estec
European Space Research
and Technology Centre
Keplerlaan 1
2201 AZ Noordwijk
The Netherlands
T +31 (0)71 565 6565
F +31 (0)71 565 6040
www.esa.int

DOCUMENT

ESA Re-entry Safety Requirements

Prepared by	**ESA Re-entry Safety WG**
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1 Scope

This ESA Standard specifies the re-entry safety requirements for the design and operations of the ESA space systems. The re-entry safety requirements are intended to protect human health and Earth environment from the effects of space systems, or elements thereof, re-entering in the Earth atmosphere.

This ESA Standard applies to the re-entry of any ESA uninhabited space system, i.e. procured by ESA or operated under ESA responsibility. In particular, this standard applies to any uninhabited space object that during its trajectory has exceeded 100 km altitude or has exceeded the orbital velocity, i.e. 7,9 km/s, and for which re-entry is planned or possible.

Uninhabited space systems include, but are not limited to:

a. Spacecraft, including mated configurations of space debris remediation missions,

b. Launch vehicle orbital stages (e.g. upper stages),

c. Unmanned steered vehicles,

d. Return items, either recoverable or non-recoverable (e.g. return capsules, re-entry recorders).

This ESA Standard does not provide safety requirements for the re-entry, fallback or landing of:

a. Space systems inhabited at the time of the re-entry,

b. Non-orbital launch vehicles stages, or elements thereof, under the responsibility of the launch service provider and regulated by launch range safety requirements,

c. Sounding rockets or balloons operating below 100 km altitude and not exceeding the orbital velocity, i.e. 7,9 km/s.

2 Normative references

The following normative documents contain provisions which, through reference in this text, constitute provisions of this ESA Standard. For dated references, subsequent amendments to, or revision of any of these publications do not apply. However, parties to agreements based on this ESA Standard are encouraged to investigate the possibility of applying the more recent editions of the normative documents indicated below. For undated references, the latest edition of the publication referred to applies.

ECSS-S-ST-00-01	ECSS system – Glossary of terms
ECSS-Q-ST-30	Space product assurance – Dependability
ECSS-Q-ST-30-02	Space product assurance – Failure Mode Effects (and Criticality) Analysis (FMEA/FMECA)
ECSS-Q-ST-40	Space product assurance – Safety
ECSS-Q-ST-40-12	Space product assurance – Fault tree analysis – Adoption notice ECSS / IEC 61025
ECSS-U-AS-10	Space sustainability – Adoption Notice of ISO 24113: Space systems – Space debris mitigation requirements
ECSS-E-ST-32-02	Space engineering – Structural design and verification of pressurized hardware
ESSB-ST-U-001	ESA planetary protection requirements
ESA/ADMIN/IPOL (2014)2	Space Debris Mitigation Policy for Agency Projects – ESA Director General's Office, 28/03/2014
ISO 24113:2011	Space systems – Space debris mitigation requirements – 15/05/2011

3 Terms, definitions and abbreviated terms

3.1 Terms from other normative documents

a. For the purpose of this standard, the terms and definitions from ECSS-S-ST-00-01 apply, in particular for the following terms:

1. anomaly
2. availability
3. contamination
4. deviation
5. failure
6. failure detection isolation and recovery
7. failure mode
8. failure mode, effects and criticality analysis (FMECA)
9. fault
10. hazard
11. launch range
12. launch segment element
13. launch vehicle
14. maintainability
15. planetary protection
16. reliability
17. risk
18. safety
19. space segment element
20. spacecraft
21. space system
22. system

b. For the purpose of this standard, the terms and definitions from ECSS-E-ST-32-02 apply, in particular for the following term:

1. pressure vessel

c. For the purpose of this standard, the terms and definitions from ESA/ADMIN/IPOL(2014)2 apply:

1. casualty risk
2. disposal
3. ESA space system
4. end of life
5. space debris
6. re-entry

d. For the purpose of this standard, the terms and definitions from ISO 24113:2011 apply:

1. break-up
2. end of mission
3. launch vehicle orbital stage
4. protected region

3.2 Terms specific to the present standard

3.2.1 casualty

person who is killed or seriously injured by accident

3.2.2 casualty area

equivalent impact area specified by the formula $\left(A_i^{1/2} + A_h^{1/2}\right)^2$ where A_i is the average projected area of the fragment, and A_h is the cross-section of a human being conventionally equal to 0,36 m^2

3.2.3 controlled re-entry

type of re-entry where the time of re-entry is controlled and the impact of fragments on the Earth surface is confined to a designated zone

3.2.4 declared re-entry area (DRA)

area on the Earth surface where the re-entry debris are enclosed with a probability of 99% given the delivery accuracy

3.2.5 destructive re-entry

type of re-entry involving mass ablation or generation of fragments before the possible impact on Earth surface

NOTE An uncontrolled re-entry is always destructive. A controlled re-entry can be destructive or non-destructive depending on the type of vehicle and trajectory. For example: the nominal re-entry of the ESA Automated Transfer Vehicle (ATV) and other non-reusable uninhabited ISS resupply and cargo vehicles is destructive controlled; the nominal re-entry of the Space Shuttle and other reusable re-entry vehicles, e.g. the ESA Intermediate Experimental Vehicle (IXV), is non-destructive controlled.

3.2.6 disposal orbit

final orbit acquired after end of mission for permanent disposal on which end of life occurs and which allows to achieve the required long-term clearance of protected regions

3.2.7 explosive fragment

fragment containing explosive substances which can release energy or trigger fire on the Earth surface

3.2.8 fragment

piece produced by fragmentation of a space system during re-entry due to ablation, mechanical stresses, explosions or induced separation, or the space system itself if not fragmented into pieces

3.2.9 hazardous chemical substance

substance, raw, semi-finished or finished, in whatever physical state and with specified characteristics that can result in a mishap

NOTE 1 Examples of substance include chemical elements, mixtures of chemical elements, chemical compounds, mixtures of chemical compounds.

