) Limiting the release of objects into the useful orbital regions.

(2) Preventing fragmentation in orbit.

(3) Proper disposal during the end of operation.

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

(5) Collision avoidance for manned or man-able systems.

(6) Quality, safety, and reliability assurance.

5.2 Refrain from releasing objects

5.2.1 Requirements

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

(1) General;

- a) S/C and launch vehicle orbital stages shall be designed so as not to release space debris into Earth orbit during normal operations.
- b) Space debris released into Earth orbit as part of normal operations, other than as covered by (2), shall remain outside the GEO protected region, and its presence in the LEO protected region shall be limited to a maximum of 25 years after release.

(2) Combustion-related products;

- a) Pyrotechnic devices shall be designed so as to avoid the release into Earth orbit of products larger than 1 mm in their largest dimension.
- b) Solid rocket motors shall be designed and operated so as to avoid releasing solid combustion products into the GEO protected region.
- c) In the design and operation of solid rocket motors, methods to avoid the release of solid combustion products that might contaminate the LEO protected region shall be considered.

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

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

(2) Mission-related objects, such as yo-yo de-spinners and fasteners under the responsibility of designers (ISO 24113, 6.1.1)

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

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

ISO 24113, 6.1.1.2 states that if objects must unavoidably be released despite the requirements in 6.1.1.1, the orbital lifetime of such objects in LEO and the interference with GEO is to be limited as described in ISO 24113, 6.1.1.2 (a typical example is the support structure utilized in a multiple payloads mission).

5.2.2 Work breakdown

Table 2 shows the work breakdown as delineated in ISO 24113 to prevent the release of debris.

Table 2 — Work breakdown for preventing the release of debris

Process	Subjects	Major work
Preventive measures	Identification of released objects and design measures	a) Take preventive design to avoid releasing objects that would turn into space debris. (ISO 24113, 6.1) b) If objects might be released unintentionally, designers should investigate design problems and take appropriate action during design. c) If release is unavoidable, designers should estimate the orbital lifetime of released objects and check compliance with 6.1.1.2.
Corrective action	Troubleshooting	[Reference: If an object would be released unexpectedly, it is recommended to investigate and take appropriate action to avoid repeating the release in the following missions.]

5.2.3 Identification of released objects and design measures

As ISO 24113 states, launch vehicle designers shall avoid intentional release of space debris objects. If there are unavoidable reasons (such as, for example, serious technical problems), such objects are identified and their orbital lifetimes estimated and minimized.

(1) Mission related objects

Release of the following objects shall be avoided (ISO 24113, 6.1.1):

a) Nozzle closures for propulsion devices and certain types of igniters for solid motors, which are ejected into space after ignition (particularly if their orbital lifetimes are longer than 25 years).

b) Clamp bands that tie the S/C and launch vehicles

c) Structural elements that support the upper S/C used in multi-payloads launches

[Remark: Usually allowed if release is unavoidable and the object's orbit lifetime will be short; in which case the disposal orbit of these elements complies with ISO 24113, 6.1.1.2.]

(2) Combustion products from pyrotechnic devices

Adequately designed devices are selected to avoid the release of combustion products. It is possible to apply parts that trap all combustion products larger than 1 mm inside for segregation.

(3) Combustion products from solid motors

ISO 24113 requires that solid motors do not generate slag in a GEO. On the other hand, for LEO, although this is not directly prohibited, it is recommended to consider using methods to avoid the release of slag. To prevent the generation of slag, the first option is to design nozzles adequately so that there is no pocket at the upstream of the nozzle that may trap melting metals. Another solution is to develop propellants that do not contain metal (e.g. aluminium).

The orbital lifetime of released objects is assessed as specified in ISO 27852. This International Standard designates acceptable analysis methodologies the user employs dependent upon the orbit regime. The available simplified tools that may be admissible (depending upon orbit regime and ISO 27852 requirements) to estimate the long-term orbital lifetime are:

— NASA Debris assessment software (DAS) https://orbitaldebris.jsc.nasa.gov/Mitigation/das.html);

— ESA DRAMA (an account at https://sdup.esoc.esa.int must be created to obtain a license before downloading); or

— CNES STELA (https://logiciels.cnes.fr/content/stela?language=en).

5.3 Break-up prevention

5.3.1 Requirements

ISO 24113 requires that break-ups be prevented as specified in ISO 24113, 6.2:

(1) Intentional break-ups

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

(2) Accidental break-ups

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

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

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

While ISO 16127 specifically addresses the prevention of S/C break-ups, it also provides useful information and procedures for preventing launch vehicle break-up (ISO 20893).

5.3.2 Work breakdown

Table 3 shows the work breakdown as delineated in ISO 24113 to prevent orbital break-up.

Table 3 — Work breakdown for preventing orbital break-ups

Process	Subjects	Major work
Preventive measures	Identification of sources of breakup	Identify components that may cause fragmentation during or after operation.
	Design measures	(1) Develop preventive designs to limit the probability of accidental break-up during operation no greater than 10^{-3}. Confirm it with FMEA. (2) Provide functions to prevent break-ups after disposal. (3) A self-destruct system should be designed to prevent unintentional destruction caused by miss-command or solar heating.
Risk detection	Monitoring during operation	The monitoring function is provided under the flight safety requirement aspect. After passing the flight safety range, some parameters are monitored to ensure performance, and functions for completing the mission and disposal actions, including controlled re-entry, are conducted.
Actions in operation phase	Preventive measures for break-up	Energy sources for break-up should be removed (residual propellants, high-pressure gas, etc.) or designed to be safe so as not to cause break-ups after the end of operation.

5.3.3 Identification of the sources of break-up

The following launch vehicle subsystem elements can potentially cause break-ups:

— propulsion sub-systems and associated components (Rocket engines and solid motors, tanks, tank pressurizing systems, valves, piping, etc.);

— electrical batteries;

— pressure vessels and other equipment (such as pneumatic control systems, etc.); and

— self-destruct systems for range safety.

5.3.4 Design measures

The following aspects are to be incorporated into launch vehicle design.

(1) Avoiding intentional break-up

Missions that involve intentional break-ups that can potentially eject fragments into outer space are prohibited unless required to prevent potential loss of human life after re-entry

(2) Avoiding accidental break-ups during operation

Per ISO 24113, t*he probability of accidental break-up must be no greater than 10^{-3} until its EOL.*

“ISO 16127 Space systems - Prevention of break-up of unmanned spacecraft” is designed to apply to the S/C, but its “Annex - A Procedure for Estimating Break-up Probability” provides adequate instruction to engineers who wonder how to cope with complicated subsystems such as liquid rocket engines.

To prevent the unintentional explosion of self-destruct charges, the Command Destruct Receivers are recommended to be turned off after passing through range safety areas to prevent explosion by miss-command.

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

The following items are the typical measures to prevent fragmentation for each of the items identified in 5.3.3. More detailed guidelines for each sub-system or component are described in Clause 8.

a) Residual propellants in the propulsion systems and associated components

— Burning residual propellants to depletion.

