RÉPUBLIQUE
FRANÇAISE
Liberté
Égalité
Fraternité

cnes
CENTRE NATIONAL
D'ÉTUDES SPATIALES

FSOA GOOD PRACTICE GUIDE
FOR ORBITAL SYSTEMS

RÉPUBLIQUE FRANÇAISE
Liberté
Égalité
Fraternité

cnes
CENTRE NATIONAL D'ÉTUDES SPATIALES

FSOA GOOD PRACTICE GUIDE (ORBITAL SYSTEMS)

	Name and acronym	Date and signature
Drafted by	CNES expert group, Coordinated by CNES Space Safety Office for Orbital Systems DOA/SME/LOS	
Checked by	DOA/SME/LOS	Not Applicable (translation of the authorized French version of this guide)
	DOA/SME	
Application authorised by	DOA/D	
	IGQ/D	

INTERNAL/EXTERNAL DISTRIBUTION			
Acronym/Company	Name (+ email address if external)	Observation for	
		Action	Information
French Space Agency (CNES)	DTN, DOA, DTS and DS/PF Sub-Directorates		X
French satellite operators			X
Arianespace			X
ESA	Safety Office		X

DOCUMENT ANALYSIS PAGE

Classification (+ qualification for Limited Distribution): **Not sensitive**		
Keywords: **LOS, compliance, technical regulation, re-entry**		
Authors: **LOS Office, Orbital Systems and CNES expert group**		
Abstract: This Good Practice Guide is intended to help operators who wish to submit a French Space Operations Act compliance file. It covers requests relating to orbital systems and provides information to help demonstrate compliance with the technical regulation (see DA4). It is created under Article 54 of the technical regulation.		
Configuration management: **yes**	From: **23/09/2024**	By: DOA/SME/LOS
Contract:		
Host software: **Word MS-Office**	Number of extra pages:	

RECORD OF REVISIONS

Version	Date	Chapters modified/Reason/Nature of the change
1.0	15/03/2022	Creation
2.0	12/12/2022	Version for official consultation

3.0	03/06/2024	**Official version**
		<u>Additions:</u>
		• Reference documents:
		  ○ **DEBRISK** tool user guide for satellite applications.
		  ○ **ELECTRA** tool user guide for satellite applications.
		• Updated applicable regulatory documents.
		• Use of the new CNES template.
		• Addition of hypertext links to the table in § 2 to help browse articles in the technical regulation.
		• List of acronyms used in this guide.
		
		<u>Changes/clarifications:</u>
		• Update of the "probability of collision estimation" section by the CNES Space Surveillance department - §3.5.
		• Time horizon (sliding windows) for the "Data sharing" requirement - §3.6.2.
		• Update of the "environmental impact" section with the INERIS study - §5.2.
		• Reorganisation of the "On-Orbit Servicing" and "Constellations" chapters - §7 and §8.
		• Update to the "Mission extension" section - §9.
		
		<u>Deletions:</u>
		• Detailed Debrisk methodology (detailed description in the user guide supplied with the software) - §10.2
		• STELA appendix (information moved to STELA user guide as reference document [RD5])

REFERENCE DOCUMENTS

Reference		Document title
RD1	**LOS-GR-CNF-8-CNES** **Rev 1-Iss 4 dated 25/03/2015**	FSOA Good Practice Guide (former version).
RD2	**DSO/DA/3S-2020.0025443 dated 20 May 2020.**	Appointment of expert group for updating the FSOA Good Practice Guide.
RD3	**DBK-NT-LOG-0567-CNES**	DEBRISK tool user guide for satellite applications.
RD4	**ELECT-MU-2200-314-CNES**	ELECTRA tool user guide for satellite applications.
RD5	**STELA-NT-ETUDES-363-CNES**	STELA tool user guide for satellite applications.
RD6	**DSO/AQ/SF-2020.0026415**	Guide for assessing the probability of success for satellite end-of-life operations.
RD7	**N/A**	Documentation on the INERIS method for assessing the environmental impact (available upon request, French only)
RD8	**DCS-2024.0004634**	Cyber hygiene guide for orbital systems

APPLICABLE DOCUMENTS

Reference		Document title
DA1	**NOR: ESRX0700048L**	French Space Operations Act No. 2008-518 of 3 June 2008 (amended) https://www.legifrance.gouv.fr/loda/id/JORFTEXT000018931380
DA2	**NOR: ESRR0825834D**	Decree No. 2009-643 of 9 June 2009 (amended) on authorisations issued implementing French Space Operations Act No. 2008-518 of 3 June 2008 https://www.legifrance.gouv.fr/loda/id/JORFTEXT000020719487
DA3	**NOR: ECOJ2206380A**	Order of 23 February 2022 (amended) on the composition of the three sections of the dossier mentioned in Article 1 of Decree No. 2009-643 of 9 June 2009 on authorisations issued implementing French Space Operations Act No. 2008-518 of 3 June 2008 (amended) https://www.legifrance.gouv.fr/loda/id/JORFTEXT000045243297 ***English version available upon request***
DA4	**NOR: ESRR1103737A**	Order of 31 March 2011 (amended) on the Technical Regulation implementing Decree No. 2009-643 of 9 June 2009 on authorisations issued implementing French Space Operations Act No. 2008-518 of 3 June 2008 https://www.legifrance.gouv.fr/loda/id/JORFTEXT000024095828 ***English version available upon request***

ABBREVIATED TERMS

Acronym/abbreviation	Definition
GPG	Good Practice Guide
FSOA	French Space Operations Act (in french LOS – Loi sur les Opérations Spatiale)
TR	Technical Regulation
ADR	Active Debris Removal
AVURNAV	Avis d'Urgence aux NAVigateurs (Navigational Warnings)
CAESAR	Conjunction Analysis and Evaluation Service, Alerts and Recommendations
CAD	Computer-Aided Design
CDM	Collision Data Message
CEA	Chemical Equilibrium Application
CID	Current Interrupt Device
CIDL	Configuration Item Data List
COTS	Commercial off-the-shelf
CPE	Cell Passage Event
CSG	Centre Spatial Guyanais (Europe's Spaceport in Kourou, French Guyana)
CSpOC	Combined Space Operations Centre
CSS	Chinese Space Station
PL	Payload
DJD	Design Justification File
DML	Declared Material List
DoD	Depth of Discharge
DPL	Declared Process List
DV	Delta-v
ECSS	European Cooperation for Space Standardization
EEE	Electrical, Electronic and Electro-mechanical (components)
ELECTRA	Launch and Re-Entry Safety Analysis tool
EM	Engineering Model
EMC	ElectroMagnetic Compatibility
ESD	Electro-Static Discharge
ESOC	European Space Operations Centre
EUSST	EU Space Surveillance and Tracking
FDIR	Fault Detection, Isolation, and Recovery
FDS	Flight Dynamic System
EOL	End of Life
FEEP	Field Emission Electric Propulsion

FOCUS	Fast Orbit Calculation Utility Software
GEO	Geostationary Earth Orbit
GNC	Guidance, Navigation and Control
GNSS	Global Navigation Satellite System
GPW	Gridded Population of the World
SA	Solar Generator
GTO	Geostationary Transfer Orbit
HEO	Highly Elliptical Orbit
HRL	High-Rate Longlife
IADC	Inter-Agency Space Debris Coordination Committee
ISS	International Space Station
LBB	Leak Before Burst
LEO	Low Earth Orbit
MASTER	Meteoroid and Space Debris Terrestrial Environment Reference
MCI	Mass, balance and inertia
MEO	Medium Earth Orbit
MICD	Mechanical Interface Control Document
MLI	Multi Layer Insulation
MMH	Methylhydrazine
MSA	Monitoring Safety and Alert
MSI	Monitoring Safety and Intervention
UM	User Manual
NIDA	Honeycomb
NOTAM	NOTice to AirMen
NTO	Nitrogen Tetroxide
ODR	Re-entry orbit
OOS	On-Orbit Servicing
PF	Platform
KP	Key point (or milestone)
PNEC	Predicted No Effect Concentration
PoC	Probability of Collision
SPF	Single Point of Failure
PSO	Position in orbit
PTC	Positive Thermal Coefficient
PVT	Position Velocity Time
QO	Operational qualification
QT	Technical Qualification
RA	Random Re-Entry
RC	Controlled re-entry
RNA	Assisted Natural Re-entry

RNC	Uncontrolled re-entry
RPO	Rendez-vous and Proximity Operations
RUL	Remaining Useful Lifetime
AOCS	Attitude and orbit control system
SCC	Satellite Control Centre
RAMS	Reliability, Availability, Maintainability and Safety
SoC	State Of Charge
SPOUA	South Pacific Ocean Uninhabited Area
SRM	Solid Rocket Motor
SSA	Space Situational Awareness
STELA	Semi Analytic Tool for End of Life Analysis
STM	Space Traffic Management
TC	Telecommand
TM	Telemetry
UVD	Under-Voltage Detector
TRV	Toxicological Reference Value
ZdR	Re-entry Area

ACKNOWLEDGEMENTS

Since its creation in the late 2010s, the French Space Operations Act (FSOA) Good Practice Guide has been constantly supplemented and improved, in line with legislative developments and changes to the space ecosystem. In addition to its main purpose, which is to help French operators comply with the requirements of the Technical Regulation, this guide has now become a benchmark for promoting practices that respect both the orbital and terrestrial environments.

As such, French Space Agency (CNES) Space Safety Office would like to thank all the experts from the CNES technical departments who contributed to this document. There are so many of them, it would be impossible to name them all.

Thanks also go to the operators and manufacturers who helped produce this guide through their feedback, comments, studies and contributions.

CONTENTS

FIGURES

TABLES

1 PURPOSE

> ***Article 54: Guide of good practices***
>
> *1. Two guides of good practices, one for launchers and the other for satellites, are drawn up by the CNES, jointly with the profession, through a working group representative of the operators and industrial firms concerned, in order to characterise certain practices in force, thereby helping to demonstrate compliance with this technical regulation.*
>
> *These guides are based on practices validated by the experience acquired in the development, operation and inspection of space systems. They are in particular based on standards, technical specifications constituting standards, and standards recognised by the profession relating to the safety of life, property, public health and the environment within the context of space operations. The contents of these guides comply with the applicable requirements for protection of intellectual property as well as industrial and scientific assets.*
>
> *2. Compliance with all or part of the requirements of this technical regulation is deemed to be acquired if the operator can demonstrate compliance with the relevant recommendations of these guides.*
>
> *The use of a guide of good practices is neither mandatory nor exclusive.*

This guide is intended to help operators submitting a French Space Operations Act compliance file. It contains proposals for meeting all the technical requirements of the Technical Regulation.

Software tools enabling to compute certain criteria required by the Technical Regulation are described and highly recommended. They are also used by the FSOA Compliance Analysis Officer to check compliance with the Technical Regulation. These tools are described in §10.

This document has been drafted by a group of CNES experts with extensive experience in both designing and operating space vehicles. The guide was also submitted to a large panel of French operators, duly amended and supplemented based on their feedback, as indicated in article 54 of the Technical Regulation.

This guide can therefore be seen as a kind of state of the art for space objects claiming to respect the orbital and terrestrial environment, in the context of a changing landscape due to the emergence of the Newspace. Updates will be made in line with changes to the orbital context and the French Technical Regulation.

Note:

The articles of the technical regulation are indicated throughout this guide as a reminder (grey boxes as above). The applicable versions are the French versions found in the official texts accessible on the Légifrance website.

This document is an English translation of the "Guide des Bonnes Pratiques LOS pour les systems orbitaux". Only the French text shall prevail in case of conflict between the French text and the translation thereof.