NOTE 2 Physical state can be gaseous, liquid, solid.

3.2.10 hazardous floating wreck

fragment surviving re-entry and buoyant over waters that can constitute an obstacle or hazard for navigation, fishing or environment

3.2.11 nominal

corresponding to the specifications or performance levels announced by the designer or the operator of the space system

NOTE 1 Specifications and performance levels include margins, probability distribution functions or dispersions within a certain confidence level for the parameters relevant to the re-entry of the space system.

3.2.12 nuclear power source (NPS)

device that uses radioisotopes or a nuclear reactor for electrical power generation, heating or propulsion

3.2.13 population density

number of inhabitants over a specified area divided by the area extension

3.2.14 pressurized fragment

fragment containing pressurized substances which can release energy on the Earth surface

3.2.15 radioactive substance

substance designated in national law or by a regulatory body as being subject to regulatory control because of its radioactivity

3.2.16 re-entry probability

probability that a re-entry occurs

3.2.17 safety re-entry area (SRA)

area on the Earth surface where the re-entry debris are enclosed with a probability of 99,999% given the delivery accuracy

3.2.18 space object

human-made object, whether functional or not, during its launch, in-orbit presence or re-entry

3.2.19 uncontrolled re-entry

type of re-entry where the time of re-entry or the zone of impact of fragments on the Earth surface are not controlled

3.3 Abbreviated terms

For the purpose of this document, the abbreviated terms from ECSS-S-ST-00-01 and the following apply:

Abbreviation	Meaning
AIS	abbreviated injury scale
ATV	automated transfer vehicle
AVURNAV	avis urgent aux navigateurs
DML	declared material list
DRA	declared re-entry area
DRAMA	debris risk assessment and mitigation analysis
DRD	document requirements description
FDIR	failure detection isolation and recovery
FMEA	failure modes, effects analysis
FMECA	failure modes, effect and criticality analysis
FTA	fault tree analysis

Abbreviation	Meaning
GEO	geostationary Earth orbit
GTO	geostationary transfer orbit
HEO	highly elliptical orbit
ICRP	international commission on radiological protection
ICSU	international council for science
ISS	international space station
LEO	low Earth orbit
NOTAM	notice to airmen
NOTMAR	notice to mariners
NPS	nuclear power source
ORIUNDO	on-ground risk estimation for uncontrolled re-entries tool
RAMS	reliability, availability, maintainability and safety
REACH	registration, evaluation, authorization and restriction of chemicals
RHU	radioisotope heat unit
RoHS	restriction of hazardous substances directive
RSR	re-entry safety report
RTG	radioisotope thermo-electric generator
SEL	Sun-Earth lagrangian point
SDMP	space debris mitigation plan
SDMR	space debris mitigation report
SPOUA	south Pacific Ocean uninhabited area
SRA	safety re-entry area
UN	United Nations
UTC	coordinated universal time

4 Re-entry safety introduction

4.1 Re-entry casualty risk

A threshold for the maximum re-entry casualty risk is required to limit the risk of casualties. The re-entry casualty risk threshold is established by ESA at Agency level for all ESA space systems.

4.2 Re-entry hazards

4.2.1 General

Hazards to human health, Earth environment, and damages to assets, associated to the re-entry of a space system, can be caused by:

- Impacting fragments,
- Floating fragments,
- Pressurized or explosive fragments,
- Hazardous chemical substances,
- Radioactive substances.

4.2.2 Impacting fragments

Fragments of a space system surviving re-entry can reach the Earth surface with sufficient kinetic energy to cause human casualties or damages to assets. Casualties can also result from indirect effects, e.g. secondary fragments, splatter, bounce, and crater ejecta.

In general, a substantial fraction of the mass of a spacecraft or launch vehicle orbital stage can survive re-entry depending on its design, trajectory, and atmospheric conditions. Physical, chemical, thermal and mechanical properties of the structures and components, e.g. heat capacity, melting temperature, heat of melting, heat of ablation, thermal conductivity, density strength, fracture toughness and fatigue crack, and system configuration have a significant role on the re-entry survivability. Materials with high melting temperature or heat capacity, such as Titanium alloys, Beryllium alloys, stainless steels, ceramics, and silicon carbides, are more likely to survive than Aluminium alloys.

4.2.3 Floating fragments

Fragments which survive a re-entry and have a mass to volume ratio allowing them to float over water (e.g. oceans, seas, rivers, lakes, etc.) can represent a hazard for human population, ships or assets in case of an accidental contact. Pressure vessels from spacecraft and launch vehicle stages, e.g. propulsion tanks, are the most likely items to float.

4.2.4 Pressurized or explosive fragments

Pressurized fluids or explosive substances contained in re-entering pressure vessels reaching the Earth surface represent a hazard since they can result in violent release of energy, potentially leading to damages to constructions, creation of secondary hazardous fragments, or injuries for human population (e.g. soft tissue effects involving eardrum).

4.2.5 Hazardous chemical substances

Uncontrolled release of hazardous chemical substances, which are present in a re-entering space system, represent a risk for human health and Earth environment. Atmospheric effects due to ablation and dispersion of chemical substances during re-entry events at high altitudes (e.g. 100-60 km) are, currently, considered less critical due to relatively low mass of the re-entering objects and fast dilution into air. Effects on the Earth surface are generally worth of a higher concern because of eco-toxicity and impact on human health and Earth environment. In most cases, effects due to ceramics can be neglected, while propellants and some metal alloys are considered hazardous, e.g. Beryllium. Dilution of hazardous fluids substances in the oceans is currently considered of lower concern, while possible dilution of some chemical substances into local watercourses or basins (e.g. rivers, lakes) can represent a hazard for the local ecosystem.