— Venting residual propellant until its amount is insufficient to cause a break-up by ignition or pressure increase from tanks and lines.

b) High pressure fluids

— Venting pressurized systems

c) Range safety systems

— Prevention from inadvertent commands, thermal heating, or radio frequency interference

5.3.5 Monitoring during operations

ISO 16127, 4.3.1, requires monitoring of critical parameters to detect the symptoms that can lead to break-up, loss of mission capability, or the loss of orbit and attitude control function, and requires immediate action to be taken when any symptoms are detected. However, it is not usually feasible for launch vehicles because they are designed to have very limited functions available to terminate operation during flight, except for range safety operations.

5.3.6 Preventive measures for break-up after mission completion

After separation of payloads, the major sources of break-ups (examples listed in 5.3.3) should be mitigated (vented or operated in safe mode) according to ISO 16127, 4.4.

Residual propellants and other fluids, such as pressurants, should be depleted as thoroughly as possible, by either depletion burns or venting, to prevent accidental breakups by over pressurization or chemical reaction. Opening fluid vessels and lines to the space environment, directly or indirectly, at the conclusion of EOM passivation, is one way to reduce the possibility of a later explosion.

5.4 Disposal manoeuvres at the end of operation

5.4.1 Requirements

ISO 24113, 6.3 requires removing an S/C or launch vehicle orbital stage from the protected regions after EOM as follows:

(1) Probability of successful disposal

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

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

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

(2) GEO disposal maneuvers

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

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

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

$\Delta H = 235 + 1\,000\ Cr\ A/m$

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

(3) LEO disposal maneuvers

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

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

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

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

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

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

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

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

[Information]: For an S/C, ISO 26872 provides more detailed requirements and procedures for the disposal of GEO missions to comply with the high-level requirements stated in ISO 24113, and ISO 16699 provides more detailed requirements and procedures for the disposal of launch vehicle orbital stages in LEO missions.

5.4.2 Work breakdown

Table 4 shows the work breakdown as delineated in ISO 24113 to protect orbital regions:

Table 4 — Work breakdown for the preservation of the LEO-protected region

Process	Subjects	Major work
Preventive measures	Estimate the orbital lifetime and define a disposal plan	Estimate the orbital lifetime after payload separation, and define a disposal maneuver plan.
	Disposal planning	One of the following methods is applied. (ISO 16699): (1) Controlled re-entry (2) Maneuvering to reduce the orbital lifetime (3) Augmenting its orbital decay by deploying a device (4) Allowing its orbit to decay naturally (5) Maneuvering it to an orbit with a perigee altitude sufficiently above the LEO protected region
	Disposal function and resources	Functions and resources to remove orbital stages (examples: restart function of main engine, secondary propulsion systems, or independent thrusters) from the protected orbit region should be provided.
Action in operation phase	Disposal sequence	Disposal operations are executed in the proper sequence.

5.4.3 LEO mission

5.4.3.1 Estimate the orbital lifetime and define a disposal plan

For LEO missions, ISO 16699, 5.3 shows the planning and documentation for a disposal manoeuver. ISO 27875 shows the steps and tools to estimate the orbital lifetime in more detail. The precision of analysis is dependent on the algorithm, and high-precision algorithms need several hours to complete analysis, which is not adequate for use in the early phases when the exact operation plan has not been fixed. Tools should be selected during the design phase with consideration of the certainty of planned orbit and disposal timing.

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

(1) ISO 27852 introduces "STELA" available via the CNES freeware server. As of August 2016, the latest version is 3.0, and it can be downloaded from https://logiciels.cnes.fr/STELA.

(2) NASA is releasing "DAS (Debris Assessment Software)" (since April 2012, latest version is v 2.0.2), which has functions to analyze various debris related matters comprehensively, including the orbital lifetime analysis. (https://orbitaldebris.jsc.nasa.gov/mitigate/das.html)

(3) ESA provides the DRAMA tool available at https://sdup.esoc.esa.int/web/csdtf/home.

(4) Other viable Commercial Off-The-Shelf (COTS) toolkits exist to determine orbit lifetime.

5.4.3.2 Disposal planning

ISO 16699 provides more detailed requirements and guidance for the orbital stages. An EOMDP is required. The process of developing it is described in detail in Clause 7 of ISO 16699.

5.4.3.3 Disposal function and resources to transition to disposal orbit

(1) It is recommended to provide liquid propellant engines with a re-start function to perform a disposal manoeuver after payload separation.

(2) In some cases, other propulsion devices, including attitude control thrusters, can be used.

(3) Drag-enhancement, Solar Radiation Pressure, or other devices can also be used but in very rare cases.

5.4.3.4 Reliability of accomplishing disposal maneuver

ISO 24113 requires that the conditional probability of successful disposal should be larger than 0,9 (ISO 24113, 6.3.1.12). In the case of the S/C, this requirement limits the long stay in orbit after mission termination unnecessarily (e.g. only for housekeeping to check the health).

In the case of the orbital stages, the time interval between the EOM (payload separation) and the completion of disposal maneuvers would not be long (several days at the longest); however, note that the re-ignition of an engine after a long ballistic phase (to reach the proper impact zone), with propellant settling and thermal problems, can also significantly lower the probability of success.

5.4.4 GEO mission and other high-elliptical orbit missions

5.4.4.1 General

Detailed requirements and procedures for GEO S/C are defined in ISO 26872. The concept of disposal methods for launch vehicle orbital stages is not considerably different from those for the S/C.

There are several methods to launch a GEO S/C, and the typical methods would be the following:

(1) High Elliptical GTO: This is the most typical case in which the perigee altitude is within or close to the LEO protected region, and the apogee altitude is near GEO. The S/C is transferred to GEO by firing its apogee kick propulsion system.

(2) Direct injection: The orbital stages reach the circular orbit near GEO. The S/C is transferred to GEO with the S/C control function.

(3) Other elliptical orbit: the apogee altitude is higher than GEO, and the perigee altitude is inside or near the LEO protected region

5.4.4.2 High elliptical GTO

In the case of the “High elliptical GTO” mentioned in 5.4.4.1 (1), orbital stages left in GTO after payload injection generally 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, 5.6, since it is difficult to estimate lifetime in GTO with a specific value, it is recommended to provide the maximum lifetime corresponding to the planned perigee altitude with indicating 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).

As is often the case, the customer of the launch service wishes to define the perigee altitude as high as possible to reduce propellant consumption for the apogee kick operation or to avoid any decay when they apply electrical propulsion systems.

In such cases, it is difficult to reduce the orbital lifetime to within 25 years. Therefore, the orbital stages are left to orbit at an apogee altitude low enough so as not to have interference with the GEO protected region, even considering long-term perturbations

If the orbital stages have a re-start function in the main engine, the decreasing of either apogee altitude or perigee altitude is possible. Lowering the apogee altitude immediately precludes interference with the GEO protected region, but orbital lifetime cannot be shortened significantly. On the other hand, lowering the perigee altitude takes longer time to avoid interference with GEO, but it is more efficient at reducing the orbital lifetime.

The orbital elements of GTO are strongly affected by the perturbation caused by the tidal effect, which stems from the gravitational effects of the sun and the moon. If the Right Ascension of the Ascending Node (RAAN) could be controlled well by adequately selecting the lift-off time, the orbital lifetime could be greatly reduced.