2 CORRESPONDENCE WITH THE TECHNICAL REGULATION

NC: not covered in this issue

Article No.	RT article title	BPG section
Obligations related to carrying out operations		
38-1	Inspection plan during on-orbit control	3.7.2
38-2	Validation of procedures	3.7.1
39	Ability to control the space object	3.7.1
39-1	Identification of space objects	3.6.2
39-2	Propellant management	3.9
39-3	Cybersecurity	6.1
39-4	Case of an On-orbit service for a vehicle for which control has already been authorised	7
Prevention of fragmentation		
40	1. Intentional release of debris	3.2
40	2. Accidental break-up	3.2.1
40	3. Passivation	3.3
40-1	Intentional destruction	NT
40-2	Devices for active debris removal	3.2.2
Prevention of collisions		
41	Prevention of the risks of collision with manned objects	3.6.2
41-1	Collision avoidance capability	3.6.2
41-2	Availability of collision avoidance manoeuvres	3.6.2
41-3	Probability of collision with a space object	3.5
41-4	Prevention of collisions at separation from a launcher or dispenser	3.6.2
41-5	Coordination in the event of a collision alert between two operators controlling manoeuvring space objects	3.6.2
41-6	Trigger threshold for collision avoidance manoeuvres	3.6.2
41-7	Data sharing	3.6.2
Prevention of saturations of orbits		
41-8	Disposal obligation	3.8
41-9	Maximum orbital life before atmospheric re-entry	3.8
41-10	Characteristics of a graveyard orbit between protected region A and protected region B	3.8
41-11	Characteristics of a graveyard orbit above protected region B	3.8
41-12	Reliability of disposal operations	3.10
41-13	Limitation of the orbit of non-manoeuvring space objects	3.4
41-14	Radio electric emissions	6.2
Particular risks		
42	Nuclear safety	NT
43	Planetary protection	NT
Specific Technical Requirements for the Return to Earth of a space object		
44	Quantitative objectives for the human safety for return to Earth of a space object	4
45	Requirements concerning uncontrolled re-entry of the space object foreseenat its end of life	5
46	Prevention of risks arising from the fall-back of the space object or fragments	4.7

	thereof during a controlled re-entry.	
46-1	Controlled re-entry to a site	4.9
47	Non-nominal re-entries	4.8
Specific Technical Requirements for On-orbit servicing		
47-1	Collection of debris created	7.1
47-2	Survival and collision	7.1
47-3	Compatibility of target object	7.1
47-4	Mission impact on a third party	7.1
47-5	Proximity zone volumes and corridors	7.2
47-6	GO/NOGO criteria	7.2
47-7	Coordination of control centres	7.2
47-8	Vehicle/Ground communications	7.2
47-9	Secure on-orbit service communications	7.2
47-10	Vicinity check	7.2
47-11	Emergency avoidance capability	7.2
47-12	Good operating tests of the servicing vehicle	7.2
47-13	Plume effect prevention	7.2
47-14	Qualification of approach and docking concepts	7.3
47-15	Inspection before docking	7.3
47-16	Performance for approach phase safety	7.3
47-17	Electrostatic and electromagnetic compatibility at contact	7.3
47-18	Control of the composite in the attached phase	7.4
47-19	Separation reliability	7.5
47-20	Integrity of target object at separation	7.5
47-21	Separation dynamics	7.5
Constellations		
48-1	Probability of disposal of the satellites of a constellation	8.1
48-2	Probability of causing casualties on the ground for megaconstellations.	8.2
48-3	Incorporation of experience feedback	8.1
48-4	Intra-constellation collisions after disposal	8.1
48-5	Collision avoidance capability for megaconstellations	8.2
48-6	Vital system tests before reaching operational orbit for megaconstellations	8.2
48-7	Maximum duration of disposalfor the satellites of a megaconstellation	8.2
48-8	Separation of intra-constellation planes	8.1
48-9	Separation between megaconstellations	8.2
48-10	Limitation of optical disruptions by the satellites of a megaconstellation.	8.2
Mission extension		
49-1	Conditions for mission extension	9

Table 1: Correspondence between RT articles and BPG chapters

3 LIMITING THE GENERATION OF IN-ORBIT DEBRIS

3.1 INTRODUCTION

The need to prevent debris from being generated in-orbit applies both during the operational phase of the mission and after the mission has ended.

During the operational lifetime of a satellite, this need can be guaranteed via:

- design rules that minimise the risks of in-orbit fragmentation/explosion,
- the implementation of health tests on the platform before it reaches its operational orbit,
- the establishment of on-board and on-ground sub-systems monitoring and, more generally, of platform health check,
- the use of avoidance manoeuvres to reduce the risk of accidental collision with catalogued orbital objects,
- a wise choice of mission orbit.

These measures meet the requirements of not generating debris via spontaneous fragmentation with a probability of 1×10^{-3} over the operational duration of the mission, and of not generating debris via collision with orbital objects throughout the satellite's entire orbital lifetime.

After a satellite's operational mission, debris generation is prevented by:

- the choice of disposal orbit (in particular by limiting the satellite's remaining time in orbit for objects operating in LEO, or by freeing up the GEO zone at end-of-life),
- passivation of the object at the end of its operational lifetime to reduce the risk of fragmentation after the operational mission.

A passivation procedure must be established before the end of the design phase and, if necessary, updated prior to disposal, to take account of any failures that would occur during the mission and that would affect the vehicle's passivation capability.

3.2 ENSURING GOOD SATELLITE DESIGN

Article 40: Space environment protection
1. Intentional release of debris
The space systems implemented by the operator shall be designed, produced and implemented such that they do not generate debris during an operation when it takes place nominally.

The above provision shall not apply:

- *to the pyrotechnic systems. However, these shall not generate products with the largest dimension of 1 mm or more;*
- *to solid or hybrid propellant boosters. They shall not however generate combustion debris of 1 mm or larger in protected regions A and B.*

However, the on-orbit release of a single additional service module is acceptable. As a space object, this module shall comply with all the provisions of the third part of this Order.

This requirement, which is designed to prevent the generation of debris from space objects, is now recognised internationally and included in numerous regulations and standards.

The generation of any debris, however small, poses a potential future risk to other operational objects and even the satellite itself.

It is therefore important to avoid any deliberate release of items such as: electrical cable clamps, devices to prevent the deployment of solar panels or antennae, apogee kick motor heat shields, solid propellant thrusters nozzle closure, observation instrument protections (lens caps), explosive bolts, springs, straps, yo-yo systems, etc.

If it is not possible to avoid generating these items, they must be retained to prevent them from being released into outer space.

Exceptions are made for pyrotechnic systems and solid or hybrid propellant boosters. In this case, the items generated and released will need to be identified (number, size, orbit evolution, time present in outer space, etc.) and their dimensions must remain smaller than 1 mm.

Releasing an additional service module is also permitted. However, this will become an object in its own right and the operator must demonstrate its compliance with the technical regulation.

By additional service module, we mean a module of benefit to the space object, which could be, for example, a propulsion module.

3.2.1 Design and layout of high-risk systems

Article 40: Space environment protection
2. Accidental break-up
The probability of occurrence of accidental break-up of any space object shall be less than 10^{-3} until the end of the disposal operations of this space object

Its calculation shall include failure modes of propulsion and power systems, mechanisms and structures, but shall not take account of any external impacts.

In the event of detection of a situation causing such a failure, the operator must be capable of planning and taking corrective measures to avoid all disintegration.

The operator must identity all the energy sources available in the satellite and the corresponding hazardous items that could result in accidental disintegration (partial or full) of the satellite. It must set out the design rules and margins used for these high-risk items.

For each hazardous item, it must list the failure modes and their probability of occurrence resulting in the generation of debris. Only destructive failures of non-redundant items will be considered. Typically, fail-safe items will be deemed safe. A "severity vs. probability of occurrence" risk rating matrix may be added to the analysis to refine the information provided.

The probability of occurrence for a failure mode is calculated over the operational lifetime of the satellite from injection by the launcher up until the disposal phase. See §3.10 for the reliability calculation methodology.

The combination of probabilities for each failure mode is used to demonstrate compliance with the requirement.

LBB (Leak Before Burst) technologies, the use of venting-valve-type devices and electrical protection against battery overcharging, are helpful to reduce the risk of debris generation.

If possible, these high-risk systems should be located in areas with low debris/micrometeoroid fluxes. Information on impact fluxes on the different surfaces of satellites (impacts on external surfaces and internal impacts passing through the primary structure) and means of protection can be found in **IADC-04-03** "Protection Manual". Information on space component vulnerabilities can be found in **IADC-13-11** "Spacecraft Component Vulnerability for Space Debris Impact". www.iadc-home.org

In addition to high-risk systems, the process for checking satellite equipment resistance to debris and micrometeoroid impacts defined in **ISO 16126** ("Space Systems - Assessment of survivability of unmanned spacecraft against space debris and meteoroid impacts to ensure successful postmission disposal") can be used for any function deemed critical, beyond the end-of-mission aspect. Document **IADC-04-03** "Protection Manual" contains examples of possible types of protection. Generally speaking, a space between one or more sacrificial walls and the object to be protected provides good protection at low mass.

Specific case of on-board batteries

To prove a low risk of accidental disintegration for the batteries on board a space object, one could, for example:

- Specifying the various protection systems implemented at cell level (PTC, CID, HRL, etc.)
- Mentioning certification obtained on flight models (**UN 38.3** type for battery transportation, **IEC 62133-2:2017** concerning safety aspects, etc.).
- Identifying the battery charge/discharge ranges and their compatibility with the thermal environment expected in flight (taking account of the manufacturer's recommendations).

- Provide reports on abuse testing on battery packs (including overcharging, short-circuit and overheating tests to ascertain the temperature at which thermal runaway occurs and the associated consequences).

Long-term strength of materials (degradation of paint, MLI, etc.)

The strength requirements for materials during the mission are defined by specific standards (for example **ECSS-E-ST-32-08** "Space engineering/Materials" and **ECSS-Q-ST-70** "Space product assurance/Materials, mechanical parts and processes" See www.ecss.nl). Extending the verification period to the duration of the presence in orbit, or 100 years if re-entry is not planned at the end of the operational mission, is recommended.

3.2.2 Handles and stabilisation system to prevent rotation and promote ADR

> ***Article 40-2: Devices for active debris removal***
> *Any space object shall be designed, produced and implemented in such a way as to facilitate, after its disposal, seizure or capture by an Active Debris Removal (ADR) servicing vehicle, as applicable.*

In the absence of international standards, the use of appendages already fitted to the vehicle is possible, provided that it can be demonstrated that the torques and forces involved are compatible with the design of the said appendages.

Similarly, for small cubesat-type satellites that cannot carry specific devices and do not have appendages that can be used for this purpose, the structure of the cubesat can be deemed sufficient to replace these devices and facilitate potential future capture.

Devices to facilitate capture may include:

- Mechanical capture interfaces, such as a handle or docking plate, to enable the satellite to be captured by a service vehicle and mechanical loads to be transferred between the two objects,
- Equipment to stabilise the satellite's attitude (detumbler type), making it easier for a service vehicle to approach,
- Relative navigation aids (corner cube reflectors, sights, etc.) to minimise the risk of collision during operations in the proximity zone.

3.3 PASSIVATING POWER RESERVES

> ***Article 40: Space environment protection***
> ***3. Passivation***
> *Any space object shall be designed, produced and implemented so that, following the disposal phase:*
>
> - *all on-board energy reserves are permanently depleted or placed in a state such that they entail no risk of generating debris;*
> - *all on-board energy production means are permanently deactivated, or all the equipment directly supplied by these energy production means are placed in a state such that they entail no risk of generating debris;*
> - *the entire radio electric transmission capacity of the platform and payload shall be permanently interrupted.*
>
> *The provisions of paragraph 3 (Passivation) of this article do not apply to controlled re-entries.*

Foreword: "Permanently" means:

- Long-term stable state (failure tolerance), adopting a solution that presents the best stability in the environment encountered (thermal, radiation) excluding collision,
- With confirmation that the process has been engaged (activation of drainage systems) or that the target thresholds or states have been reached.

Passivation of an object is an effective measure for significantly reducing the risk of an accidental explosion generating space debris after the object has reached the end of its life.

Similarly, an object impacted by debris or a micrometeoroid is less likely to result in accidental disintegration, and therefore a large quantity of debris, if it is passivated.

It is highly recommended to passivate a system or item of equipment as soon as it is no longer required for further operations.

There is currently no requirement to be able to passivate the space object a controlled re-entry is planned at the end of life. However, it is highly recommended to implement systems enabling the passivation of the object in the event that controlled re-entry is no longer feasible due to a platform anomaly.

Note: however, these systems could be disregarded for the calculation of disposal reliability since not required under Article 40.3.

A sufficient level of passivation is achieved when there is not enough residual power to cause potential spontaneous fragmentation, regardless of the long-term evolution of the state of the passivated systems (protection taking account of the potential effects of mechanical, electrical and/or chemical degradation over time and in the long term for the components of the passivated systems).

The expected levels are specified further on in this chapter.

The energy sources to be considered are those of the platform and the payload, and may include batteries, high-pressure vessels, self-destruct devices, flywheels, reaction wheels, etc.

The design of on-board energy sources must take account of the following influences:

- The environmental extremes expected during the operational lifetime and after passivation, excluding the re-entry phase,
- Mechanical degradation during the mission and following passivation,
- Chemical breakdown,
- The effect of potential satellite failure modes during the mission, and their consequences on the capability to passivate the satellite.

Prior to the disposal phase, the passivation procedures may need to be updated to take account of any failures that have occurred during the mission and affecting the satellite's passivation capability.

The effects of propulsion system passivation on the final orbit of the vehicle must be taken into consideration and described in the application file.

No operation generating space debris larger than 1 mm may be performed during the passivation process, except for the release of frozen propellant, in accordance with Article 40.1 referred to in §3.2.