4.2.6 Radioactive substances

Uncontrolled release of radioactive substances, which can be present in a re-entering space system, represent a risk for human health and Earth environment. On-board radioactive substances can be classified in two classes:

a. Nuclear Power Sources (NPS), which include, e.g.:
   - Radioisotope Heater Units (RHU), where natural decay of radioisotopes is exploited for thermal control,
   - Radioisotope Thermo-electric Generators (RTGs), where natural decay of radioisotopes is converted into electricity.

b. Sealed radioactive substances, which usually involve small quantities of radioactive material (e.g. sub-grams) and are part of some payload instruments.

4.3 System reliability for controlled re-entry

When a controlled re-entry is planned for a space system, the re-entry operations need a reliability level of the platform system and sub-systems sufficient to ensure the successful execution of the re-entry manoeuvres to comply with the re-entry casualty risk requirement.

4.4 Planetary protection

For the purpose of this document, planetary protection is relevant in the specific case of return mission to Earth from other planets or other celestial bodies. The Committee On Space Research (COSPAR) is the body of the International Council for Science (ICSU) in charge of maintaining and promulgating recommendations on planetary protection according to the UN "Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies", 27/01/2967.

4.5 Ground control and tracking

The controlled re-entry of a space system relies on a ground control centre for the execution and monitoring of the re-entry manoeuvres both in the nominal and non-nominal re-entry scenarios.

4.6 Re-entry notification

For controlled re-entries, a notification procedure is needed to warn the relevant air and maritime traffic control authorities to prevent re-entry hazards.

4.7 Retrieval

Retrieval operations of a re-entered space object, e.g. a space system, or elements thereof, can be:

- foreseen in the frame of a specific mission objective;
- required in the case of fragments or substances hazardous for human health and Earth environment.

Retrieval operations can be required by the UN 2345 (XXII) according to article 5, bullet 5, of the "Agreement on the Rescue of Astronauts, the Return of Astronauts and Return of Objects Launched into Outer Space", 19/12/1967, stating: *"[…] a Contracting Party which has reason to believe that a space object or its component parts discovered in territory under its jurisdiction, or recovered by it elsewhere, is of a hazardous or deleterious nature may so notify the launching authority, which shall immediately take effective steps, under the direction and control of the said Contracting Part, to eliminate possible danger of harm"*.

5 Re-entry safety requirements

5.1 Re-entry casualty risk

a. The space system shall be designed and operated such that the re-entry casualty risk does not exceed 10^{-4} for all re-entry events.

NOTE 1 ESA space system can include, but are not limited to:

- ESA spacecraft, including mated configurations of space debris remediation missions,
- ESA launch vehicle orbital stage (e.g. an upper stages),
- ESA unmanned steered vehicles,
- ESA return items, either recoverable or non-recoverable (e.g. return capsules, re-entry recorders).

NOTE 2 A re-entry event can be controlled or uncontrolled.

NOTE 3 For ESA space systems for which the System Requirements Review was kicked-off after the entry into force of the ESA Space Debris Mitigation Policy for Agency Projects (2014), if the predicted casualty risk for an uncontrolled re-entry exceeds 10^{-4}, an uncontrolled re-entry is not allowed and a controlled re-entry assuring re-entry casualty risk less than 10^{-4} is only allowed.

NOTE 4 The re-entry casualty risk of a space system that is intentionally partitioned before re-entry is obtained by summing up the re-entry casualty risk figures of all the individual parts. Therefore, partitioning of a space system, e.g. close to the time of re-entry, can be used to influence the overall re-entry casualty risk, but cannot be used to create multiple re-entry events required to comply individually with the re-entry casualty risk requirement.

5.2 Re-entry hazards

5.2.1 General

a. The re-entry of the space system, or elements thereof, shall not result in hazards to human population, harmful contamination of the Earth environment, and damages to assets, due to:

1. Impacting fragments,
2. Floating fragments,
3. Pressurized or explosive fragments,
4. Hazardous chemical substances,
5. Radioactive substances.

b. For controlled re-entry, the nominal re-entry trajectory of the space system shall not skip over the Earth atmosphere after the execution of the last de-orbit manoeuver.

NOTE For controlled re-entry from LEO circular orbits, it can be sufficient to target a perigee altitude lower than 50 km.

5.2.2 Impacting fragments

a. The re-entry casualty risk shall include all the impacting fragments of the space system with a kinetic energy equal or greater than 15 J at their impact on Earth surface.

NOTE The 15 J kinetic energy threshold for a human casualty is derived from the AIS level 3 (out of 6 levels), which identifies a severe injury (e.g. an open fracture of humerus). The AIS scale was specified by the Association for the Advancement of Automotive Medicine.

b. For controlled re-entry, the re-entry impact zone of the fragments of the space system shall be selected as follows:

1. For space systems performing destructive controlled re-entry, the Safety Re-entry Area (SRA) is specified to ensure that for the nominal and non-nominal re-entry scenarios the following conditions are fulfilled:
   (a) The SRA extends over an ocean uninhabited area, with clearance of landmasses, air and maritime traffic routes, and any kind of assets.
   (b) The SRA does not enter into the territorial waters of any State, which extends over the range of 12 nm (22,2 km) from the coastline of the State.
   (c) In case the SRA enters into the Economic Exclusive Zone of a State, which extends over the range of 200 nm (370,4 km) from the coastline of the State, the States is informed in due time by the operator of the space system.

(d) The SRA does not enter into maritime protected areas and these areas are not contaminated by release of hazardous or radioactive substances from the space system.

2. For space systems performing non-destructive controlled re-entry up to touchdown, the selection of the touchdown zone and the re-entry specifications are agreed with the ESA relevant Authority.

NOTE 1 Examples of assets are offshore installations.

NOTE 2 Landmasses include also the continent Antarctica and its ice shelves.

NOTE 3 The South Pacific Ocean Uninhabited Area (SPOUA) or other possible ocean uninhabited areas, which maximize the fitting of the fragments footprint compatibly with the mission operational orbit and de-orbit operations, can be considered as preferred options for the re-entry impact area. The SPOUA was found as the largest unpopulated area compatible with the mission specifications for the re-entries of the ESA ATVs. The SPOUA was specified as the area delimited by the longitude range from 185° East (i.e. -175°) to 275° East (i.e. -85°) and latitude range from 29° South to 60° South.