In some missions, perigee altitude can be as high as a few thousand km, and natural forces are not available to decay the orbit. In this case, the apogee altitude is placed 200 km lower than the GEO altitude.

5.4.4.3 Direct injection

In the case of direct injection, the orbital stage and payloads are typically sent directly into or near the GEO protected region. Then, the payloads perform manoeuvres to move to the planned operation orbit in GEO, and the orbital stage will be left outside the GEO protected region.

5.4.4.4 Other elliptical orbits

There are missions which are not GEO missions but inject payloads in an elliptical orbit. ISO 24113 will require the same measures for such missions as required for GTO missions. This means that the following are required:

— Elliptic orbit: if apogee altitude is lower than the GEO area, and the perigee altitude is above the LEO area. As long as there will be no risk to the GEO and LEO protected regions for at least 100 years, there will be no suggestions for those objects.

— Very high elliptic orbit: if the apogee altitude is higher than the GEO area, and circularization above the GEO altitude is not reachable, this orbit should be avoided.

5.5 Ground safety from re-entering objects

5.5.1 Requirements

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

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

b) The re-entry of a spacecraft or launch vehicle orbital stage (or any part thereof) shall comply with the maximum acceptable casualty risk according to above a).

ISO 27875 provides procedures for assessing, reducing, and controlling the potential risks that the S/C and launch vehicle orbital stages pose to people and the environment when those space vehicles re-enter the Earth’s atmosphere and impact the Earth’s surface. ISO 27875 does not show quantitative criteria for the expected number of casualties (Ec), which is defined by appropriate regulatory bodies.

NOTE ISO 24113, 6.3.4 mentions “casualty risk”, which is usually understood as human casualty, but, as ISO 2787 mentions, there are another risk including environmental pollutions. Therefore “casualty risk” is understood as comprehensive “re-entry risk” defined by approving agents.

5.5.2 Work breakdown

ISO 27875 indicates the risk assessment procedure. Table 5 shows the work breakdown as delineated in ISO 24113 to assure ground safety from re-entry.

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

Process	Subjects	Major work
Preventive measures	Identification of requirements	Identify the re-entry safety requirements imposed contractually, voluntarily, or by national or international authorities.
	Hazard analysis to estimate the casualties	Hazard analysis should be conducted to estimate the expected number of casualties and the pollution on the ground.
	Design measures	(1) Design should be conducted to limit the casualty risk to be set in accordance with norms issued by approving agents. (2) Prevent environmental pollution on the ground. (3) If the expected number of casualties is larger than the requirement, a controlled re-entry should be planned (ISO 27875).
Risk detection	Notification of impact	For controlled re-entry, notifications should be sent to all countries that may be affected or should be sent through the NOTAM and NMs systems.
Action in operation phase	Conduct controlled re-entry and Monitoring	(1) Conduct controlled re-entry as planned. (2) Monitor the re-entry procedure and take adequate action in abnormal situations.

5.5.3 Preventive measures

5.5.3.1 Identification of requirements

The first step is identification of re-entry safety requirements imposed contractually, voluntarily, or by national or international authorities. ISO 27875 indicates the risk assessment procedure without mandating quantitative requirements (as of 2016).

[Information]: Many of the world's space agencies apply 0,0001 as the limit of the expected number of casualties.

5.5.3.2 Hazard analysis

As specified in ISO 27875, 5.2 and 5.5, safety requirements should be identified, and the hazard risks should be estimated using approved processes, methods, tools, models, and data. Then, the estimated risk should be assessed to determine the necessity of risk reduction measures.

If the expected number of casualties exceeds the criteria, in spite of the design improvement (5.5.3.3, or ISO 27875, 6.3), the impact area should be controlled according to ISO 27875, 6.2. Because the system concept can be affected significantly depending on whether the controlled re-entry will be applied, decisions are made at an early enough time to be reflected in the system specifications.

[Information 1]: At present, there is no consensus on the standard analysis tools or algorithms, analysis conditions, thermal properties of materials, distribution model of human population with prediction models for the future, or even equations to calculate casualties from the size of object impacts. These factors depend on the technical judgment or management decisions of organizations.

[Information 2]: Several national agencies have developed re-entry survivability analysis tools for their own use. For rough estimation, there are several analysis tools available in the world, such as DAS (Debris assessment software) provided by NASA (available at https://orbitaldebris.jsc.nasa.gov/mitigate/das.html) and the DRAMA tool by ESA (available at https://sdup.esoc.esa.int/web/csdtf/home). However, both tools are used to obtain very rough estimations; therefore, the official value is estimated with the tool officially authorized by the responsible organization.

5.5.3.3 Design measures

5.5.3.3.1 Design for demise

Even in the case of a controlled re-entry, since the risk of re-entry on the ground is assessed by the product of the failure rate of related functions and the expected number of casualties in the case of natural re-entry, it is better to design as much as possible for objects to be easily demised.

Generally, the following methods are recommended for the design phase, but some of them can be limited to the orbital stages.

(1) Selection of adequate 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. Generally, propellant tanks and high-pressure bottles made of titanium have been found on the ground after surviving a re-entry. There are tanks made of aluminium alloy, which seems to be better in terms of thermal characteristics that encourage demise.

(2) Multiple materials, thinner wall thickness, etc.

Sometimes, a material that does not undergo demise can be replaced by multiple materials that do undergo demise and still maintain structural integrity. For example, a dummy mass or balance weight can be designed as a set of multiple metal plates instead of one thick, solid mass.

If there is enough structural margin, and if it is possible to reduce wall thickness without changing the dimensions, the material can undergo demise more readily.

(3) Exposure to the ablation environment

Components that will be exposed to the ablation environment can undergo demise more readily. If propellant tanks or high-pressure bottles are located so that they are exposed to the atmosphere during re-entry, they can undergo demise more readily. However, this exposure to the atmosphere incurs disadvantages during the orbit phase in terms of protection from the thermal effects and debris impact.

5.5.3.3.2 Prevention of environmental pollution on the ground

Efforts are also be made to avoid polluting the environment with toxic substances (including radioactive materials) as required in ISO 27875, 5.4.

5.5.3.3.3 Specific design for controlled re-entry in subsystem level

Subsystem engineers, who are involved in controlled re-entry from the aspects of not only propulsion sub-system but also power, guidance, and communication sub-systems, consider specific functions and performance, as well as support of the ground station. It is also necessary to define uninhabited regions, such as broad ocean areas, which accept the footprint of survived fragments. For these reasons, the decision to use a controlled re-entry method is made early in the design and development cycle, before system specifications are set.

For example, a controlled re-entry could take a longer operation time to complete and result in a longer exposure to the radiation environment. Therefore, all systems are qualified for this additional lifetime and required to meet radiation hardness design requirements.

5.5.4 Risk detection: Notification

ISO 27875, (6.4) defines these notifications in case of a planned re-entry event.

5.5.5 Countermeasures: Controlled re-entry and Monitoring

In the case that controlled re-entry is planned, it is recommended to monitor the progress and confirm the consequences.

5.6 Collision avoidance

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

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

[Information]: For the launch vehicle, the only way to avoid collision is to coordinate the lift-off time so as not to collide with known objects and ensure no collisions until the JSpOC determines the orbital characteristics of orbital stages and other released objects.