3.3.1 Electrical passivation

The hazards inherent to the electrical subsystem after disposal are:

- An **increase in temperature** above 100°C, which can cause unwanted chemical reactions within the battery leading to thermal runaway. This reaction results in a sharp increase in temperature and the generation of gases inside the battery cells. The rapid nature of this phenomenon can cause the battery cell pack to explode,
- **Overcharging of the cells** making up the battery, which can lead to an increase in pressure within the cells and then to deflagration,
- An **electrical short circuit** inside the equipment leading to overheating, gas release or even explosion (chemical condensers for example).

Electrical passivation must result in:

1. **Isolating the power sources** (the solar generator) from the rest of the satellite's loads,
2. And **discharging its battery**.

3.3.1.1 ISOLATION OF POWER SOURCES

Two options for isolating power sources are proposed:

1- The passivation diagram will be based on a cut-out device, of the **Solar Array section opening relay** type, resulting in zero current from the solar panels. The total absence of current fully meets the LOS requirement, even if a residual voltage may be present at the GS sections (100V open circuit voltage for a 30V bus in the case of permanent front illumination), but in an open circuit (therefore at zero current) and with a potential referenced to the structure via resistors, avoiding floating potential.

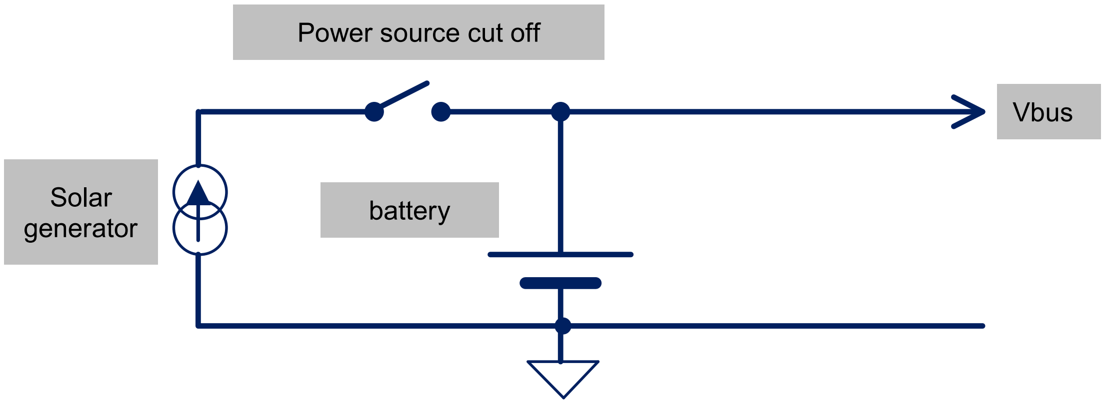


Figure 3-1: Passivation diagram with GS section opening relay

2- The passivation diagram will be based on the **short circuiting of GS sections via relays**.
A current may flow in each GS section, but as the contacts of the connectors and the short-circuiting armature have very low resistance, thermal dissipation will be insignificant and will not lead to any risk of degradation.
Blocking diodes prevent short-circuiting of the battery, which will not have yet been emptied at this stage of electrical passivation.
This solution must be covered by a design qualification.

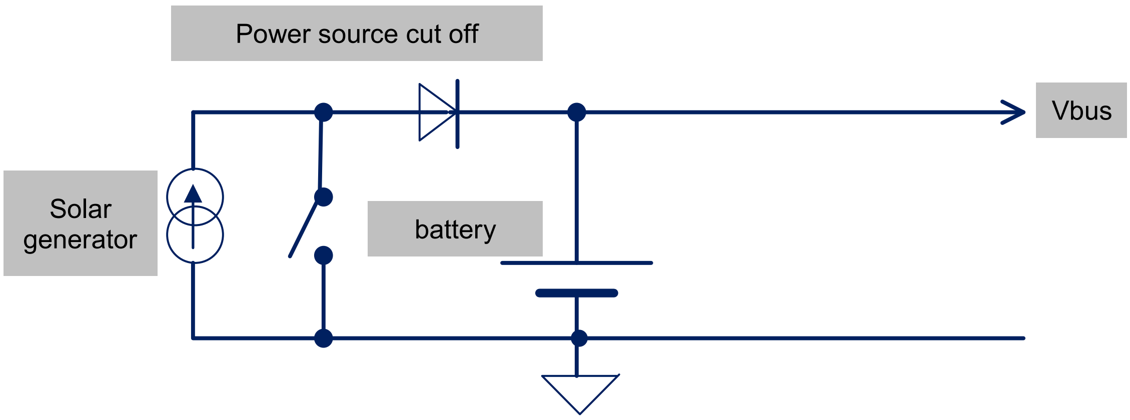


Figure 3-2: Passivation diagram with short-circuit relay for GS sections

If it is difficult or actually impossible to produce one of these two systems, i.e., in the case of an **end-of-life scenario without disconnection or short-circuiting of the GS sections**, a file must be submitted, justifying the risks in the event of aggravated damage to the battery (overheating at the interface, overcharging, thermal runaway, etc.) demonstrating, based on test campaigns, that there is no risk of spontaneous deflagration of the battery.

In the event of proven and unavoidable deflagration of the battery (based on a qualification or demonstration failure), a containment "sarcophagus" proposal must be implemented and tested. This sarcophagus must contain the deflagration and discharge the gases outside the satellite to avoid any structural breakage and debris emissions.

This is the simplest solution, which may be suitable for nanosatellites because of the extremely small size of their batteries (a few cells at most).

A 3rd alternative solution, which is not recommended due to the remaining risks, involves disconnecting the battery from the rest of the electrical sub-system, **without disconnecting the solar generator**, having emptied it insofar as possible, therefore fully eliminating the risk of battery explosion. This is because, as the solar generator is likely to continue producing power and supplying the electrical equipment that remains permanently connected to the supply bus (central computer, TC receivers, power management module), there is still a risk of electrical degradation of the powered components in this equipment, even if any generation of debris should remain contained inside the equipment's casing. This solution is not recommended because there is no long-term way of controlling the behaviour of the supply voltage, and therefore the behaviour of the equipment that will remain connected to it. ***However, for a system design for which the installation of a system for opening or short-circuiting GS section lines would be prohibitive due to the high power of the GS, a supporting file must be submitted specifying***:

- The system for cut-out and drainage to less than 1% of the battery SoC,
- The disconnection diagram for the electrical equipment,
- The remaining risk of degradation and failure propagation for uninterruptible electrical equipment, in particular the power conditioning and distribution module.

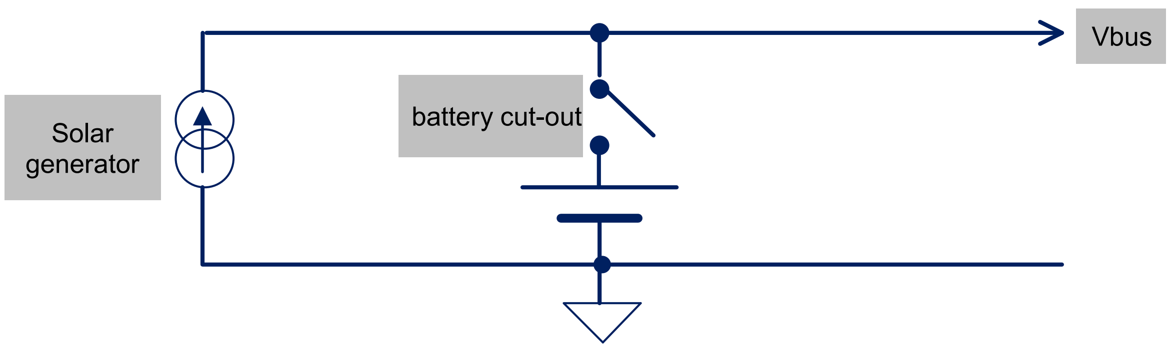


Figure 3-3: Passivation diagram with battery disconnection relay (solution not recommended)

3.3.1.2 BATTERY DISCHARGE

Once the power source cut-out device has been operated, the battery must be completely drained (i.e., with a state of charge of less than 1%) via the permanent and uninterrupted consumption of equipment on the power supply bus.

Equipment is fitted with converters that are switched off automatically if the voltage falls below a given threshold.

In an electrical system design with an 8-cell lithium battery connected in series, the maximum voltage is 33.6 V and the converter cut-out thresholds are generally defined between 18 and 21 V.

A single cell of a lithium battery with a no-load voltage of less than 2.5 V has a SoC of less than 1%, which is the limit required to be able to declare the battery's electrical passivation.

On an 8-cell battery, a SoC of less than 1% will be guaranteed when the voltage is below 8x2.5 = 20V.

So logically, with converters that cut out between 18 and 21V, the corresponding battery will be drained to less than 1%.

It is recommended that the cut-out threshold for the last active converters during electrical passivation be set to N x (2.4V +/-150mV), where N is the number of lithium cells in series in the battery. This threshold will be adapted to suit the battery technology used.

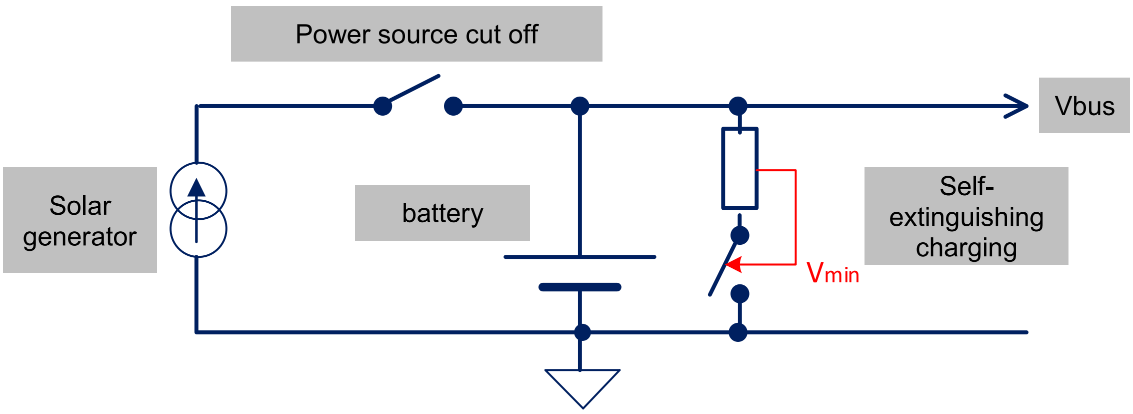


Figure 3-4: Passivation diagram with GS section opening relay and battery discharge via equipment consumption

If the last converters cut out at a voltage well above this threshold, a drain resistor will be required, the value of which will be defined without any time constraint other than the battery state of charge falling below 1% within 3 months. The resistor may be permanently connected initially (using a launch pad configuration strap, for example), as the battery depletion time constant is designed for cases of delayed launches where the battery cannot be recharged.

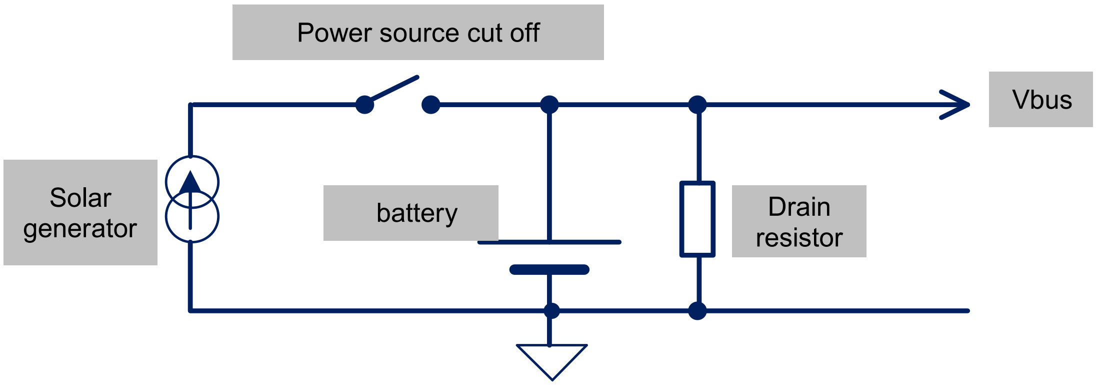


Figure 3-5: Passivation diagram with GS section opening relay and battery discharge via drain resistor

Example:

- 20Ah battery at 8V,
- 1 kilohm resistor,
- the drain current will be equal to 8mA, the resistor will dissipate 64mW throughout the satellite's lifetime and end of life,
- the full battery will be completely depleted after 20Ah/8mA = 2,500 hours (100 days).
- in standby mode on the launch pad, the maximum DoD of 10% will be reached in 240 hours (10 days).

The drain resistor can also be linked to the battery by toggling a relay to prevent the battery from being depleted if it is stored on the ground for a very long time in flight configuration.