5.2.3 Floating fragments

a. The re-entry of the space system shall not create hazardous floating wrecks.

5.2.4 Pressurized or explosive fragments

a. Pressurized fluids or explosive substances contained in surviving fragments shall not create a hazard to human population.

NOTE Pressure vessels are examples of surviving fragments which can contain pressurized fluids or explosive substances.

5.2.5 Hazardous chemical substances

a. The relevant regulations regarding to prohibition and restriction of specific chemical substances and their limited use for space activities shall be applied.

NOTE EU and national regulations and directives (e.g. REACH and RoHS) are already applicable to the procurement of ESA space systems.

b. Hazardous chemical substances contained in the space system shall not reach the Earth surface.

c. Chemical substances contained in the space system shall not have hazardous effects on human health and Earth environment after re-entry.

5.2.6 Radioactive substances

a. The use and re-entry of radioactive substances present in the space system shall be compliant with the ESA Safety Policy for Nuclear Power Sources and subject of approval by the ESA relevant Authority.

b. Any possible re-entry of the space system shall comply with the radiation protection measures and guidelines from the ICRP.

5.3 System reliability for controlled re-entry

a. The reliability of the space system shall be such that the re-entry casualty risk requirement is met by including the probability of failures preventing the nominal controlled re-entry.

NOTE The method for the calculation of the re-entry casualty risk is explained in Annex A.

b. The probability of availability of energy to perform controlled re-entry shall be at least 0,99.

5.4 Planetary protection

a. For return missions to Earth from other planets or celestial bodies, the ESA standard ESSB-ST-U-001 on planetary protection shall be applied.

5.5 Ground control and tracking

a. The operator of the space system shall keep an up-to-date record of the space system status demonstrating the ability of the space system and the availability of the energy resources to perform the de-orbit and re-entry manoeuvres to comply with the re-entry safety requirements.

b. For a controlled re-entry, an operation control centre shall ensure full and continuous coverage such that the space system can be safely manoeuvred until the completion of all the re-entry manoeuvres.

c. Human operators should be available at any time during the re-entry operations such that they can be able to intervene in case of unforeseen failures during the manoeuvres of the space system.

d. In the case of premature or accidental re-entry, the operator of the space system shall implement all measures to minimize the casualty risk for human population.

e. For a controlled re-entry of the space system, the re-entry shall be confirmed with available observational means.

NOTE In addition to the telemetry data, the re-entry confirmation can be fulfilled by various observational means, including but not limited to, in situ observation of the re-entry, observation from space, or no show events on space surveillance systems.

5.6 Re-entry notification

a. The operator of the space system performing controlled re-entry shall contact the relevant authorities overseeing the affected air and maritime traffic space to supply them, in line with the authorities' procedures, with a re-entry notification including all the technical information the authorities need in order to issue NOTAM and NOTMAR / AVURNAV messages.

b. For a space system performing destructive controlled re-entry, a re-entry notification shall be planned and executed in accordance with the following rules:

1. The coordinates of the DRA for the nominal re-entry scenario are specified.
2. A set of possible back-up DRAs corresponding to at least two back-up de-orbit scenarios per day is specified in case of emergencies or anomalies.
3. A macro re-entry zone is specified as envelop of all possible de-orbit scenarios foreseen over 7 days through a polygon with up to 8 points, such that the polygon can be linearly interconnected in an orthogonal map projection without crossing the internal area.
4. The re-entry epoch is provided in UTC.
5. For each re-entry opportunity a time window extended from the re-entry time minus 1 hour and the re-entry time plus 2 hours is foreseen in order to account for the fallout of all the fragments.
6. The coordinates of the re-entry macro-zone are provided in the format required by the air and maritime traffic authorities.
7. The re-entry macro-zone is transmitted not later than 6 days before the re-entry event for the NOTMAR / AVURNAV and not later than 2 days before the re-entry event for the NOTAM.
8. The re-entry macro-zone contains all foreseen re-entry opportunities for 7 days, starting from the time of the nominal re-entry opportunity.
9. In case of replanning of the re-entry, if the new re-entry plan is not included in the first re-entry notification plan:
   (a) The first re-entry notification is cancelled and a new re-entry notification is prepared.
   (b) If there are substantial changes in the impact time outside of the period tolerances, which have been already communicated to the authorities, the re-entry replanning is re-iterated to target the first re-entry opportunity not earlier than 7 days before the date of issue of the new plan.

NOTE 1 The coordinates of the DRA forms the baseline of the NOTAM and NOTMAR / AVURNAV messages.

NOTE 2 An example of coordinate notation is referring to longitude smaller than 180˚, East/West, in degrees, minutes, and seconds.

c. For a space system performing non-destructive controlled re-entry up to touchdown, a re-entry notification procedure shall be agreed and authorized by the ESA relevant Authority:

   1. The procedure includes at least the analysis of the DRA and SRA in case of a break-up event along the nominal trajectory and document the impact on the Earth surface.

d. The operator of the space system shall inform the ESA relevant Authority about the issue of the re-entry notification procedure and the conclusion of the re-entry event.

5.7 Retrieval

a. Retrieval operations shall be performed every time wrecks from a re-entered space system, or elements thereof, represent hazard to human health or Earth environment.

b. The retrieval operations shall be executed in accordance with the local national safety regulations and in agreement with local government authorities.

6 Re-entry safety requirements verification

6.1 Re-entry casualty risk

a. The compliance of the space system with the re-entry safety requirements shall be documented in a Re-entry Safety Report in accordance with the DRD in Annex B.

6.2 Re-entry hazards

6.2.1 General

a. The verification of the compliance of the space system with the re-entry safety requirements shall include the following hazard causes:

1. Impacting fragments,
2. Floating fragments,
3. Pressurized or explosive fragments,
4. Hazardous chemical substances,
5. Radioactive substances.