However, since the dispersion of flight trajectories is not good enough to ensure the avoidance of collision with all known objects, the best practice is to at least avoid collision with manned or man-able systems whose operational plan is disclosed (ISS, etc.), primarily for safety reasons. When it is obvious that lift-off times or flight trajectories conflict with very important S/C, it is desirable to avoid these lift-off times or flight trajectories.

The criteria and procedures for collision avoidance have not been globally defined yet. The basic concept is that the launch service provider should assure that each stage of the launch vehicle, payload, and other objects separated from the stages would not collide for a few days (two days, for example) after lift-off until the JSpOC determines the orbital characteristics of orbital stages and all the objects separated from them.

NOTE It is not easy to estimate the probability of conjunction of flight trajectories with ISS over a period of a few days within the limited time typically available for analysis using the data from the updated operation plan of the ISS. Further, for vehicles whose dispersion of flight trajectories is large, it can be difficult to determine the launch windows. Since there is no clear requirement for this issue, these recommendations are considered a best practice. ISO/TR 16158 can support those analyses.

5.7 Reliability and QA

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

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

The trade-off between cost reduction and quality/reliability always exists in the development of space systems. Leveling QA according to the importance of a mission is typically conducted during project management. However, note that orbital stages with low quality can become debris in orbit and pose a risk to other space operators.

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

6 Debris-related work in the development lifecycle

6.1 General

A typical phased planning of the development lifecycle is illustrated in Figure 2, according to ISO 14300-1.

From an early phase in the lifecycle of the orbital stages, the preservation of the orbital environment is considered when creating a system concept and is realized throughout the development and operation.

6.2 Concept of debris-related work in each phase

The following debris-related activities are considered in each phase:

(1) The Mission Requirement Analysis Phase (pre-phase A) consists of an initial definition of launch performance according to the strategy of launch service business. The debris mitigation requirements are identified as a part of the requirements, such as design requirements and regulatory constraints

(2) The Feasibility Phase (phase A) consists of exploring the various possible concepts so as to meet the defined objectives (performance, cost, and schedule), as defined in ISO 14300-1, 8.2.3, The major debris related specifications are 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 design reliability, which affect system design and cost.

(3) The Definition Phase (phase B) consists of a general concept of the launch vehicle system as defined at the end of the feasibility phase, as defined in ISO 14300-1, 8.2.4. All the major debris mitigation concepts that impact functions, performance, allocation of resources, and reliability are reflected in the System Level Technical Specification.

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

(5) The Production Phase (phase D) consists of manufacturing and delivery to the customer (typical example is a launch service provider). Qualification of the product design and production procedures marks the end of the production phase.

NOTE In the routine production flow after qualification, a pre-shipment review is conducted to confirm the configuration and quality to proceed to launch site operations. This means that the detailed configuration and mission profile of the vehicle have been defined for each launch mission according to the mission analysis. Flight trajectory, propellant allocation, disposal sequence, etc. are confirmed.

(6) During the Utilization Phase (phase E), at the final launch preparation at the launch site, lift-off time is confirmed, ensuring to avoid collision risks between manned mission systems if required, followed by lift-off.

(7) During the Disposal Phase (phase F), after injection of payload, disposal manoeuvers and break-up prevention procedures are conducted.

In all of the above phases, debris-related characteristics are identified and realized in design and implemented by the completion of disposal. The output of each phase is reviewed at the end of each phase.

Debris-related measures that have an impact on design and options for solutions are described in Clause 5. Subsystems and component-level considerations are provided in Clause 8. A typical phased planning of the development lifecycle can be illustrated as depicted in Figure 2, according to ISO 14300-1.

NOTE When the mission is inside the qualified launch vehicle system, a set of review system can be simplified, for example, a Preliminary Mission Analysis (PMAR) could replace a PDR, a Final Mission Analysis (FMAR) could replace a CDR, and a Launch Readiness review (LRR) could replace a QR.