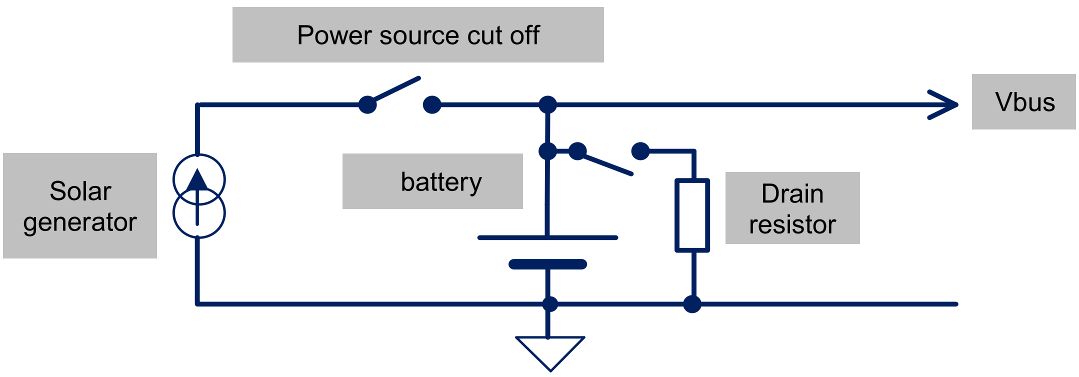


Figure 3-6: Passivation diagram with GS section opening relay and battery discharge via switchable drain resistor

Electrical passivation implementation:

Electrical passivation diagrams must be established and specified in the satellite design description.

In addition to the capability, for the entire duration of the operation, to carry out disposal operations (article 39), on-board passivation automation may be necessary to achieve the reliability objective required by the technical regulation, particularly if the passivation sequence is carried out on a low-redundancy system design.

In this case, the on-board electrical architecture must be established such that it allows satellite's on-board management to activate this electrical passivation (electrical disconnection of the solar generator, cut-out of all extinguishable equipment). This automation could, for example, be based on no TC received from the ground for several days/weeks, with the implementation of a 'watch dog'.

It should also be possible to engage/disengage this device if reliability figures are high at start of life and if essential redundancies or resources are not degraded or lost.

Typical sequence for electrical passivation implementation:

1. Switching off equipment not required for end-of-life operations. Note that some equipment may, however, be activated/preset (e.g. heaters) to accelerate the subsequent discharge of the battery.
2. Opening or short-circuiting sections of the solar generator to isolate it from the power bus and prevent any battery recharging.
3. Connecting the drain resistor (if not already connected to the ground) to accelerate battery discharging, if the converters that are still active only switch off at a level greater than 1% of the residual SoC.
4. Monitoring the battery discharge phase until automatic cut-out of the transmitter and/or computer (upon activation of the UVD threshold of their converters), and the resulting permanent loss of visibility.

3.3.2 Passivation of propulsion systems

This paragraph applies to fluidic energy (propellants and gases) stored in tanks and circuits.

After the use of propellants and/or gases needed to reach the End-of-Life orbit, the Technical Regulation requires to further depleted/depressurised them to achieve almost total drainage or isolation as defined below.

One can identify the following situations:

- Liquid propellants for chemical propulsion*:
  - Propellants in direct contact with their inert pressurising gas (diaphragm-free tank),
  - Propellants separated from their inert pressurising gas (diaphragm tank),
- Gaseous, two-phase (gas/liquid) and supercritical fluids, for pressurisation, cold gas and electric propulsion,
- Propellants stored in solid form,

* the case of chemical propulsion with two-phase propellants is covered by the 2nd bullet point.

The risk of explosion for a tank pierced by debris may increase with residual internal pressure, but research on quantifying this is still ongoing. It is therefore necessary to minimise the residual internal pressure insofar as possible, as well as the amount of propellant remaining in the system (chemical energy and potential mechanical energy through vaporisation if the temperature rises).

The power reserve depletion strategy must be defined. To this end, the operator must:

- Provide a detailed description of the design of the propulsion system and the passivation system if present, with the design elements required to understand the passivation strategy, such as flow-restricting items (capillary tube, sonic flow orifice, sintered filter, etc.), circuit emptying valves (pyrovalve, microperforator, etc.), if necessary, zero-force draining equipment (gas opposite drain), etc.
- Provide the detailed sequence resulting in propellant drainage and gas depressurisation.

The ability to achieve the target thresholds must be proven (for example by means of pressure loss tests on the nozzles used, sufficient opening time, delta qualification of the equipment used for passivation, etc.).

3.3.2.1 DEPRESSURISATION AND DRAINAGE OF INEXHAUSTIBLE LIQUID CHEMICAL PROPELLANTS

Propellant tanks may be emptied using a passivation system qualified for this use, **except** in the following cases:

- Biliquid system, tank without diaphragm and passivation of the two propellants inside the platform or in a way that enables the potential mixing of the two propellants in a restricted space.
- Propellants composed of explosive salts diluted in a solvent (e.g. LMP103-S or AF-M315E)

Chemical propellants in direct contact with their pressurising gas (i.e., diaphragm-free tank)

The chemical propellants must be depleted and the pressure reduced insofar as possible. This can be achieved, for example, through the thrusters discharging the propellants, a two-phase mixture of gas-liquid propellant and then gas (propellants in gaseous form and pressurising gas).

The amount of propellant remaining must be reduced insofar as possible. The pressures to be reached in the tank depend on the behaviour of the fluids. They must be less than:

- NTO: 1 bar absolute at 10°C
- MMH: 0.15 bar absolute at 10°C
- Hydrazine: 0.5 bar absolute at 20°C

The worst-case end-of-life pressure, i.e., where the inexhaustible propellant is potentially broken down into gas and the temperature is 200°C, must also be well below the burst pressure of the sub-system (tanks, pipework, valves, etc.). This can be demonstrated via a calculation using a chemical equilibrium tool such as CEA (Chemical Equilibrium Applications, developed by NASA and which can be made available) or via the following formula:

$$P_{res}^{final}[bar] = \frac{8.314 \cdot (273.15 + 200)}{100} \times \frac{R_{brkdown} \times {m_{prop}^{final}}/{M_{prop}^{mol}} + {m_{press}^{final}}/{M_{press}^{mol}}}{V_{tank}} < P_{prop}^{burst} \quad (1)$$

Where:

m_{prop}^{final} : the mass of inexhaustible propellant [g]

M_{prop}^{mol} : the molar mass of the propellant [g/mol]

m_{press}^{final} : the final mass of pressurising gas [g]

M_{press}^{mol} : the molar mass of the pressurising gas [g/mol]

V_{tank} : the volume of the tank [L]

$R_{brkdown}$: the molar breakdown ratio @200°C, i.e., the number of moles of gas after breakdown of one mole of propellant. Where:

- For hydrazine: breakdown ratio = 2.00
- For MMH: breakdown ratio = 4.00
- For NTO: breakdown ratio = 3.00

P_{prop}^{burst} : the burst pressure of the entire propulsion subsystem (tank, piping, valves, etc.).

For propellants composed of explosive salts diluted in a solvent (e.g. LMP103-S or AF-M315E), the pressure and the quantity of remaining propellant must be lowered insofar as possible by using the thrusters, but without exposure to space vacuum. In addition, the worst-case end-of-life pressure, i.e., where the inexhaustible propellant is potentially broken down into gas and the temperature is 200°C, must be well below the burst pressure of the sub-system (tanks, pipework, valves, etc.). This can be demonstrated via calculation using a chemical equilibrium tool such as CEA (Chemical Equilibrium Applications, developed by NASA, which can be made available), or via the previous formula (1), adjusting the breakdown ratio R_{decomp} (equal to 5 for LMP103-S).

Chemical propellants separated from their pressurising gas (i.e., diaphragm tank)

The chemical propellant under the diaphragm must be depleted insofar as possible, so that only inexhaustible propellant remains in the tank and pipework. This can be done, for example, through the thrusters discharging the propellant.

On the other hand, the worst-case end-of-life pressure, i.e., where the inexhaustible propellant is potentially broken down into gas and the temperature is 200°C, must be well below the burst pressure of the sub-system (tank, pipework, valves, etc.). This can be demonstrated via a calculation using a chemical equilibrium tool such as CEA or by using the previous formula (1), adjusting the breakdown ratio R_{decomp} (See values above for Hydrazine, Mon, MMH and LMP103-S).

If this condition is not reached at the end of system drainage, and if it is not propellant with explosive solid residue at 0 bar, a depressurisation system must be installed on the pressurising gas side.

3.3.2.2 DRAINAGE OF GASEOUS, TWO-PHASE AND SUPERCRITICAL INEXHAUSTIBLE PROPELLANTS

The fluids must be depleted insofar as possible, this can be achieved through the thrusters where possible or by a dedicated system qualified for this. The tank pressure to be achieved at 10°C must be less than 0.5 bar absolute.

3.3.2.3 PROPELLANTS STORED IN SOLID FORM

These include, for example, the propellants used for FEEP-type thrusters, such as indium or caesium, and other materials such as iodine, which is being considered for electric or cold gas propulsion. The operator must demonstrate that an increase in the temperature above 200°C of the residual mass must not compromise the structural integrity of the propulsion system. If the propellant vaporises or breaks down into gaseous components, the pressure must remain below the system's burst pressure.

3.3.2.4 PREVENTING "SIDE EFFECTS"

The purpose of this paragraph is to define a non-exhaustive list of “side effects” that could be generated by the introduction of a specific passivation system and which the operator must demonstrate have been perfectly controlled.

The passivation system and its implementation must not:

- Pose a risk of generating debris,
- Prevent any disposal operation from being carried out.

In particular, with the beginning-of-life pressures and if depressurisation is carried out inside the platform, it must not:

- Affect the mechanical strength of the platform, its equipment or its protection (e.g. MLI),
- Create dielectric breakdown in the vicinity of equipment with a substantial electric field.

With the beginning-of-life pressures and if depressurisation is carried out outside the platform, it must not:

- Generate centrifugal forces that could affect the mechanical strength of the platform and specifically its appendages (solar panels, etc.),
- Generate a Delta-v that significantly changes the orbit in an uncontrolled manner.

Demonstrated system reliability is taken into account when assessing the probability of being able to successfully carry out disposal manoeuvres (see paragraph 3.10).

The fluid passivation strategy must consider the fluids present in the pipes and be in line with electrical passivation.

3.4 SELECTING THE OPERATIONAL ORBIT

Article 41-13: Limitation of the orbit of non-manoeuvring space objects *Systems not equipped with propulsion capable of modifying the orbit shall be designed, produced and implemented for orbits with an apogee of less than 600 km.*

The space environment is such that the orbits most populated by space debris are between 600 and 1,000 km in altitude, which explains the identified need for systems that are able to manage collision risks above 600 km in altitude.

The term " propulsion capable of modifying the orbit " refers to the object's ability to carry out collision avoidance manoeuvres effectively and in a sufficiently short time (typically less than 24 hours), and possibly manoeuvres for transfer and station keeping, as well as for disposal.

The performance of the on-board propulsion system must be proven, demonstrating that it is capable of handling the cases mentioned above.

A drag-sail that cannot be used to manage a collision risk cannot be considered a propulsion device. As such, this requirement is not in redundancy with the requirements on re-entry duration.

3.5 ESTIMATING THE PROBABILITY OF AN IN-ORBIT COLLISION

Article 41-3: Probability of collision with a space object
The probability of occurrence – calculated before the launch – for the entire duration of the space operation, of an accidental collision with a space object larger than 1 cm shall be evaluated and minimized. In addition, this estimate shall include the return to Earth phase for a space object operating in region A.

To meet this requirement, a number of aspects need to be addressed. Firstly, the space population and its evolution must be modelled, and then the risks of collision between the satellite and other objects must be estimated during the various phases of the space operation (and the return-to-Earth phase for objects operating in Zone A), taking account of any avoidance capabilities.

The strategy recommended by the CNES Space Safety Office is to use the MASTER software (see paragraph 10.4) proposed by ESA to estimate the flux of objects impacting the target orbit during the different phases, and to use these fluxes to estimate a probability of collision for the whole mission.

3.5.1 Methodology

This section presents the recommended methodology for estimating the probability of collision over the entire orbital lifetime of a space object (excluding the phase following disposal operations for objects not operating in Zone A).

Section §3.5.1.1 first describes how the probability of collision is calculated for a given orbital phase.

Section §3.5.1.3 then describes how avoidance manoeuvres and their effect on the probability of collision are modelled, followed by section §3.5.1.4 showing how the probabilities of collision obtained for the different orbital phases are added together to obtain the overall collision probability.

Section §3.5.1.5 then describes how the detection capabilities of space surveillance systems are modelled to determine whether or not an object in the population is detectable.

Finally, section §3.5.1.6 deals with a few specific features relating to the phase beginning with disposal operations (and ending with atmospheric re-entry for objects operating in zone A).