6.2.2 Impacting fragments

a. A re-entry casualty risk analysis shall be performed for the space system, or elements thereof, which are planned to re-enter or which have the possibility that their trajectory is altered resulting in a re-entry in accordance with DRD from Annex A.

NOTE Failures or orbit instability can be causes for re-entry. For example, a spacecraft which does not foresee re-entry in its nominal scenario, e.g. operating close to Sun-Earth Lagrange points and planning heliocentric disposal orbits or launched into GTO with their own orbit raising systems to reach GEO, can re-enter in case of failures.

b. In the case of an uncontrolled re-entry of the space system, the re-entry casualty risk analysis for impacting fragments shall demonstrate for the nominal and non-nominal re-entry scenarios that the maximum casualty risk is lower than the maximum allowed re-entry casualty risk.

c. In the case of a controlled re-entry of the space system, the re-entry casualty risk analysis for impacting fragments shall demonstrate for the nominal and non-nominal re-entry scenarios that the maximum casualty risk is lower than the maximum allowed re-entry casualty risk and the SRA is compliant with the re-entry safety requirements.

d. The re-entry casualty risk analysis shall be performed with the ESA tool DRAMA.

NOTE The ESA tool DRAMA is available free of charge upon request to the ESA office in charge of development and maintenance of the tool (https://sdup.esoc.esa.int).

e. In case the analysis with the ESA tool DRAMA show non-compliance with the re-entry casualty risk requirement or the geometry of the space system is not suitable for analysis with the ESA tool DRAMA, a higher fidelity tool shall be used.

f. The use of tools other than the ESA tool DRAMA for the re-entry casualty risk analysis shall be approved by the ESA relevant Authority specified in the Space Debris Mitigation Policy for Agency Projects.

g. The re-entry casualty risk analysis shall be performed and documented in accordance with the DRD in Annex A.

h. For a space system with mass less than 5 kg, compliance with the re-entry casualty risk may be demonstrated by review of design.

i. During the operation phase of the space system, the re-entry trajectory, the re-entry casualty risk for impacting fragments, and the SRA and DRA shall be re-assessed:

1. At the time of any detected flight anomaly or in-orbit failure affecting the nominal re-entry functions;

2. Before planning any major deviation from the nominal plan, including but not limited to, change or extension of the mission, or anticipation of the re-entry.

6.2.3 Floating fragments

a. An analysis shall be performed to demonstrate that fragments surviving the re-entry of the space system do not result into hazardous floating wrecks.

b. The analysis should demonstrate that all impacting fragments have the physical properties to allow them not to float over waters or they do not result into a hazardous floating wreck.

c. The expected characteristic of the floating fragments shall be listed, including:

1. Physical state of the fragment and fluid substances;

2. Maximum size along the three main orthogonal directions of the fragment and volume of fluid chemical substances;

3. Mass of the fragment and fluid chemical substances;
4. Material and chemical composition of the fragment and fluid chemical substances;
5. Type of hazard associated to the fragment and fluid chemical substances.

6.2.4 Pressurized or explosive fragments

a. In case of re-entry of pressurized or explosive substances on-board the space system at the time of its re-entry, an explosion risk analysis shall be performed in order to specify:
   1. The probability of explosion with respect to the altitude and the effect on the fragmentation of the space system, or elements thereof, along the re-entry trajectory.
   2. The probability and the effects of a detonation, deflagration, and distant focusing overpressure, in case of expected impact on the Earth surface of the space system, or elements thereof.

6.2.5 Hazardous chemical substances

a. A review of design shall be performed to show that no hazardous chemical substances are used in the design of the space system.

b. An analysis shall be performed to demonstrate that the use of chemical substances does not lead to hazards during and after the re-entry.

c. Hazardous chemical substances that are planned to be used in the design of the space system shall be identified at SRR.

d. Use of hazardous chemical substances shall be declared in an inventory during the development phase and documented in Design Reports, DML, SDMP, SDMR, and hazard reports.

e. Information on an hazardous substance shall include at least:
   1. Name;
   2. Chemical composition;
   3. Quantity;
   4. Physical description;
   5. Hazard effects (when on Earth surface after the atmospheric entry).

6.2.6 Radioactive substances

a. A review of design shall be performed to provide compliance with the requirements from the ESA Safety Policy for Nuclear Power Sources.

6.3 System reliability for controlled re-entry

a. An analysis shall be performed to demonstrate that the space system is reliable such that the nominal and non-nominal re-entry scenarios meet the re-entry casualty risk requirement.

b. The analysis to assess the reliability of the space system to execute the planned controlled re-entry shall be based on the RAMS methodology accepted by ESA and updated during the development phase in accordance with the standards ECSS-Q-ST-30, ECSS-Q-ST-30-02, ECSS-Q-ST-40, ECSS-Q-ST-40-12.

NOTE RAMS analyses include reliability predictions, Failure Modes, Effects Analysis (FMEA) and Failure Modes, Effects and Criticality Analysis (FMECA), Hardware-Software Interaction Analysis (HSIA), contingency analysis, Fault Tree Analysis (FTA), common-cause analysis, Worst Case Analysis (WCA), Failure Detection Isolation and Recovery (FDIR), part stress analysis, zonal analysis, maintainability analysis, and availability analysis.

c. The RAMS analysis for the de-orbit and re-entry functions shall be re-performed during the mission of the space system at least in the following case:

1. Before planning any major deviation from the nominal plan, including extension of the mission.

6.4 Planetary protection

a. The compliance with the planetary protection requirements shall be verified according to the standard ESSB-ST-U-001.

6.5 Ground control and tracking

a. A review of design shall be performed to demonstrate that the ground segment and the operator have the capability to operate the space system in compliance with the re-entry safety requirements.

NOTE ECSS-E-ST-70-11 is a standard for space segment operability.

6.6 Re-entry notification

a. A re-entry notification plan shall be specified, documented and implemented for the space system expected to re-enter in a controlled way.