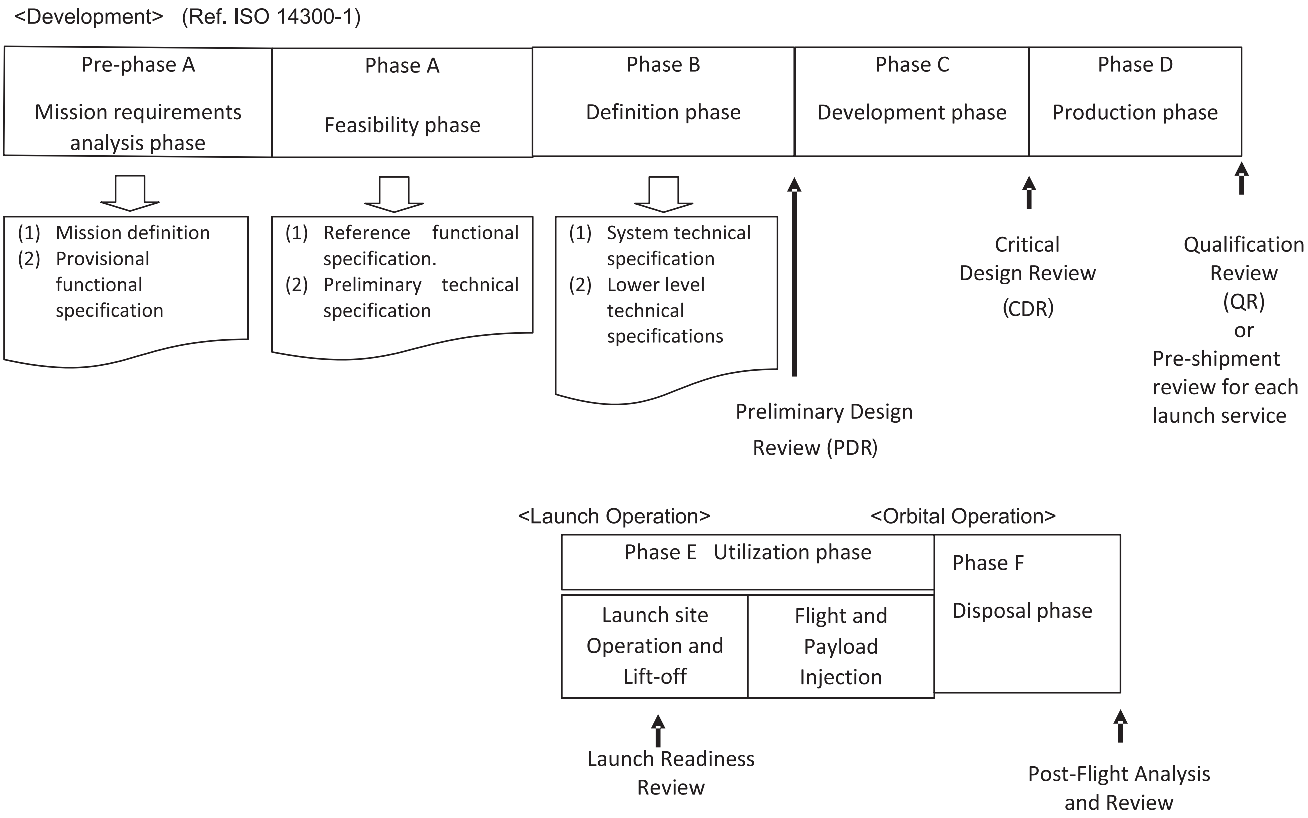

Figure 2 — Typical Phased Planning of the Development Lifecycle

Table 6 — Major works related to debris in each phase

Phase Subjects	Pre-phase A: Mission requirements 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	1) Input debris related requirements[*4] 2) Clarify debris related design philosophy and input into the system requirements & specification[*4]	1) Mass and Propellant allocation [*4] (including that for disposal manoeuver, controlled re-entry, etc.)	1) Transfer debris-mitigation plan to operators. [*1] 2) Fix the procedure to terminate the operation[*1] (with guarantee the propellant for disposal).	1) Disposal action, which is conducted automatically[*1] (including disposal manoeuver, break-up prevention, controlled re-entry)
Quality assurance	1) Clarify QA design philosophy[*4] 2) Define QA program including parts program[*4]	1) Confirm the probabilities for successful disposal and non-break-up and other probabilities required for the launching state or the mission requirements[*1]		
Limiting of debris generation **(ISO 24113/6.1)**	1) Clarify debris-mitigation design philosophy[*1]	1) Fix the design to limit releasing objects, limit their orbital lifetime, etc.[*1]. 2) Identify the energy sources of break-up and design to prevent them[*1].	1) Monitor critical parameters to check symptoms of critical malfunctions. [*4]	1) Vent residual energy. [*1] 2) Terminate operation in the proper sequence. [*1]
Disposal **(ISO 24113/6.3)**	1) Clarify disposal concept[*1] 2) Estimate propellant for disposal[*1]	1) Design a propulsion subsystem for the planned disposal manoeuver. [*1]		1) Remove orbital stages to avoid interference with protected regions. [*1]
Re-entry safety **(ISO 24113/6.3.4)**	1) Clarify re-entry safety concept[*3] 2) Define re-entry survivability analysis method[*3] 3) Determine whether to apply controlled re-entry or not[*3].	1) Design a propulsion subsystem and attitude control system for controlled re-entry, if needed. [*1]		1) Conduct controlled re-entry. [*1]
Collision avoidance	1) Clarify avoidance procedures for COLA (Collision Avoidance for new launch) [*2]		1) Conduct COLA if necessary[*2]	

1: Complying with the requirement of ISO STDs (24113, 27875, etc.), or recommendations induced from them.

2: Best practices recommended by UN Guidelines (and IADC Guidelines referenced by the UN Guidelines).

3: Instructions given by the authorities, which are addressed in ISO STDs.

4: Management work conducted according to general project management, reliability and QA program, Safety program, etc.

6.3 Mission Requirements Analysis Phase (pre-phase A)

6.3.1 General

The main purpose of this phase is to identify the concept of a launch vehicle. From the point of view of debris-related issues, the following items are conducted during this phase:

(1) Identify the debris-mitigation requirements in ISO Standards, national regulations, etc.

(2) Identify safety, reliability, and quality requirements to ensure the ability to conduct debris-mitigation measures, including prevention of the fragmentation caused by malfunctions, etc.

6.3.2 Debris-related works

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

ISO 24113 (as of 2016) presents requirements only for mitigating the generation of debris. It does not address collision avoidance, but the UN Debris Mitigation Guidelines recommends to estimate and limit the probability of accidental collision with known objects during the systems' launch phase, and consider adjustment of the launch time, if available orbital data indicates a potential collision. (See 4.5 (1)).

6.4 Feasibility phase (phase A)

The output of this phase is reflected in the system requirements document (specifications). This document is reviewed during the "system requirement definition review (SRR)."

The various possible concepts are studied to meet the defined objectives. Mission requirements, debris-related requirements, and other regulatory rules are taken into account.

The following aspects are considered:

(1) The requirements regarding not releasing objects provide normative content for the selection of types of propulsion systems (solid, hybrid, or liquid).

(2) Break-up preventive requirements provide normative content for the safety design concept (impact on mass allocation due to tank design, safety factors, and margins, etc.) and reliability design.

(3) Disposal requirements provide normative content for the basic configuration of staging structure and the allocation of function for each stage.

(4) Re-entry safety requirements provide normative content for the design of associated sub-systems related to controlled re-entry, including the radiation hardness design for avionics.

6.5 Definition phase (phase B)

6.5.1 Work in phase B

The output of this phase is reflected in the "system specifications" and "subsystem specifications (draft)." They are reviewed during the SDR.

In this phase, the system requirements are defined in a reference functional specification and a preliminary technical specification at the system level as specified in ISO 14300-1.

[Information 1]: The principal configurations, including physical, 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 could impose a heavy burden on the functional and performance characteristics is fixed no later than in this phase.

The concept to comply with ISO 24113 should be defined in the “space-debris-mitigation plan (SDMP)” as defined in ISO 24113, Clause 7.

6.5.2 Work procedure

(1) Basic concept

Excessive low reliability 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.

(2) Consideration of debris mitigation measures in system design

a) In the allocation of propellant, the propellant for disposal manoeuvers and controlled re-entry manoeuvers are taken into account.

b) In the allocation of reliability, the probability of break-up during operation is considered.

c) In planning the controlled re-entry, the manoeuver sequence and the function and performance of the propulsion subsystem are studied by the end of this phase. Moreover, the total system, including the ground control and monitoring system, is studied by the end of this phase.

6.6 Development phase (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:

(1) Reliability and QA

Again, reliability and QA for orbital stages are essential not only for mission completion, but also for the safety of the other operating S/C in orbit. (See ISO 16127, 5.1).

(2) Break-up prevention and safety control

Major causes of break-up are explosion of the propulsion subsystem and the rupture of high-pressure vessels. To prevent those causes of break-up, appropriate design measures (prevention of the mixture of bi-propellants, robust structural design, etc.) are essential.

(3) Prevent the release of parts

According to ISO 24113, 6.1, orbital stages are designed so as not to release objects that will become orbital debris (such as clamp bands, nozzle closures, combustion-related products, igniters for solid motors, etc.) during normal operations.

(4) Disposal after the end of operation

During the design phase, sufficient propellant is allocated to carry out the disposal manoeuver.

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

a) According to ISO 27875, the expected number of casualties is estimated and limited, and ground pollution is avoided.

b) If there is significant risk on the ground, a controlled re-entry is planned. Such a plan includes the design of a re-entry trajectory with control manoeuvers, error analysis, prediction of the footprint of surviving objects, etc. Controlled re-entry requires a propulsion subsystem satisfying such objectives, sufficient propellant, and specific designs for avionics (designing for radiation hardness, etc.). These factors can require additional constraints for mass allocation. Other ground support systems are required, including ground tracking and control systems (See ISO 27875).

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 as long as the production procedures are properly controlled under the reliability and QA program. The design and production procedures are qualified at the end of this phase (See 6.7.2).

6.7.2 Qualification review

In the qualification process, the final design and manufacturing procedures are verified through testing and design evaluation or demonstration.