3.5.1.1 SIMULATION PARAMETERS

3.5.1.1.1 Radius of the space object

The radius r_t assigned to the object is one of the parameters that influences the most the probability of collision obtained. To be completely conservative, one need to use the radius of the smallest sphere completely encompassing the object (including its appendages, solar panels or antennae) from its centre of mass. In addition to the all-encompassing radius, it may also be useful to calculate probabilities of collision for smaller radii. This makes it possible to estimate the sensitivity of the results to this parameter.

If the radius associated with the space object needs to be reduced, the choice of radius must be justified via suitable studies and submitted to the CNES Space Safety Office for approval. Such a reduction could, for example, be justified by demonstrating, through simulations, that the surface subject to the vast majority of the debris and meteorite flux is known, and that we can therefore use the radius of a circle with an area equivalent to the area of the exposed surface.

3.5.1.1.2 **Orbital parameters**

Orbital parameters must be specified for each mission phase. These are usually given in the form of Keplerian parameters, but this is not always the case. It is advisable to pay special attention to the reference frame and the type of items used. For example, MASTER software expects mean elements in the sense of Liu and Alford (Liu & Alford, 1980), expressed in the Mean of System 1950 reference frame.

3.5.1.1.3 **The duration of the phases considered**

The duration of the phases considered is a very important parameter, which has a major impact on the results obtained. The orbital population taken into account depends directly on the time interval covered by the analysed phase, and the probability of collision depends more or less linearly on its duration.

3.5.1.1.4 **Risk reduction rate**

The choice of coefficient α generally depends on the mission phase under consideration, the type of orbit and the collision avoidance strategy. It must be defined and justified for each phase: this rate must be representative of the collision avoidance capabilities, taking account of the thresholds for engaging manoeuvres and their effectiveness.

An object that is non-manoeuvrable during one of the phases (during the end-of-life phase, for example) will have its rate set to zero for that phase. For a typical collision avoidance system (high availability, responsiveness < 24hr, avoidance threshold $\simeq 5 \times 10^{-4}$, in the LEO regime) the approximate mission risk reduction rate is 0.9.

3.5.1.1.5 **Properties of the space object**

These parameters include in particular the mass of the object, the surface subject to atmospheric friction, the surface subject to solar radiation pressure, the drag coefficient and the reflectivity coefficient. They are mainly used during propagation of the object's orbit, when requested.

3.5.1.2 PROBABILITY OF COLLISION FOR A GIVEN PHASE

The probability of collision for a given phase is calculated statistically, using a Poisson distribution. If λ_c is the mean collision rate over a given time interval, the probability of exactly k collisions occurring is:

$$P_{i=k} = \frac{\lambda_c^k}{k!}\, e^{-\lambda_c}$$

The probability of there being no impact is therefore:

$$P_{i=0} = e^{-\lambda_c}$$

and the probability of there being at least one collision is finally written as:

$$P_c = P_{i \geq 1} = 1 - e^{-\lambda_c}$$

If we further assume that mean collision rate λ_c is very small, the probability of collision P_c can further be approximated by:

$$P_c \approx \lambda_c$$

The collision rate λ_c is calculated from mean fluxes of objects impacting the target orbit, which are expressed as the number of objects per square metre per year. How these fluxes are obtained will be discussed later in the document. It is assumed here that there is a flux of Φ_p for each object in the orbital population. The collision rate λ_c over a period Δt is therefore calculated as follows:

$$\lambda_c = \Sigma_\text{p} \; \Phi_\text{p} \, \pi\left(r_t + r_p\right)^2 \Delta t$$

In this equation, objects are modelled by spheres, where r_t is the radius assigned to the space object (constant) and r_p is radius of the impacting object. When a period of one year is considered, the previous equation gives the Annual Collision Probability (ACP), often used as a high-level indicator of the risk incurred by the space object:

$$ACP = 1 - \exp(-\Sigma_p \Phi_p \pi\left(r_t + r_p\right)^2)$$

$$\approx \Sigma_p \Phi_p \pi \left(r_t + r_p\right)^2$$

3.5.1.3 CONSIDERING AVOIDANCE MANOEUVRES

Avoidance manoeuvres and their effect on the cumulative probability of collision can be taken into consideration in different ways. The approach used by the CNES Space Safety Office is to consider that the strategy implemented has been defined in such a way as to reduce the risks of collision by a given percentage for detectable objects. Thus, if we call $\mathbb{W}$ the set of objects in the population, $\mathbb{D}$ the set of detectable objects and $\mathbb{U} = \mathbb{W} \backslash \mathbb{D}$ all non-detectable objects, we can divide the collision rate λ_c into two parts:

$$\lambda_c = \lambda_u + \lambda_d$$

Where:

$$\lambda_u = \Sigma_{\text{p} \in \text{U}} \; \Phi_\text{p} \pi\left(\text{r}_\text{t} + \text{r}_\text{p}\right)^2 \Delta\text{t}$$

$$\lambda_d = \Sigma_{p \in \mathbb{D}} \Phi_p \pi(r_t + r_p)^2 \Delta t$$

And with the associated collision probabilities:

$$P_u = 1 - e^{-\lambda_u}$$

$$P_d = 1 - e^{-\lambda_d}$$

If $\alpha \in [0, 1]$ is the collision risk reduction rate (see 3.5.1.1.4) targeted by the strategy used, the total probability of collision becomes:

$$\begin{aligned} P_c &= 1 - (1 - P_u) * (1 - (1 - \alpha)\, P_d) \\ &= 1 - \alpha e^{-\lambda_u} - (1 - \alpha) e^{-(\lambda_u + \lambda_d)} \\ &\approx \lambda_u + (1 - \alpha)\, \lambda_d \end{aligned}$$

3.5.1.4 PROBABILITY OF COLLISION FOR ALL PHASES

The methodology above can be used to estimate the probability of collision for a given phase. If we assume that we eventually have N different phases and that phase i is associated with a probability of collision P_i for its entire duration Δt_i, the probability of collision P_c over all the phases to be considered is calculated as follows:

$$\begin{aligned} P_c &= 1 - \Pi_{i=1}^{N} (1 - P_i) = 1 - \Pi_{i=1}^{N} e^{-\lambda_{c,i}} \\ &\approx 1 - \Pi_{i=1}^{N} (1 - \lambda_{c,i}) \end{aligned}$$

And if we take account of the reduction in probability resulting from avoidance manoeuvres, the probability of collision P_c is finally written:

$$\begin{aligned} P_c &= 1 - \Pi_{i=1}^{N} \left(\alpha_i\, e^{-\lambda_{u,i}} + (1 - \alpha_i)\, e^{-(\lambda_{u,i} + \lambda_{d,i})}\right) \\ &= 1 - \Pi_{i=1}^{N} \left(1 - \lambda_{u,i} - (1 - \alpha_i)\, \lambda_{d,i}\right) \end{aligned}$$

3.5.1.5 MODELLING DETECTION CAPABILITIES

In order to take account of the effect of avoidance manoeuvres, it is therefore necessary to be able to determine whether or not debris can be deemed detectable.

As a first approach, the following graph can be used to determine the diameter of the detectable debris based on the orbit in question.

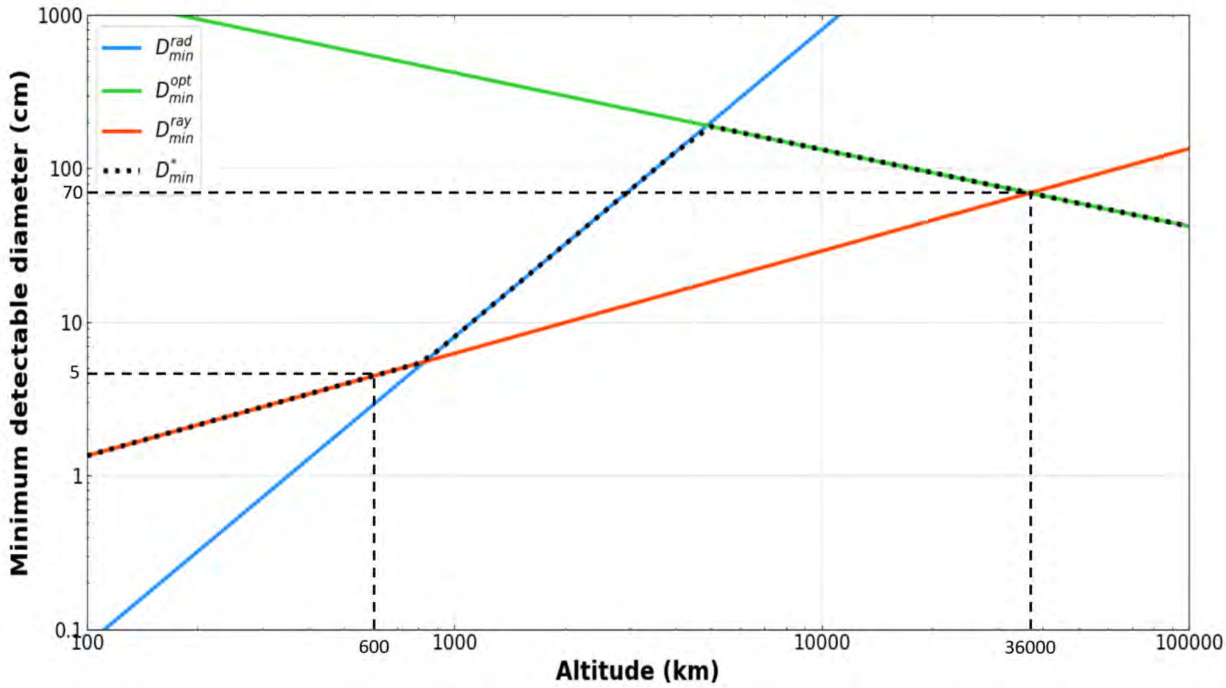


Figure 3-7: Minimum detectable diameter based on altitude (dotted curve)

Figure 3-7 shows that in the current state of radar and optical capabilities, detectable debris is that which is:

- In LEO (case at 600 km), greater than about 5 cm,
- In GEO (around 36,000 km), greater than around 70 cm.

For a more comprehensive approach, these values can be scaled, considering a size of 10 cm in LEO (<2,000 km) and up to 1 m in GEO.

For a more precise analysis, the approach recommended here is to use the same equation to estimate the minimum size that can be detected by radar (LEO) and optical (GEO) means based on the altitude, i.e.:

$$D_{min}(h) = D_{ref}\left(\frac{h}{h_{ref}}\right)^{exp}$$

Where h_{ref} is the reference altitude, D_{ref} is the reference diameter (the smallest diameter detectable at the reference altitude) and exp is a modelling parameter selected based on the means of detection in question.

The recommended parameters are given in Table 2.

	$Dref$ (m)	$href$ [m]	exp
Radar	0.32	2000.0	2.0
Optical	0.70	36000.0	-0.5

Table 2: Parameters of the equation modelling the detection capabilities of radar/optical means

To avoid overestimating detection capabilities at low altitude, the radar branch of the equation is also combined with another equation modelling the Rayleigh scattering phenomenon. Assuming that radars operate at a wavelength of around 30 cm and that the size of catalogued objects is of a smaller order of magnitude (a few centimetres), the radar equivalent area σ of a sphere in the Rayleigh region can be expressed based on its diameter D_R and wavelength λ:

$$\sigma = \frac{9\,\pi^5 D_R^6}{4\,\lambda^4}$$

This implies that:

$$D_R^6 = \sigma \frac{4\lambda^4}{9\,\pi^5}$$

The radar equivalent area σ can also be calculated based on the altitude:

$$\sigma = \frac{\pi}{4} D_{min}^2(h) = \frac{\pi}{4} D_{ref}^2 \left(\frac{h}{h_{ref}}\right)^4$$

which therefore makes it possible to calculate the distance D_R at any altitude.

Finally, if $D_{min}^{rad}(h)$, $D_{min}^{opt}(h)$ are the diameters calculated by the radar and optical branch of the equation, and $D_{min}^{ray}(h)$ is that calculated by the equation that defines D_R, the minimum diameter that an object must have to be considered detectable at altitude h is:

$$D_{min}^{*}(h) = \min(\max(D_{min}^{rad}(h), D_{min}^{ray}(h)), D_{min}^{opt}(\mathrm{h}))$$

The smallest detectable diameter can therefore be calculated at any altitude h. To determine whether a piece of debris is detectable or not, it is recommended to use the altitude of its perigee and apogee. If the orbit of the object crosses an altitude range where it can theoretically be detected, then it will be considered as such. Meteorites, on the other hand, must be systematically considered as untracked if they are taken into account.

3.5.1.6 RETURN-TO-EARTH PHASE

The orbit of the space object may change significantly during the return-to-Earth phase, such that special attention must be paid. Firstly, propagating the trajectory of the space object is recommended, by selecting a model of the orbital dynamics suitable for the orbital regime being studied (Earth potential, atmospheric friction, solar radiation pressure, etc.) and taking account of any de-orbiting or re-orbiting manoeuvres.