6.7 Retrieval

a. When retrieval operations of a re-entered space system, or elements thereof, are required, a retrieval plan shall be specified, documented and implemented, including:

1. Description of the objects, fragments or chemical substances from the space system to be retrieved.
2. Identification of the area on the Earth surface where the retrieval operations are taken place.
3. Description of the retrieval operations up to final storage.
4. Plan for means and trained operator personnel for the execution of the retrieval operations.
5. Definition of safety measures and procedures for the operator personnel in charge of the retrieval.

Annex A (normative) Re-entry casualty risk analysis – DRD

A.1 DRD identification

A.1.1 Requirement identification and source document

This DRD is called by ESSB-ST-U-004, requirement 6.2.2a.

A.1.2 Purpose and objective

The objective of the re-entry casualty risk analysis is to provide the assessment of the expected re-entry casualty risk of the space system, or re-entering elements thereof, and, for controlled re-entry, also of the fragments footprint size and location (i.e. SRA and DRA).

A.2 Expected response

A.2.1 Scope and content

<1> Introduction

a. The re-entry casualty risk analysis shall introduce the purpose, objective and the reason for its preparation.

<2> Documents

a. The re-entry casualty risk analysis shall include the list of the applicable and reference documents, including design references, analyses performed by lower level suppliers, used in the preparation of the re-entry casualty risk analysis, and any other documents relevant to re-entry safety.

<3> Acronyms and abbreviations

a. The re-entry casualty risk analysis shall include the list of the acronyms, abbreviations and definitions of special terms used.

<4> Space system modelling

a. The model of the space system, or re-entering elements thereof, for the re-entry casualty risk analysis shall include the specifications of:

1. The geometrical and physical model of the space system, or re-entering elements thereof, used for the re-entry casualty risk analysis with all relevant sub-systems, parts, components, and items foreseen in the design of the space system relevant to the re-entry.

2. All solid objects relevant in terms of mass and thermo-mechanical properties.

3. The assumptions introduced by the analysis tools with the approval, prior to usage, by the ESA relevant Authority defined in the Space Debris Mitigation Policy for Agency Projects.

4. The properties of materials used in the model for the re-entry casualty risk analysis:

   (a) Mass density,

   (b) Heat capacity,

   (c) Melting temperature,

   (d) Heat of melting,

   (e) Emissivity.

   NOTE 1 Flexible items, distributed in the structure and having low melting temperature like harness, cables, and items with small mass (e.g. screws) cannot be modelled or can be modelled in a simpler way to take their mass into account.

   NOTE 2 The model for the re-entry casualty risk analysis can be composed of simple geometry shapes, e.g. boxes, panels, cylinders, spheres, etc., which can be specified with thermo-mechanical properties of the materials foreseen in the space system design.

<5> Analysis methodology and assumptions

a. Analysis methodology and assumptions for the re-entry casualty risk analysis of the space system, or re-entering elements thereof, shall include:

1. The specification of the methodology used for the re-entry casualty risk analysis.

2. The specification of the inputs parameters: orbital state vector, attitude and sequence of de-orbit manoeuvres, used for the re-entry casualty risk analysis.

3. The calculation of the re-entry casualty risk with an accuracy according to the type of re-entry.

4. The calculation of the re-entry probability and inclusion into the re-entry casualty risk.

5. The analysis of the nominal and non-nominal re-entry scenarios for the initial and boundary conditions, the trajectory determination, and the break-up events prediction.

6. For a controlled re-entry, performance of the de-orbit trajectory and re-entry fragmentation analysis for the nominal and non-nominal re-entry scenarios with a 95% confidence level or a converged Monte-Carlo analysis to derive the DRA and SRA.

7. Safety margins and a probability distribution functions or dispersions for the input parameters of the re-entry modelling to cover their uncertainties.

8. Adoption of a specified methodology able to simulate the break-ups and ablation process during the re-entry event according to a scientifically recognized or validated aerothermodynamics and mechanical model.

9. The calculation of the probability of fragment impact in a specific area or latitude range on the Earth surface.

10. The calculation of the re-entry casualty risk by including the human population density at the time of the expected re-entry as predicted by a population model accepted by ESA.

11. The calculation of the casualty area of each fragment ($A_{C,k}$), which has a kinetic energy at the impact on the Earth surface equal or exceeding 15 J, according to the following formula:

$A_{C,k} = \left[\sqrt{A_{i,k}} + \sqrt{A_h}\right]^2$	[A-1]

where:

$A_{i,k}$ is the average projected area of the fragment surviving the re-entry,

A_h is the cross-section of a human, which is conventionally equal to 0,36 m².

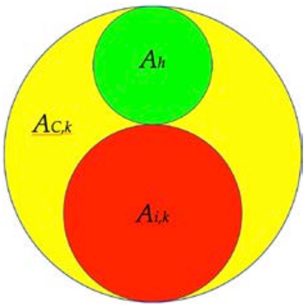

Figure A-1: Casualty area definition

12. The calculation of the re-entry casualty risk according to the following formulas:

(a) For uncontrolled re-entry ($E_{C,unc}$):

$E_{C,unc} = \sum_{k=1}^{N} A_{C,k}\, \rho_p(i, \Delta\varphi, \omega)$	[A-2]

where:

k is index for fragment,

N is the number of fragments surviving the re-entry,

$A_{C,k}$ is the casualty area of the k-th fragment,

$\rho_p(i,\varphi,\Delta\varphi)$ is the Earth population density expected in the impact area at the time of the re-entry, weighted with the probability of impact on the Earth surface depending on the orbit inclination i, the latitude step size $\Delta\varphi$, and the argument of perigee at the epoch of atmospheric capture ω (function of the orbit eccentricity);

(b) For controlled re-entry, both:

(b.1) Nominal controlled re-entry ($E_{C,con}$):