The following items are reviewed at the QR:

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

(2) List of sources of break-up energy;

(3) A monitoring system for detecting critical malfunctions that may cause break-up as far as technically feasible;

(4) A disposal operation plan and data to be transferred to the operation phase;

(5) Ground casualty expectations if the orbital stages are disposed of by orbit decay;

(6) If controlled re-entry is planned, review of the operation plan; and

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

6.7.3 Launch service

After qualification, the launch vehicles are applied to routine service. For each launch mission, corresponding to launch mission requirements, mission analysis will be done, system configuration will be defined, the hardware will be validated, and served to launch operation at the launch site.

6.8 Utilization phase (phase E)

[Information 1]: 1: Lift-off time is typically coordinated to ensure that orbital stages, payloads, and other released objects from the orbital stages do not put manned or man-able systems at risk

[Information 2]: Debris mitigation measures are conducted according to the programmed sequence of events.

6.9 Disposal Phase (phase F)

Disposal actions are automatically conducted as follows:

(1) At the end of operation, the planned disposal manoeuvers defined in the SDMP are conducted. If a controlled re-entry is planned, it is most likely conducted with ground support.

[Information 1]: Notification for controlled re-entry is given to the relevant nations, air traffic authorities, and maritime authorities.

(2) After completion of disposal manoeuvers, residual energy (propellant, high pressure fluids, etc.) is removed (according to ISO 16127 until ISO 20893 is published) unless mechanical strength to assure that a break-up will not occur until the residual fluids are depressurized to a safe level.

[Information 2]: If there is potential risk that orbital stages can have interference with payloads by the venting force, the following item is considered:

For example, when venting of residual fluids is conducted, the effects of other devices (antennas, etc.), which are exposed to the venting streams, is assessed to ensure that they do not cause undesirable disturbances to the orbital stage.

7 System-level considerations

7.1 System design

Once the maximum mass of payloads are defined along their injection orbit, geodetic conditions of launching sites and tracking stations are identified, and other conditions are defined, the system concept of the launch vehicle is studied. Then the “debris mitigation design philosophy” effects on system concept are examined, such as;

(1) Constitution of stages is defined to minimize interference with protected orbital regions, ground casualties, probability of break-ups, etc.

(2) Orbital stages are given functions for disposal manoeuvers or controlled re-entry, if required, for missions that require such actions.

(3) Solid propulsion systems, which generate slag, are not recommended for use in upper stages reaching GEO. Otherwise, the propellant is altered so that it does not generate slag or change the nozzle design so that it does not have submerged nozzles.

(4) Orbital stages, whose re-entry hazards do not comply with restrictions, are given functions for controlled re-entry.

7.2 Mission analysis for each launch mission

For each launch mission, mission analysis, which includes the following debris related items, is conducted and reviewed before the pre-shipment review.

(1) Re-confirmation of physical characteristics of payloads and their injection orbits;

(2) Disposal planning;

(3) Development of flight profile and sequence of events (debris mitigation measures, such as turning off the command destruct receivers; payload separation collision avoidance; orbit change manoeuver for disposal; venting residual fluids; and controlled re-entry, if planned.); and

(4) Propellant allocation, including consumption for disposal manoeuver or controlled re-entry.

8 Subsystem / Component design and operation

8.1 General

8.1.1 Scope

During the design related phases (Phases B, C, and D), the requirements defined in Clause 6 of ISO 24113 and other related standards are converted to design requirements and allocated to the design specifications for system, subsystems, or components. Those allocated specifications support engineers engaged in each sub-system design.

The following subsystems are mentioned in this clause:

(1) Propulsion subsystem;

(2) Guidance and Control subsystem;

(3) Electric power-supply subsystem;

(4) Communication subsystem;

(5) Structure subsystem; and

(6) Range safety subsystem (the same as the Self-destruct subsystem).

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

While Clause 3 of ISO 24113 introduced system-level design concepts, this clause presents a more detailed allocation of functions and performance for each subsystem. Table 7 shows the relationships between the requirements in the ISO Standards and the recommended actions for each subsystem.

Table 7 — Debris-related technology and design of affected subsystem

	Name of debris-related technology	Subsystem					
		Propulsion	Guidance and Control	Power supply	Communication	Structure	Range safety
1	Releasing of parts, slags, etc.		-				
	(a) Fasteners, clamp bands, etc.					Yes	
	(b) Slag from solid motors	Yes					
	(c) Others						
	(d) Support structures for multi-payloads launching					Yes	
2	Prevention of fragmentation						
	(a) Explosion of engines, propellant tanks, etc.	Yes					
	(b) Rupturing of high pressure vessels	Yes					
	(c) Rupturing of Batteries			Yes			
	(d) Unintentional activation of self-destruct devices for range safety system						Yes
3	Disposal from protected regions	Yes	Yes	Yes	Yes		
4	Ground safety						
	(a) Re-entry control	Yes	Yes	Yes	Yes		
	(b) Improvement of demisability	Yes				Yes	
	(c) Avoidance of toxic material	Yes					

8.2 Propulsion subsystem

8.2.1 Debris-related design

This clause applies to the main (and Vernier) engines (motors), attitude control thrusters, ullage thrusters (or motors), etc.

The items to be considered are shown in Table 7.

Table 7 — Debris-related measures in the propulsion subsystem

Mitigation measures	Propulsion sub-system	Major components				
		Liquid engine, Thrusters	Propellant tank	Pressure vessels	Valve, piping	Solid motor
Refrain from releasing objects	Yes	-	-	-	-	Yes (slag)
Break-up prevention	Yes	Yes	Yes	Yes	Yes	Yes
Disposal maneuver	Yes	Yes	Yes	-	-	-
Ground safety	Yes	-	Yes	Yes	-	-
Re-entry control	Yes	Yes	Yes	-	-	-

8.2.2 Considerations for propulsion subsystems

8.2.2.1 Refrain from releasing objects

To refrain from releasing objects, the following items are considered, per ISO 24113:

(1) In the case of solid motors, igniters and nozzle closures should be designed to not be released whenever possible, especially when they remain in orbit for a long time. Solid motors, which contain metal and have submerged nozzles, tend to generate and exhaust slag. They are not recommended for use in GTO or near GEO and should be avoided in LEO as much as possible.

(2) Auxiliary propulsion systems (ullage motors, retro motors, etc.) should not be separated, especially when they are injected into a long-lived orbit.

8.2.2.2 Break-up prevention

ISO 24113 requires the probability of fragmentation during operation to be 0,001 or smaller except for such external factors as collision with debris.

The following are typical modes of fragmentation relating to the propulsion subsystem:

(1) Failures of engine or thrusters (failures of combustion related elements, turbo-pumps, turbines, heaters of thrusters, etc.);

(2) Explosion caused by a mixture of the homogeneous set of fuel and oxidizer (As a typical example, a propellant tank design combining the fuel and oxygen tanks, separating them only by a common bulkhead, has caused many explosions, which are probably due to a defect of the bulkhead, which allowed the mixture of propellants);

(3) Rupture of highly pressurized tanks or vessels caused by defects of tank structure, failures of regulators, valves, etc.;

(4) Certain types of gas jet thrusters can cause fragmentation due to cold-start induced by the failure of the heater for the catalyst bed;

After the EOM (injection of payloads), energy sources of break-up as the forms of residual propellants and high-pressure gasses are vented or relieved, according to ISO 24113, 6.2, and ISO 16127. As addressed in 8.2.3.1, the function and performance for venting and relieving residual fluids will be accomplished by coordinated work among related components, such as engines, tanks, pressure vessels, valves, piping, etc.