If necessary, this phase can be divided into N separate sub-phases. For example, it is possible to generate an ephemeris of the object's trajectory and sample it regularly enough to capture the evolution of the orbit. The time step to be used therefore depends on the object's trajectory and the time remaining in orbit following disposal operations. If it lasts 25 years, for example, selecting one orbit every year may be appropriate. If it lasts 6 months, however, it would be preferable to select an orbit every month. In general, it is advisable to check the sensitivity of the results obtained in relation to the time step chosen. Note that a time step of less than one month is not recommended, as the statistical validity of the calculated fluxes and the associated probability of collision would not be guaranteed.

Finally, it is important to remember that a space object that is initially manoeuvrable will no longer be so once it has been passivated. Where this is the case, a risk reduction rate α equal to zero must be used when calculating the probability of collision.

3.5.2 Recommended tools for estimating the probability of collision

3.5.2.1 FLUX CALCULATION

As mentioned above, calculating the probability of collision is based on the estimated flux of objects impacting the target orbit on average. To calculate them, using the most recent version of MASTER with the most recent population files is recommended. The use of other software is acceptable if the database of space objects is more recent and representative of the orbital population than the MASTER one. The version of the tool available in early 2024 (8.0.3) is based on pre-generated population files, which currently cover the period from 1957 to 2016 for the historical population, and from 2017 to 2036 for prediction.

The software must be started in "target orbit" mode, considering objects of 1 cm or more ("expert settings" tab, after activating the expert settings in the project options). The generation of CPE (Cell Passage Events) files must be activated ("data dump" tab), as these files will then be processed to estimate the probability of collision. It is advisable to run a separate simulation for each phase, and divide the phases into several sub-phases if significant orbit changes take place.

***Note**: The MASTER software allows several phases to be entered, each phase associating a target orbit with a time interval. Although it is theoretically possible to process several phases in a single simulation, in practice it is not advisable to do so. Firstly, the properties of the studied object may change between different phases. An object that is initially manoeuvrable, for example, will no longer be so after its end-of-life, so it is necessary to be able to process the fluxes calculated for each phase separately. Above all, it would appear that MASTER version 8.0.3 does not work correctly when several phases are entered and CPE file generation is requested. The calculation stops after processing the 1st phase and simply ignores the others. This anomaly has been* *reported to the software maintenance team and will be rectified in a future version.*

The sources to be selected for the debris are the condensed sources, which contain all the individual sources proposed by MASTER. Activating the flux calculation for meteorites using the Grün model based on a Taylor distribution for velocities is also recommended. Although meteorites are unlikely to have much influence on the results obtained, given the size of the objects in question (> 1 cm), it is nevertheless preferable not to ignore them by default.

***Note**: Please note that the information in the CPE files for meteorites is not defined in the same reference frame as for debris. The orbit of the impacting object and the point of impact are expressed in a geocentric ecliptic reference frame, and not in the inertial reference frame. However, only the flux value is used for meteorites, as they are systematically considered not detectable. The estimated probability of collision should therefore not be affected.*

Note that MASTER allows you to request the propagation of the orbit associated with each phase. When this option is enabled, the entered orbit will be propagated using the semianalytic propagator FOCUS (*Fast Orbit Calculation Utility Software*) (Gonzales & Kinkrad, 1989). Otherwise, the orbit will be deemed static, with the exception of the line of nodes and the line of apsides, which will be propagated using a simple analytical equation. Whether or not this option is enabled depends on the object studied and the phase in question. If the object is expected to perform station-keeping manoeuvres periodically, then a static orbit is best suited for the operational phases. If this is not the case, propagation of the orbit will probably enable more realistic results to be obtained. For the return-to-Earth phase, it is recommended to generate ephemeris and to sample them at sufficiently regular intervals to capture the change of orbit. Orbit propagation is therefore of limited interest, but can still be enabled.

***Note**: If propagation is enabled for one of the orbits, it is necessary to enter various properties for the space object, namely its mass, the surface subject to atmospheric friction, the surface subject to solar radiation pressure, the drag coefficient and the reflection coefficient.*

Finally, it is important to reiterate that the population files available only cover a relatively limited period (up to 2036 at the time of writing). MASTER allows to enter mission phases extending beyond this date, but it generates the following warning: "*The specified time interval is not covered by the population files. [...] This may lead to wrong results*". The software does not process non-covered periods and the associated fluxes are set to zero by default. Meteorites always seem to be taken into account, as their population files are not in principle linked to a fixed time period. The workaround to be implemented by the operator is to use the 2036 population for any subsequent year.

3.5.2.2 CALCULATION OF ORBITAL CHANGE DURING THE RESIDUAL PHASE AFTER DISPOSAL

The specifics of the return-to-Earth phase were discussed in section 3.5.1.6, especially the importance of paying particular attention when modelling the trajectory of the space object. In practice, several ways of operating may be recommended. Use of the STELA tool (see 10.1 for more information) provided by CNES is recommended to propagate an initial state vector throughout the residual phase in orbit, or until re-entry of the space object. In particular, this tool is used to check mission compliance with FSOA Technical regulation requirements regarding clearance of protected areas (LEO and GEO - see §3.8)

If the MASTER tool is used to calculate fluxes, it is also possible to simply activate the "propagation" option for the orbit associated with the end-of-life phase. As mentioned above, this option enables propagation of the orbit entered using the FOCUS semi-analytical propagator. This prevents the need to sample an ephemeris, and therefore to run and post-process several MASTER simulations. However, it is important to bear in mind that these two propagators are not equivalent and that the results may therefore vary depending on the method chosen. As the two propagators have been broadly validated, the trajectories generated should, in principle, remain relatively consistent. To be sure, however, it may be useful to compare the predicted re-entry dates (where possible).

3.6 REDUCING THE RISK OF COLLISIONS

In the rest of this guide, a catalogued object is understood as a space object tracked by ground facilities and for which ephemeris can be provided by space surveillance systems (for example EUSST or US radar facilities).

Note: *At the time of writing this guide, it is accepted that the vast majority of objects of around 10 cm (in LEO) or larger are catalogued (see Figure 3-7). In the future, with improved monitoring facilities, this order of magnitude could decrease.*

To reduce the risk of collision, the operator can act by:

- Favouring manoeuvrable objects, where the manoeuvring capability benefits from a high level of availability and responsiveness,
- Selecting a low probability of collision (PoC) threshold,
- In the event of a collision alert, estimating the orientation of the operated space object to deduce the hard body radius and orientate it to minimise the transverse surface,
- Selecting an operational orbit that is not crowded, and limiting the time during which the object will have to cross densely populated orbits,
- Selecting a type of atmospheric re-entry for objects operating in Zone A that minimises re-entry time,
- Minimising the size of the object, including appendages and antennae,
- Minimising the incident flux of secondary objects via careful attitude management during the mission,
- To carry out avoidance manoeuvres, selecting systems with sufficiently high overall reliability (at least > 0.9) over the cumulative time spent in orbit (to calculate the reliability of a system, refer to section §3.10).

3.6.1 Good practices regarding collision avoidance

The good practices for meeting collision avoidance requirements are set out below. They are largely based on operational experience acquired through CAESAR service and EUSST framework.

The operator must manage collision risks by applying a **threshold for the probability of collision** (PoC) beyond which it must perform avoidance action.

A risk is considered to be managed when the new calculated risk is reduced to T/10 where T is the operator's PoC threshold.

Note: *The value of the PoC threshold is defined by the operator in its internal processes and in conjunction with one or more collision avoidance services. CNES's current collision avoidance practice for the operated fleet, in conjunction with the CAESAR service and more generally the collision avoidance service developed in the context of the EUSST, has resulted in the definition of a PoC threshold equal to* 5×10^{-4}.

The collision risk management procedure proposed by the operator must satisfy a minimum level. The collision avoidance service the operator signs up to must therefore have at least the following capacities:

- Analysis of all available CDMs (Collision Data Messages) and in particular those calculated and supplied free of charge by the CSpOC, which are deemed to be the global baseline.
- Systematic daily supply of ephemeris (with covariance) to Space-Track including manoeuvre plans.
- Consideration of external measurements (radars and telescopes, etc.) when available to improve knowledge of the position of the secondary object: calculating orbit restitution and updating the CDMs in question.
- Analysis-validation and creation, if necessary, of primary object covariance matrices when those of the operator's flight dynamics centre are unrealistic or non-existent.
- Available 24/7: for manoeuvrable satellites, the operator must be responsive (i.e., available) in less than 2 hours (telephone contact and not time to carry out a collision avoidance manoeuvre) to hazardous close-approach information from the CDM provider.
- Consideration of uncertainty in object covariance matrices when calculating the PoC.
- Feedback to the operator's control centre: the detection service must be certain that the operator's control centre has actually acknowledged the alert and is managing it; A reliable feedback process between the collision avoidance service (generating the alert) and the control centre must be established by the operator.
- Calculation of optimal manoeuvres to reduce the risk, when those of the operator's flight dynamics centre are unrealistic or non-existent.
- Multiple collision management: case of several risks of collision with different secondary objects over a short period of time such that they cannot be processed independently (the issue being finding a manoeuvre that makes it possible to manage the risks within a reasonable time frame).
- Detection of close approaches with manoeuvrable secondary objects: the threshold criterion alone is not sufficient in this case.
- Ability to coordinate with any control centre in the world.
- Once the action has been defined, check that it does not generate another risk.
- Ability to provide support to the control centre, without requiring a permanent internet connection: to avoid issues linked to lost internet access during the critical risk analysis phase.

Note:

The aim of collision avoidance is to avoid hazardous collisions (Hazard = Probability x Consequence) Currently, we do not consider the "Consequence" (this term is always equal to 1), but with the improvement of detection means one will have to manage many close approaches with small secondary objects ("small" in terms of kinetic energy). This phenomenon risks worsening risk management with large secondary objects. The orbit of potential debris following a collision should eventually also be considered (e.g. in the vicinity of the ISS, in the LEO or HEO regime, etc.) in the Consequence part.

3.6.2 Technical Regulation requirements associated with collision avoidance

Article 39-1: Identification of space objects
The space systems shall be designed, produced and implemented and their mission defined so that all space objects are unambiguously identifiable by the space surveillance systems as early as possible and within three days after injection.

This article deals mainly, but not exclusively, with "small objects" injected simultaneously and belonging to different operators. Unambiguous identification by ground systems can enable rapid contact to be made with the concerned operator and confirm or deny a risk of collision with a third-party satellite.

Identification requirements can be met by separating the payloads sufficiently upon injection so that they can be seen by space surveillance networks within around 3 days.

The operator will nevertheless be able to guarantee, with the help of the launch operator or the operator of a "dispenser" (for a smart dispenser type third-party service), that there is no risk of the satellites colliding with each other during the period in which they are unidentified or (for manoeuvrable satellites) unable to perform a collision avoidance manoeuvre.

1. **Systems to improve tracking using ground facilities (radar, telescopes and lasers).**

   Objects can improve their visibility to radar or optical means by carrying reflectors or other devices (radar/optical reflectors or transponders). For satellites in a megaconstellation, optical systems must not contravene the apparent magnitude requirement of Article 48-10.

2. **Systems to enable objects identification**

   Note that the requirement does not require on-board systems to be carried or the use of an identification system, although this is recommended.

Article 41-2: Availability of collision avoidance manoeuvres
Space systems of manoeuvring objects shall be designed and implemented such that they are available for performance of a collision avoidance manoeuvre within a maximum of 5 days after injection, or, in the case of a multiple launch of several satellites by a same operator, as soon as possible after injection, with a strategy minimizing the period of unavailability of the collision avoidance capacity.

For multiple injections (constellations), a typical period of one week is acceptable. In addition, still in the context of these multiple injections, the operator can provide guarantees through the injection strategy chosen (risk of satellites colliding with each other) and make a statistical estimate of the risk of collision with objects > 10 cm when the collision avoidance system of the injected satellites is not active.

The operator is not required to implement a manoeuvre within this time frame, but at the very least to complete the commissioning of the equipment required to carry out this type of manoeuvre and to ensure that the ground facilities (including interfaces with space surveillance systems) are able to withstand such operations.

This 5-day period is also applicable, and achievable, by cubesats launched on their own, by prioritising the tasks to be carried out post-launch.

For a multiple launch with several injected satellites from the same operator, it will be necessary to show that the operations performed at the beginning of life are prioritised towards the earliest possible availability of the manoeuvring capacity, rather than towards switching the payload on.

Article 41: Prevention of the risks of collision with manned objects
The space systems shall be designed, produced and implemented and their mission defined so that, during the space operation and for three days following the end of the operation, the risks of collision with manned objects for which the orbital parameters are accurately known and available are limited.