$E_{C,con} = 1 - \prod_{k=1}^{N} \left(1 - \sum_{n} \sum_{m} \left(P_{i,k}\right)_{n,m} \left(\rho_{p,k}\right)_{n,m} \left(A_{C,k}\right)_{n,m} \right)$	[A-3]

where:

k is index for fragment,

N is the number of fragments surviving the re-entry,

n and m are indices for impact area bins,

$(P_{i,k})_{m,n}$ is the impact probability of the k-th fragment in the (m,n) area bin of the Earth surface,

$(\rho_{p,k})_{m,n}$ is the Earth population density expected in the (m,n) impact area bin at the time of the re-entry for the k-th fragment,

$(A_{C,k})_{m,n}$ is the casualty area of the k-th fragment in the (m,n) impact area bin;

and

(b.2) Failed controlled re-entry ($E_{C,con,fail}$):

$E_{C,con,fail} = E_{C,unc} P_f$	[A-4]

where:

$E_{C,unc}$ is the re-entry casualty risk for uncontrolled re-entry,

P_f is the probability of system failures leading to uncontrolled re-entry or affecting the nominal controlled re-entry;

(c) For a space system, or re-entering elements thereof, with no nominal plan for a re-entry, but having a non-zero probability to approach re-entry conditions ($E_{C,prob\_re-entry}$):

$E_{C,\mathrm{prob}\_re-entry} = E_{C,unc} P_{re-entry}$	[A-5]

where:

$E_{C,unc}$ is the re-entry casualty risk for uncontrolled re-entry,

$P_{re-entry}$ is the re-entry probability;

(d) For re-entry involving a combination of possible re-entry scenarios ($E_{C,comb}$):

$E_{C,comb} = \mathrm{E}_{C,nom} P_{nom,} + \sum_{r=1}^{Z} E_{C,non-nom,r}\, P_{non-nom,r}$	[A-6]

where:

$E_{C,nom}$ is the casualty risk for the nominal controlled re-entry,

P_{nom} is the probability to perform the nominal controlled re-entry (e.g. the reliability of the system to perfom the controlled re-entry),

r is index for non-nominal re-entry scenarios,

Z is the number of non-nominal re-entry scenarios,

$P_{non\text{-}nom,,k}$ is the probability to have the k-th non-nominal re-entry scenario,

$E_{C,non\text{-}nom,k}$ is the casualty risk associated to the k-th non-nominal scenario.

13. For controlled re-entry, the calculation of the Declared Re-entry Area (DRA) and the Safety Re-entry Area (SRA) for the nominal and non-nominal re-entry scenarios.

NOTE 1 A re-entry casualty risk analysis is performed for any space system when re-entry is planned, or re-entry is expected as a result of natural orbital decay, or the space system operates along an unstable operational orbit (e.g. Sun-Earth or Earth-Moon Lagrangian points missions, HEO) and possible failures related to orbit injection manoeuvres, station-keeping manoeuvres or disposal manoeuvres can lead to a probability of re-entry higher than zero. For failures occurring when the space system is still carried as payload on the launch vehicle orbital stage, it is up to the launch safety authority to request a re-entry casualty risk analysis for the combined system launch segment element (e.g. launch vehicle orbital stage) and space segment element (e.g. spacecraft) or also for the separated space segment element in the case of an accidental re-entry.

NOTE 2 Monte Carlo simulations are performed to improve the accuracy of the assessment of the SRA and DRA. Converged Monte Carlo analysis means that the variation of the DRA and SRA dimensions from the previous realization to the current one is less than 1% of the current value. A minimum of 100 realization is advised.

NOTE 3 Safety margins and probability distribution functions or dispersions can be specified for the parameters relevant for re-entry, e.g.: orbital state at time of the de-orbit boosts, duration of the de-orbit boosts, magnitude of the de-orbit boost, thrust specific impulse, thrust pitch angle, atmospheric density, wind velocity, drag coefficient of the space segment element, mass of the space segment element, altitude of the break-up events and their resulting fragments Delta-Vs (due to thermo-mechanical or explosion effects). For example, for a controlled re-entry, safety margins and probability distribution functions or dispersions are taken into account to assess the consequences of possible deviations in the trajectory leading to shifts of the fragments footprint.

NOTE 4 The probability of break-up events depends on atmospheric parameters, ablation processes, mechanical loads and possible explosions affecting the fragmentation and trajectory. Explosions with fragmentation effects on the structure can be driven by possible residual sources of energy on board like ergols.

NOTE 5 Tools for re-entry casualty risk analysis are usually classified in "object-oriented" and "spacecraft-oriented" tools. For example, in a "object-oriented" tool the fragmentation approach is characterized by the following simplifications:

- The major spacecraft break-up altitude and major break-up events are pre-determined and lead to the release of all components or, alternatively, to the release of compounds with their own release conditions for sub-components (the prediction of the break-up altitudes can be based on valid physical considerations, similitudes, or probabilistic assessments).
- All released components are pre-determined and have simplified shapes (typically spheres, plates, cylinders, boxes).
- All released components are considered randomly tumbling to enable an average heating and ablation simulation, and melt from the outside layer-by-layer, hence maintaining their shape type.
- The trajectory analysis of all fragments considers translational motion only (3 degrees of freedom).

NOTE 6 For an uncontrolled re-entry along a circular orbit with inclination *i*, the re-entry is expected to occur in the latitude range *[-i, i]*. In case of uncontrolled steep or eccentric re-entries, instead, the affected latitude range are identified.

NOTE 7 High resolution global Earth population data based on census data are availble via the Gridded Population of the World (GPW) project. Human population evolution predictions are regularly updated and maintained by the United Nation in the Probabilistic Population Prospect (PPP) project. The GWP and PPP Median evolution model are implemented in the ESA tool DRAMA. Additionally, an online version of the population density model is available through ESA (i.e. ESA tool ORIUNDO, available from https://sdup.esoc.esa.int/web/csdtf/home).

NOTE 8 Non-zero probability to approach re-entry conditions can occur with disposal on a HEO or on an orbit around Sun-Earth Lagrange Points.

NOTE 9 The re-entry casualty risk is computed in the practice through the casualty expectation approximating the casualty probability.