[Information]: Complete depletion of fluids is sometimes impossible in complicated propulsion systems. ISO 16127, (5.3.2.1) shows the tailoring guidance for such cases.

8.2.2.3 Disposal maneuver

In the case that disposal manoeuvres need stronger forces than can be obtained by passivation, re-start functions of the main engines or auxiliary propulsion systems, including independent devices attached specifically for such purposes, will be needed.

The following characteristics are designed to comply with disposal manoeuver requirements:

(1) Re-start functions of the main engines or auxiliary propulsion systems, which are available after payload separation is designed;

(2) Mission is designed to keep a sufficient amount of propellant for disposal manoeuvres;

(3) Tanks are designed to allow a safe and reliable re-start function of main engines or auxiliary propulsion systems; and

(4) Electric power subsystem and other subsystems support disposal manoeuvres.

8.2.2.4 Ground safety and re-entry control

Propulsion subsystems have several elements that survive re-entry, including major components of liquid engines, propellant tanks made of stainless steel or titanium, pressure vessels made of titanium, large valves, motor cases, and nozzles of solid motors. Design efforts are applied to minimizing objects that survive re-entry, but if the total number of casualties still cannot be made smaller than the requirement, a controlled re-entry is planned.

When a controlled re-entry is planned:

(1) The propulsion system used for the final burn is designed to have enough thrust to provide enough delta velocity within a short period.

(2) In the event that controlled re-entry takes an extended amount of operation time, longer than a simple disposal operation, radiation hardness design is applied for electronic devices and, more generally, for the avionics.

8.2.3 Considerations for component design

8.2.3.1 Liquid propulsion systems

8.2.3.1.1 Main liquid engine

Engine reliability is a dominant factor in limiting the probability of break-up to be lower than 0,001 as required by ISO 24113. As already mentioned in 5.7, it is important to ensure sufficient reliability and quality. In ISO 16127, 5.1 contains the requirements for reliability and quality control to prevent failures that could lead to a break-up event.

[Information]: When the probability of break-up for complicated systems, like a large engine system, cannot be identified independently by separating it from other failures, ISO 16127, which is applied to the S/C, says “Where the break-up event is at system level, i.e., the break-up is a symptom of one or more failures at system level, the break-up probability should be reviewed indirectly by its system reliability” in sub-Clause A.3 of Annex-A.

To conduct disposal manoeuvres, it is desirable to have an engine re-start function. Otherwise, auxiliary propulsion systems have the function of supporting disposal manoeuvres, as low thrust engines described hereafter.

8.2.3.1.2 Gas jet thrusters (and other low thrust engines or motors)

Low thrust engines or motors can be designed for various purposes including attitude and trajectory control, acceleration for propellant settling before re-start, retro thrust to avoid collision, etc.

[Information]: Certain types of gas jet thrusters can cause fragmentation when they are forced to start in cold start conditions due to the failure of the heater for the catalyst bed. Such types of thrusters are only used if it has been confirmed that their design precludes such a failure mode or if by FDIR techniques are employed to avoid the cold starts.

8.2.3.1.3 Design of propellant tanks

Design of propellant tanks takes into consideration the following debris mitigation aspects:

(1) Tank volume can be defined considering the propellant consumption for disposal manoeuvres and controlled re-entry, if required.

(2) For ground safety from the tanks surviving re-entry, it is desirable to select materials which likely demise during re-entry. Large main tanks made of stainless steel have been found on Earth without melting, and small tanks, motor cases, and pressure vessels (even smaller than 1 m in diameter) made of titanium have also been found on Earth. Therefore, it is desirable to replace large tanks with aluminium tanks (as an example), and small tanks could be replaced by an aluminium skin overwrapped with composite materials or other materials that are easy to demise.

(3) To prevent explosions caused by mixing of propellants, particularly in the case of auto-ignition of a two-liquid type propulsion system, care is taken so that tank arrangement prevents mixture of liquids. Moreover, common bulkhead tanks are avoided if not reliable and robust.

[Information 1]: If the design of a small tank does not include a venting mechanism (in the case of small tanks with bladders, etc.), a sufficient safety margin is provided (as per ISO 16127, 5.3.2).

[Information 2]: Tanks with a common bulkhead for a set of homogeneous propellants can be risky because:

a) Impact of tiny debris can penetrate the tank skin and common bulkhead.

b) Unbalance of pressure between outer and inner tanks can defect the common bulkhead.

c) Aging and erosion of the common bulkhead by one of the propellants can induce mixture of propellants.

[Information 3]:: In designing a venting mechanism, the following items are taken into consideration:

a) When venting residual liquid propellants from tanks, the gradient of decreasing pressure takes into account the vapour pressure inside the tanks so as not to cause boiling of liquid propellant, followed by rupture.

b) When venting liquid at a certain pressure drop, adiabatic expansion can cause freezing around the venting lines. The venting line is designed and operated so as not to cause stack of the venting flow.

(4) There was a case of rupture of a main tank after the end of operation, which was assumed to be caused by pressure increase due to the evaporation of residual cryogenic propellant. Tanks are equipped with a pressure relief mechanism and venting of residual propellant is conducted at the end of operations.

8.2.3.1.4 Design of pressure vessels

If the orbital stage stays in orbit for a long period of time (longer than a few years, for example), high pressure vessels (and high pressure propellant tanks) are designed either to be able to relieve pressure after the end of operations, or to have safety margins that do not allow rupture until the bleed valve attached to the pressure regulators reduces the inner pressure low enough.

If the pressure vessels are made of titanium, they can survive re-entry.

8.2.3.1.5 Design of valves and piping

In design of valves and piping, the following points are considered:

(1) It is desirable to have a mechanism to vent and minimize residual propellants after the end of operations.

NOTE Some propellant can be allowed to become trapped in lines as long as the amount is insufficient to cause a break-up by ignition or pressure increase.

(2) The failure rate of valves and pressure regulators, which can induce fragmentation of tanks or vessels, is controlled so that the probability of break-up is less than 0,001 for the total system.

(3) Venting lines are designed to prevent blockage from freezing propellants. (ISO 16127, 5.3.2)

[Information]: Venting or relieving is not meant to pose adverse effects on payloads or orbital stages.

8.2.3.1.6 Design of engine control avionics

If a controlled re-entry is planned, the radiation hardness design is considered.

8.2.3.2 Solid motors

Solid motors whose propellants contain aluminium and which are equipped with submerged nozzles can generate and inject slag while in orbit. ISO 24113 does not recommend the use of such motors for GTO or GES direct-injection missions to avoid contamination of the GEO protected region. ISO 24113 also encourages the development of technology that avoids the generation of slag for LEO missions

[Information]: Solid rocket motor propellant ingot defects can cause break-ups. Non-destructive inspection of the ingot of solid motors can be useful to confirm whether they could cause a break-up.