To meet this requirement, the operator may:

- Demonstrate that the apogee of the worst-case (highest) injection orbit is located at a lower altitude than that of manned stations (ISS, CSS, etc.).
- Demonstrate that the perigee of the worst-case (lowest) injection orbit is located at an altitude above that of the manned stations (ISS, CSS, etc.) and that the object will not intersect the orbit of these stations during its operational phase, including during its disposal (for example, for a non-manoeuvrable system, by propagating the worst-case injection orbit and demonstrating that the final orbit is located well above that of these stations).
- Emphasise that it has precise knowledge of the orbit of the space object and share this data openly and transparently so that any risks with these stations can be dealt with, or is signed up to a space surveillance service.

Article 41-4: Prevention of collisions at separation from a launcher or dispenser
At separation between the launcher or dispenser and the space object it injects:

1. The operator controlling the space object injected shall ensure that the launcher or dispenser operator can guarantee:

- *that each object it injects is on a trajectory leading to no collision with either the launcher or the dispenser, nor with the other injected objects, for a minimum duration of 5 days following injection, or until the space object is capable of performing collision avoidance manoeuvres;*
- *that each of the injected objects follows a trajectory that does not lead to a collision with manned objects for a minimum duration of 3 days following injection, or until the space object is capable of performing collision avoidance manoeuvres;*

2. The operator controlling the dispenser which injects one or more space objects shall guarantee:

- *that each of these objects is on a trajectory leading to no collision with either itself or with the other injected objects, for a minimum duration of 5 days following injection, or until the space object is capable of performing collision avoidance manoeuvres;*
- *that each of the injected objects follows a trajectory that does not lead to a collision with manned objects for a minimum duration of 3 days following injection, or until the space object is capable of performing collision avoidance manoeuvres.*

Because of launcher dispersions, introducing a requirement of non-collision with catalogued objects (or extending the 3-day period for risks of collision with manned stations) would disallow too many launch opportunities.

The aim here is to cover the period of collision avoidance unavailability solely for risks between injected objects and with the launcher/dispenser.

Bullet 1 of this article suggests that the satellite operator include this requirement in its interface document with the operator of the selected dispenser.

Bullet 2 is aimed at new operators responsible for 'smart dispenser' type orbital systems which perform the 'last kms' and inject their 'clients' (satellites) after they themselves have been separated from the launcher. These new operators are, of course, required to comply with the whole Technical Regulation governing orbital systems.

Note: *A French launch operator or a launch operator operating from within French national territory, and therefore subject to the FSOA, is already required by article 17-9 of the Technical Regulation to carry out this study. Other foreign launch operators have already carried out this analysis at the request of their customers.*

Article 41-1: Collision avoidance capability
Space systems of manoeuvring objects shall have an operational capability to detect a risk of collision and manage it either by carrying out a remote-controlled or autonomous manoeuvre to avoid the secondary object, or by ensuring coordination with the secondary object's control centre when it is controlled, in order to decide on which of the object(s) is to perform such a manoeuvre. The post-manoeuvre trajectory shall be such as to substantially reduce the initial collision risk.

This coordination with the control centre of the secondary object can be carried out by the operator itself, but also via a collision avoidance service which will have the necessary contacts and any additional information on the other object (e.g. system manoeuvrability), and will be able to facilitate exchanges.

If coordination is not possible, an avoidance manoeuvre is recommended. Good practices in post-manoeuvre risk reduction are described below.

Article 41-5: Coordination in the event of collision alert between two operators controlling manoeuvring space objects
In the event of a confirmed collision alert between two manoeuvring space objects, the operator bound by these regulations shall coordinate with the other operator in order to decide on a manoeuvre strategy leading to manoeuvring at least one of the two objects.

A "confirmed collision alert" is a situation where the threshold for engaging collision avoidance manoeuvres defined by the operator and the collision avoidance services used (see article 41-6 below) is exceeded.

If coordination is not possible, the avoidance manoeuvre is recommended in conjunction with the collision avoidance service used.

Article 41-6: Trigger threshold for collision avoidance manoeuvres
In the event of a collision alert with a catalogued space object, the collision avoidance measures take priority over the mission. The collision probability threshold above which the operator must implement

measures to avoid a collision shall be defined, and its adequacy shall be demonstrated, in the operational concept.

The methods used to assess the probabilities of collision vary according to the operators and/or STM entities providing this calculation service. It is not possible, at this stage, to have an internationally recognised standard method, so the thresholds above which manoeuvring is necessary are left to the discretion of the operators, who must justify their relevance.

The relevance of the threshold can be justified by defining it in relation to the collision avoidance services used and by implementing the good practices described in §3.6.1.

The FSOA requirement is for the operational process to be rigorously tracked in the operator's documentation.

Article 41-7: Data sharing

The operator shall share, as soon as possible after injection by the launcher and within 3 days, the necessary updated information with any pertinent actor or entity, in order to control the risks of collision with the catalogued space objects it could encounter. This information shall be at least the following:

- *ephemeris, resulting from the operator's own orbit determination means, or from Space surveillance systems;*
- *manoeuvre plan;*
- *covariances.*

The catalogue referred to in this article is the catalogue used by the contracted collision avoidance service.

There is a stage for checking the consistency between the data provided and reality: the quality of the covariance matrices and the data supplied must be checked. This data can be certified by an external body.

The frequency of data provision is ideally once a day (with a sliding window of 7 days), although in a GEO orbit, once every three days (with a sliding window of 15 days) is generally sufficient.

Note: This requirement also applies to any non-manoeuvrable object, although manoeuvring plans obviously do not have to be provided. This is because carrying a GNSS-type on-board system can help improve the accuracy of the ephemeris provided by a space surveillance system, and it is important for the operator to be able to help improve the tracking of its object to enable better implementation of measures to avoid other objects.

In the general case where orbit restitution relies on the operator's own means, it is necessary to safeguard these operations, in particular to cover cases of degraded injection:

- Designate ground stations for the first acquisitions taking account of margins on the date on which the satellites will come into visibility, and favour a "holding point" and "autotrack" mode for the antenna, if possible, rather than a designation based on ephemeris.
- Make orbit calculation methods redundant if possible, for example: angular and Doppler measurements.
- Have several first acquisition stations, located at different sites, for robustness in the event of failures of these ground facilities and to improve the quality of orbit restitution.

- Favour continuous power-on of the on-board transmitter (when on-board power constraints allow) in order to guarantee satellite telemetry is received even in the event of a very degraded injection, which would results in obsolete station visibility planning.
- If the number of stations or on-board/ground contacts is low, and orbit calculation relies mainly on on-board means (GNSS), switch on this equipment as soon as possible.
- Do not start up the on-board propulsion system until knowledge of the orbit is stabilised from ground.
- Be able to receive orbit information from external entities (launch operator, 18th sq, etc.) to help "find" the satellite in the event of an abnormal injection.

3.7 OPERATIONAL ASPECTS OF RISK MANAGEMENT

3.7.1 Risk of lack of control over the space object

Article 38-2: Validation of procedures
The space object control procedures shall be tested and validated by the operator before the launch, except for degraded cases which do not require any immediate reaction by the operator and end-of-life procedures if it is shown that there is no risk of having to perform an emergency disposal.

The operational sequences involving the object control procedures shall be tested and validated by the operator before the launch for the mission's critical phases (LEOP, disposal, critical operations in orbit).

The operator fully complies with the article above by demonstrating that it has identified/developed/validated all the operational sequences required to conduct nominal operations for its vehicle, as well as for degraded operations requiring immediate intervention by the SCC. Validation can be carried out either using a digital simulator, an EM (Engineering Model) hardware equivalent to that of the mission (or a combination of software/hardware resources), or in case a previous mission using the exact same procedure has already been performed.

The strategy adopted by some operators, which consists of carrying out a technical qualification (QT) phase followed by an operational qualification (QO) phase, meets the requirement of this article.

Article 39: Ability to control the space object
The space system shall be designed, produced and implemented in such a way that the operator, for the duration of the operation, can receive information about the status of the space object and send it commands, with the aim of:

- *preventing on-orbit collisions;*
- *being able to perform disposal or any other operation intended to keep the object intact.*

The rules and good practices below are largely drawn from the CNES's experience of low orbit satellite operations.

3.7.1.1 RISK OF COLLISION

As described above, the operator must set up an operational organisation capable of dealing with the risks of collision as quickly as possible. The time taken to reduce risks of collision depends on the system (on-board constraints, frequency of on-board/ground contact, etc.). Aiming for a time of less than 12 hours to interact with the satellite (i.e. perform a collision avoidance manoeuvre or act on a manoeuvring plan) is recommended, which in particular requires a 24/7 intervention capability if the risk reduction measures are not automated.

It is recommended that periods of unavailability or non-manoeuvrability of the satellite be kept to a minimum.

In cases where a ground loop is not sufficiently robust or responsive, implementing an on board automatic mechanism for managing the risks of hazardous close approaches is recommended (e.g. in the case of close formation flying or on-orbit servicing).

Signing up to a space surveillance service such as EUSST (service free of charge) or the CSPoC also ensures good coordination with other operators to prevent the risk of an in-orbit collision, and is therefore strongly recommended.

Note: the capabilities required for an effective collision avoidance service are listed in section 3.6.1.

3.7.1.2 RISK OF PREMATURE SATELLITE LOSS

- **Securing operations and preventing operational errors**
    - Maintaining a constant level of skill in the operational teams, in particular including a certification/training process;
    - Providing through-life support for ground facilities, and reducing, insofar as possible (typically to a few hours), periods of unavailability resulting in impossible on-board/ground communication;
    - Implementing a quality process to track changes in operational systems and products (software, procedures, data, etc.) and their validation status;
    - Maintaining simulation systems to test and validate new procedures before using them in operations;
    - Making sure there are enough human and material resources for the implementation of specific operations on the satellite (for those that are not automated or non-routine and require it);
    - Securing passivation commands on the ground so that they are not issued following an operational error.
- **Detecting faults as early as possible**
    - It is recommended that periods without contact with the satellite should be kept to a minimum (12 hours maximum is a good order of magnitude for satellites with no automated collision avoidance capability), so that the satellite's state and orbit can be ascertained with sufficient precision to manage risks of collisions;
    - The satellite's critical parameters must be monitored on ground so that any malfunction can be detected as early as possible and automatically;
    - The platform equipment required to carry out disposal operations must be subject to special monitoring (e.g. regular expert assessments with telemetry sampling, periodic health check of redundant equipment, etc.). This level of monitoring must be reassessed during operation, typically annually, to take account of the state of the satellite (performance and failures) and in-flight feedback from other equivalent satellites/equipment.
- **Identifying (anticipating) slow degradation of performance**
    - Performance and trend reports made at regular intervals, for example annually during operation reviews, should make it possible to anticipate any abnormal equipment degradation. They also ensure that the satellite has and will have the capacity required to continue the mission;
    - It is advisable to maintain an expert assessment capability as regards operation of the platform, ideally from its manufacturer. This expert assessment is used for investigative purposes in the

event of a failure, but also to define, if necessary, alternative operating modes or new on-board settings to enable disposal operations to be carried out in a degraded mode (which was not initially planned);

- Tools (e.g. based on statistical analysis or artificial intelligence) can help to identify unusual behaviour;
- These practices will be set out for constellations, which inherently benefit from statistics on the behaviour of sub-systems.

- **Securing the capability to carry out disposal operations**
  - Disposal procedures need to be kept up to date and developed as necessary to take account of changes to satellite performance and feedback from satellites using a similar plateform;
  - Before launch, it is recommended to analyse the robustness of the passivation strategy to the different equipment failures/degradations and, if necessary, to propose alternative passivation strategies if this situation is encountered (without carrying out a full validation of all possible scenarios);
  - During the operational phase, in the event of equipment failure or any other critical event affecting the satellite, it is essential to assess the potential impacts on disposal operations, which may involve redefining a new passivation procedure;
  - It must be demonstrated that the altitudes encountered during disposal operations are compatible with the flight envelope of the space object (for example via convergence analyses of the AOCS modes used).
  - The critical satellite (the minimum satellite required for disposal operations, as defined below) must be identified. **It is essential to draw up an inventory of failure cases which, if they occur, bring the satellite into a critical state**, possibly requiring urgent disposal. This could be, for example, accelerated performance degradation, loss of equipment with the risk of rapid loss of redundancy, etc. If these kinds of emergencies are identified, a suitable organisation needs to be put in place to deal with them (teams and decision-making process).

Defining the critical satellite:

A critical satellite configuration is a configuration with a SPF (Single Point of Failure) in one of the functional chains or equipment required for nominal end-of-life operations (de-orbiting, passivation or disconnection). By extension, the remaining propellant mass and the electrical power capacity (loss of SA string, battery capacity, etc.) are included in the criteria for the critical satellite.