NOTE 10 See also Annex C of ESSB-HB-U-002 for further information about how to perform a re-entry casualty risk analysis.

<6> Results

a. The results of the re-entry casualty risk analysis shall include:

1. For each fragment expected to survive the re-entry as a minimum the following characteristics:
   (a) Maximum size along the three main orthogonal directions and average size,
   (b) Average and maximum projected area,
   (c) Mass per fragment and per material type, if multi-material,
   (d) Material,
   (e) Casualty area,
   (f) Impact velocity,
   (g) Impact flight path angle,
   (h) Impact kinetic energy;
2. Earth population density data expected at time of the re-entry;
3. The re-entry casualty risk of the space system;
4. For controlled re-entry, the DRA and SRA.

Annex B (normative) Re-entry safety report (RSR) - DRD

B.1 DRD identification

B.1.1 Requirement identification and source document

This DRD is called by ESSB-ST-U-004, requirement 6.1a.

B.1.2 Purpose and objective

The objective of the Re-entry Safety Report is to document the activities performed by the Project to assure the compliance with the re-entry safety requirements.

B.2 Expected response

B.2.1 Scope and content

<1> Introduction

a. The RSR shall introduce the purpose, objective and the reason for its preparation.

<2> Applicable and reference documents

a. The RSR shall list all the applicable and reference documents in support of the generation of the document.

b. Any document relevant and supporting to the re-entry safety compliance verification, including also documents produced outside the scope of contracts with ESA, shall be provided for the review.

<3> Re-entry management

a. The RSR shall describe the organization including responsibilities and authorities, the activities, processes and procedures to be applied by the Project to fulfil the applicable re-entry safety requirements specified in clause 5 and the requirements verification specified in clause 6 of ESSB-ST-U-004.

<4> Re-entry plan

a. The RSR shall include a re-entry plan containing as a minimum:

1. Description of the re-entering space object, including design information of the space system,
2. Definition of the re-entry strategy,
3. Determination of the trajectory and definition of the flight rules for the nominal and non-nominal re-entry scenarios,
4. Identification of all possible sources of hazard associated to the re-entry,
5. Identification of public and worker population potentially exposed to hazards associated with the re-entry and mitigation measures implemented.

NOTE 1 Information of the vehicle includes size, mass, propellant types, pressurized vessels potential for high-energy release, hazardous chemical substances or radioactive substances.

NOTE 2 Re-entry strategy can be controlled or uncontrolled.

<5> Re-entry safety analyses

<5.1> Re-entry casualty risk

a. The RSR shall include rationale for the compliance with the requirements in clause 5.1 and all the actions according to the requirements verification in clause 6.1.

<5.2> Re-entry hazards

<5.2.1> General

a. The RSR shall include rationale for the compliance with the requirements in clause 5.2.1 and all the actions according to the requirements verification in clause 6.2.1.

<5.2.2> Impacting fragments

a. The RSR shall include rationale for the compliance with the requirements in clause 5.2.2 and all the actions according to the requirements verification in clause 6.2.2.

<5.2.3> Floating fragments

a. The RSR shall include rationale for the compliance with the requirements in clause 5.2.3 and all the actions according to the requirements verification in clause 6.2.3.

<5.2.4> Pressurized or explosive fragments

a. The RSR shall include rationale for the compliance with the requirements in clause 5.2.4 and all the actions according to the requirements verification in clause 6.2.4.

<5.2.5> Hazardous chemical substances

a. The RSR shall include rationale for the compliance with the requirements in clause 5.2.5 and all the actions according to the requirements verification in clause 6.2.5.

<5.2.6> Radioactive fragments

a. The RSR shall include rationale for the compliance with the requirements in clause 5.2.6 and all the actions according to the requirements verification in clause 6.2.6.

<6> System reliability for controlled re-entry

a. The RSR shall include rationale for the compliance with the requirements in clause 5.3 and all the actions according to the requirements verification in clause 6.3.

<7> Planetary protection

a. The RSR shall include rationale for the compliance with the requirements in clause 5.4 and all the actions according to the requirements verification in clause 6.4.

<8> Ground control and tracking

a. The RSR shall include rationale for the compliance with the requirements in clause 5.5 and all the actions according to the requirements verification in clause 6.5.

<9> Re-entry notification plan

a. The RSR shall include rationale for the compliance with the requirements in clause 5.6 and all the actions according to the requirements verification in clause 6.6.

<10> Retrieval

a. The RSR shall include rationale for the compliance with the requirements in clause 5.7 and all the actions according to the requirements verification in clause 6.7.

Annex C (informative) RSR delivery with respect to milestones

Table C-1 presents the Project milestones at which a delivery of the Re-entry Safety Report (RSR) is expected. The document can be prepared either as self-standing RSR or incorporated into Space Debris Mitigation Plan (SDMP) and Space Debris Mitigation Report (SDMR), depending on the project phase (as per ESA Space Debris Mitigation Policy for Agency Projects).

Table C-1: Re-entry Safety Report (RSR) delivery with respect to milestones

Document	Review												DRD Ref.
	MDR	PRR	SRR	PDR	CDR	QR	AR	ORR	FRR	LRR	CRR	ELR	
RSR	(X)	(X)	(X)	(X)	X	XX	XX	XX	XX	XX	XX	XX	ESSB-ST-U-004, Annex B
(X): preliminary X: final XX: confirmation/review/update													

Bibliography

ECSS-S-ST-00	ECSS system – Description, implementation and general requirements
ESSB-HB-U-002	ESA Space Debris Mitigation Compliance Verification Guidelines
ECSS-E-ST-70-11	Space engineering – Space system operability
A/AC.105/934	Safety Framework for Nuclear Power Source Applications in Outer Space – Endorsed by the United Nations COPUOS, 19/05/2009
A/RES/47/68	Principles Relevant to the Use of Nuclear Power Sources in Outer Space – Adopted by the United Nations General Assembly, 14/12/1992