There are certain types of igniters that are ejected after ignition. Such igniters cannot be used at high altitudes where they have long orbital lifetimes (over 25 years). Nozzle closures could also not be ejected at high altitudes to remain in orbit for a long time period.

8.3 Guidance and control subsystem

8.3.1 Debris-related designs

The measures taken into consideration for this subsystem are shown in Table 9.

Table 9 — Debris-related measures in the Guidance and Control subsystem

Mitigation measures	Guidance & Control	Major components	
		Attitude monitoring sensors, etc.	Other electronic circuit
Disposal maneuver	Yes (Normal function)	-	-
Re-entry control	Yes	-	-

8.3.2 Considerations for the guidance and control subsystem

8.3.2.1 Disposal manoeuvres

To conduct disposal manoeuvers with the propulsion subsystem, the guidance and control subsystem supports the determination of orbit and attitude, controls the disposal manoeuver thrust vector, and conducts the manoeuver itself. Usually those activities will be conducted according to a part of the mission sequence of the launch program.

8.3.2.2 Controlled re-entry

In the case where a controlled re-entry is planned, the guidance and control system is required to perform the determination of position, velocity, and attitude of the vehicle body with high precision until it reaches the point of manoeuvres. The ground based ranging system or data from other operating S/C can support the guidance and control system.

Controlled re-entry can require a longer duration of operation time.

8.4 Electric power-supply subsystem

8.4.1 Debris related design

The items taken into consideration for the power-supply subsystem are shown in Table 10:

Table 10 — Debris-related measures in the power-supply subsystem

Mitigation measures	Power-supply subsystem	Major components	
		Battery	Control/ distribution device
Break-up prevention	Yes	Yes	-
Disposal manoeuver	Yes (Normal function)	Yes	-
Ground safety	Yes	Yes	-
Re-entry control	Yes	-	-

8.4.2 Considerations for power subsystems

8.4.2.1 Prevention of break-up

The battery is the only source of break-up energy in this subsystem. Batteries are designed and manufactured as described in 8.4.3.1.

8.4.2.2 Disposal manoeuver and controlled re-entry

Disposal manoeuvres and controlled re-entry are conducted by a combination of most of the propulsion, power, guidance and control, and communication subsystems. Battery capacity is designed to support the whole duration of such an operation period.

8.4.3 Consideration in component design

8.4.3.1 Design of batteries

Since the batteries are the only potential energy source for break-ups in this subsystem, they are designed and manufactured properly in all electrical and mechanical aspects so that abnormal increases of internal pressure or structural fractures never happen.

Since launch vehicles typically do not have their own power generation functions, batteries are designed to have enough capacity (even in worst-case conditions) to support disposal manoeuvres and controlled re-entry.

Batteries tend to survive re-entry. They are assessed in the survivability analysis to calculate Ec.

8.4.3.2 Design of electronics

In the case of controlled re-entry, avionics are exposed to the radiation environment longer than in the simple case, which terminates the mission at the separation of payloads. Radiation hardness design is considered for cases where controlled re-entry is a possibility.

8.5 Communication subsystem

8.5.1 Debris-related designs

The communication subsystem consists of the telemetry transmitter, radar transponder, and other communication equipment. Measuring and data transmission equipment is included in this category in this document.

Items to be considered for this subsystem are shown in Table 11.

Table 11 — Debris-related measures in the communication subsystem

Mitigation measures	Communication sub-system	Major components	
		Tele-communication	Measuring systems
Disposal maneuver	Yes (Normal function)	-	Yes (Normal function)
Ground safety	Yes	-	-
Re-entry control	Yes	Yes	Yes (Normal function)

8.5.2 Design of communication subsystem

8.5.2.1 Support for disposal manoeuver

NOTE There are no specific requirements added to the normal functions to support disposal manoeuvers.

8.5.2.2 Supporting controlled re-entry

For a controlled re-entry, additional functions and performance can be required as follows:

(1) Since longer durations of operation periods are necessary for controlled re-entry, adding to the normal operation, radiation hardness design can be required.

(2) If the functions are required to determine the initiation of controlled re-entry and monitor the condition in the re-entering trajectory, the measuring function is designed to check the health of the related functions when required.

(3) If the functions are required to receive a command from the ground for initiation or termination of re-entry, the command line is designed to remain active and receive this command.

8.5.3 Considerations for component design

8.5.3.1 Measuring instruments

NOTE To confirm basic function and performance and to maintain flight safety, this subsystem measures and transfers the basic parameters and major event signals to the ground control centre. It also includes the parameters and event signals required to confirm the completion of disposal manoeuvers and the venting of the residual fluid, if possible.

If a controlled re-entry is planned, this subsystem is used to support determination to proceed to a controlled re-entry manoeuver or cancel it, if designed to do so.

8.5.3.2 Command link

If a command link is required for controlled re-entry, the link is maintained during re-entry operations.

8.6 Structure subsystem

8.6.1 Design measures

The following items are considered:

(1) Refrain from releasing objects; and

(2) Survivability during re-entry to ensure ground safety.

8.6.2 Practices for structure subsystem

8.6.2.1 Intentional release of parts

The following objects cannot be released from the launch vehicle. Some type of capturing mechanism can be used to contain all parts and fragments, and a yo-yo de-spinner could be changed to another type of propulsion device.

(1) Clamp-bands fastening the payload to the orbital stage;

(2) Fasteners for launch vehicle interstages;

(3) Separation bolts, wire-cutters, etc.; and

(4) Yo-yo de-spinner

[Information 1]: In the case of launching of multiple payloads, one or multiple structural elements that support payloads can be released. Historically, the structural elements have been separated into a small number of fragments and released into orbit, but they are allowed internationally if their orbital lifetime is shorter than 25 years.

[Information 2]: Suborbital objects (e.g. payload fairings) released during early ascent are not of concern from an orbital debris standpoint.

8.6.2.2 Assurance of ground safety

To ensure ground safety after re-entry, structural elements are designed to be demised as far as technically possible, considering 5.5.3.2 "Hazard analysis" and 5.5.3.3 "Design measures."

8.6.3 Considerations for component design

8.6.3.1 Support truss, gimbal rod, and other structural elements

To ensure ground safety after re-entry, the support truss, gimbal rod, and other structural elements are designed considering 5.5.3.2 "Hazard analysis" and 5.5.3.3 "Design measures."

8.6.3.2 Dummy mass

So-called dummy masses, typically introduced on maiden flights or applied to maintain mass balance when a payload cancels its participation in the flight, are designed considering 5.5.3.2 "Hazard analysis" and 5.3.4 "Design measures."

8.7 Range safety subsystem (Self-destruct subsystem)

8.7.1 Debris-related designs

In this clause, the following measures are described:

(1) Prevention of accidental explosion by miss-command; and

(2) Prevention of accidental explosion due to solar heating in orbit after operation.

8.7.2 Consideration for command destruction subsystem

The command receiver is turned off after passing through the range safety area to prevent explosions caused by accidental or spurious (RFI: Radio Frequency Interference) miss-command.

8.7.3 Considerations for component design

It is sometimes necessary to attach a thermal shield to the self-destruct system to maintain its temperature within operational bounds (cook-off temperature) and prevent accidental destruction.

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