This definition means that any additional failure affecting a satellite in a critical configuration may involve a partial implementation of EOL operations. The critical satellite configuration is therefore not very resistant to any new failures.

The operator is encouraged to conduct a risk analysis on the functional chains involved in disposal, to determine their resistance to failures. This analysis, which can be summarised in a table, will enable to examine the scenarios resulting in the following 3 situations:

a. The failure is deemed isolated. Based on feedback from in-flight experience, it is considered that the probability of a second failure at the SPF is negligible. This can be tempered by the satellite's orbital lifetime. Failures will be analysed from a different perspective for a satellite at the beginning or end of its life. In this case, specific monitoring of the faulty equipment (or function) must be defined for fine monitoring purposes.

Example: loss of redundant equipment.

b. The failure is severe but not urgent. In this case, EOL operations must be scheduled within a time frame compatible with the work in business days. In this case, there is no need to do anything other than plan the operation with the various stakeholders involved. This situation also covers cases where the mission can no longer be carried out, even partially.

Example: successive losses of SA strings over time.

c. In the event of a major failure (to be specified) that could affect the integrity of the satellite in the short term, de-orbiting and/or passivation procedures are to be carried out urgently by the on-call personnel. The decision-making criteria must be clearly deterministic (equipment failure signature, threshold reached, etc.). These criteria are included in an "instruction" for on-board and coordination on-call personnel.

E.g.: major failure of equipment as SPF for the nominal configuration. This also applies to rapid degradation situations: rapid loss of power, loss of successive SA strings at short intervals, drop in temperature or voltage at a SPF as a precursor (SPF for a satellite already rendered critical following a situation described above in case "a" or existing standard SPF).

3.7.2 Inspection plan

Article 38-1: Inspection plan during on-orbit control
The operator shall draw up a plan to inspect implementation of the provisions of this Order during the on-orbit control phase. This inspection plan includes briefings with the CNES at least once a year and in particular:

- *after the initial launch and early orbit phase (LEOP);*
- *following transfer of control of the space object or group of coordinated space objects to another operator;*
- *before the beginning of the disposal manoeuvres;*
- *after the disposal manoeuvres;*
- *for on-orbit servicing operations, following performance of a service.*

Depending on the phase concerned, these briefings shall present the results of the operations performed or the availability of the vehicle for initiation of the upcoming operations, in particular:

- *status of anomalies, on-board and orbital configuration;*
- *status demonstrating the ability of the space object to perform the disposal operations (manoeuvres and passivation);*
- *availability of the energy resources (propellant management in particular) needed for the disposal manoeuvres;*
- *results of manoeuvres performed to avoid other space objects and coordination with the other operators;*
- *status of ground segments.*

Annual Operational Reviews carried out at the CNES and by certain operators, enable a to conclude on the state / to summarize the state of the satellite and in particular the platform systems required for disposal. These kinds of practices are encouraged, and inviting CNES Space Safety Office promotes a virtuous circle between operators and regulators, in a spirit of transparency.

Operators are also encouraged to provide CNES Space Safety Office with a fleet report (at least once a year), assessing the availability of the platform's functional chains and confirming the capacity for disposal.

Once on-orbit servicing has been carried out nominally, a simple notification from the operator allows the need to be met, without the need to organise a specific review.

3.8 DE-ORBITING/RE-ORBITING SATELLITES AT END OF LIFE

Article 41-8: Disposal obligation

1. The space systems shall be designed, produced and implemented such that, following their operational phase, they perform disposal by either:

- *escape from Earth's gravity;*
- *atmospheric re-entry, controlled or otherwise;*
- *entering a graveyard orbit between protected region A and protected region B;*
- *entering a graveyard orbit above protected region B.*

2. With regard to space objects which, during their operational phase, are in an orbit included within or passing through protected region A, only escape from the operational orbit by atmospheric re-entry is authorised.

3. With regard to space objects which, during their operational phase, are in an orbit included within or passing through protected region B: if the eccentricity of the target graveyard orbit for the space object after the disposal manoeuvres is less than 0.1, it shall be situated above protected region B.

Each orbital constraint linked to the chosen method is subsequently described in dedicated articles, and set out below.

Re-orbiting to above 2,000 km for a satellite in a Low Earth Orbit, initially possible in the 2017 version of the Technical Regulation, is therefore now excluded, and it will be necessary to plan for the propellant capacity to meet the natural re-entry requirements below.

Point **c)** requires geostationary satellites aiming for a near-circular graveyard orbit to undergo disposal above zone B.

On the other hand, it is possible for an orbit of the 5,000 km X 36,000 km type to choose a graveyard orbit in MEO (complying with the provisions of article 41-10) as well as to choose an atmospheric re-entry by lowering the orbit (complying with the provisions of article 41-9).

In the event of an escape from Earth's gravity, the operator will still have to carry out an orbital propagation analysis to check there is no return into the protected zones (ideally over the next 100 years), although the relevance of extrapolating over such a long term is questionable as propagation is highly dispersed. It will, in some cases, probably be difficult to guarantee non-interference with protected regions A and B.

Article 41-9: Maximum orbital life before atmospheric re-entry

If disposal of the space object leads to atmospheric re-entry, the residual time in orbit may not exceed:

- *three years for systems with an operational phase of less than 1 year; or*
- *three times the duration of the operational phase and in any case may not exceed twenty-five years.*

This residual time in orbit is considered as soon as there is no manoeuvring capacity.

For the purposes of this article, the operational phase begins when the initial operator takes control of the *object considered.*

However, it is advisable to reduce the re-entry time insofar as possible if the operator has more resources than its initial estimate.

The STELA user guide ([RD5]) in particular describes the use of the STELA software, and recommends the use of an *"equivalent constant"* solar activity greatly simplifying analysis of the satellite's natural re-entry in the LEO case. The calculation used to estimate the atmospheric re-entry time will be based on a STELA simulation with mean solar flux.

Operational phase means the duration of the authorisation requested as defined in the request file, including the object's disposal phase.

This residual time in orbit must be taken into account as soon as there is no ability to manoeuvre, i.e.:

- at the end of disposal for systems equipped with propulsion items that can be used to modify the orbit.
- when the manoeuvring capability is no longer available.

  Note: the point here is not to consider potential anomalies resulting in a loss of manoeuvring capability, but rather the nominal operations strategy.
- from injection for systems not equipped with propulsion items that can modify the orbit.

Article 41-10: Characteristics of a graveyard orbit between protected region A and protected region B
A graveyard orbit between protected region A and protected region B shall be such that, under the effect of natural disturbances and the associated uncertainties, for one hundred years following the end of the disposal phase, the space object does not return to either protected region A, nor protected region B, nor interferes with the operational orbits of the constellations already present between these two regions.

For this orbital zone, the use of graveyard orbits with low eccentricity (< 0.1) is recommended to limit the orbital zones affected after disposal.

STELA calculations need to be carried out (with suitable settings) to see how such graveyard orbits change over the next 100 years.

For further details, please refer to the STELA user guide [RD5], as well as to the use of the STELA tool (§10.1).

Furthermore, in response to the last part of the article, the operator will simply explain the rationale behind the choice of the graveyard orbit, particularly with regard to the operational constellations (GNSS type) that would be present in the MEO zone at the time the FSOA authorisation request file is submitted (in particular Galileo, GPS, Glonass, BeiDou, etc.).

Article 41-11: Characteristics of a graveyard orbit above protected region B
A graveyard orbit above protected region B shall be such that, under the effect of natural disturbances, for one hundred years following the end of the operation, the space object does not return to protected region B.

As an initial approximation, the following formula, taken from the IADC guidelines, can be used to calculate the increase in perigee altitude required to meet this requirement:

$$\Delta H = 235\ km + (1000\ \times\ C_R \times \frac{A}{m})$$

Where:

ΔH : increase in perigee altitude, in km

C_R : solar radiation pressure, typically between 1.2 and 1.5

$\frac{A}{m}$: ratio between the apparent surface area and the dry mass of the space object ($m^2.kg^{-1}$).

For further details, please refer to the STELA user guide in [RD5], as well as to the use of the STELA tool (§10.1).

3.9 ESTIMATING THE PROPELLANT BALANCE

Article 39-2: Propellant management *The probability, calculated prior to the launch, of having the propellant needed for the end-of-life manoeuvres, at each moment during the mission and up to initiation of successful disposal manoeuvres, shall be at least 0.99.*

The operator will explain how the propellant budget required for Delta-v de-orbiting is secured.

The following items will be taken into account:

- Mass of propellant at launch
- Mass of propellant required for de-orbiting (2.57 sigma scaled)
- Inhexaustible propellant (geometric or other)
- Consumption forecast (scaled as regards nominal mission duration) from launcher injection to the start of disposal.
- Consideration of potential collision avoidance manoeuvres during the operational life of the object.
- Uncertainty (2.57 sigma) in the estimate of actual consumption just before initiating disposal. This item depends on the method used by the operator, which will be specified.

This estimate is updated by the operator during the satellite's operational life, and in particular will be presented in the event of a mission extension request.

3.10 CALCULATING THE RELIABILITY OF OPERATIONS ASSOCIATED WITH DISPOSAL

Article 41-12: Reliability of disposal operations
The probability of being able to successfully carry out the disposal operations (including the passivation operations as well as the disposal manoeuvres) shall be 0.9 or greater.

This probability must be calculated before launch by the operator, considering the duration of the control phase for which the system has been qualified and taking account of all the systems, sub-systems and equipment required for these operations, their levels of redundancy, if any, and their reliability, except for ground items. Note that the calculation of this reliability does not take account of the probability of external impact.

Note: it is recommended that the ***probability of having propellant available for end of life, which must be greater than 99%, be taken into account when calculating the probability of successful disposal operations****.*

This probability is calculated based on the reliability of the equipment required to carry out end-of-life operations on the satellite, i.e.:

- De-orbiting/re-orbiting the satellite (for release from zones A or B) unless the satellite is already in its disposal orbit, in compliance with the TR.
- Fluid and electrical passivation of the satellite.

The method presented here is taken from the CNES document [RD6] "Guide to assessing the probability of success for satellite end-of-life operations", French version available upon request and in which a calculation example is set out.

Step 1: Identifying the equipment required to carry out these operations

As not using certain equipment for end-of-life operations frees up power resources, they should not be taken into account in reliability reports, unless their failure could compromise these operations. Thus, a satellite's payload is traditionally excluded from the calculation.

As a general rule, the sub-systems enabling de-orbiting manoeuvres to be performed include at least the following:

- On-board computer
- Power system
- Thermal system
- AOCS and propulsion
- TM/TC

However, some of the equipment in these on-board functional chains is not necessarily used for de-orbiting manoeuvres and the reliability estimation can therefore be made taking account of what is 'strictly necessary'.

Similarly, the sub-systems and equipment used to perform passivation (fluidic and electrical) may differ depending on the definition of the passivation sequences and should therefore be specified by the operator when estimating the reliability associated with the passivation.

***Note**: the availability **of the TM/TC system** is required (as part of the capability to control the space object) as soon as the satellite is 'operated' (by ground) to perform its disposal. At the very least, to confirm that electrical and fluid passivation is engaged.*

Step 2: Modelling the reliability of the "Successful disposal" scenario

The planned nominal scenario and any alternative scenarios must be taken into account to model the various possibilities for disposal. The modelling techniques are those conventionally used in RAMS (Reliability Block Diagram, Markov networks, Petri nets, etc.).

Step 3: Assessing equipment failure or reliability rates

Several methods are possible for assessing failure or reliability rates:

a) By carrying out a predictive reliability analysis based on a reliability guide (for example using MIL-HDBK-217 or FIDES methods). The method must be selected by the operator, who must justify its relevance,
b) Based on in-orbit feedback from similar equipment (Bayesian techniques, χ^2 (Chi-square) technique),
c) Using analogies with equipment that has already flown (expert opinion),
d) Using reliability data provided by equipment or component manufacturers.

Step 4: Calculating the overall reliability of this chain of equipment (probability of disposal)

This reliability calculation is based on the total duration of the requested authorisation, from injection and including the duration of disposal operations.

It is based on the following assumptions:

- Over the qualification period, electronic components are assumed to have constant failure rates (λ), and components are assumed to be able to fail independently of each other, unless fault propagation is identified in the RAMS analyses,
- The calculation only covers random failures,
- Exponential distribution is used to calculate reliability (R) according to the formulae:
  - Single Point of Failure:

$$R_{SPF} = e^{-\lambda_{ON} * t}$$

  - Active redundancy:

$$R_{ACTIVE}(m/n) = \sum_{i=0}^{n-m} C_n^i (1 - e^{-\lambda_{ON} * t})^i * (e^{-\lambda_{ON} * t})^{n-i} \quad \text{with} \quad C_n^i = \frac{n!}{i!(n-i)!}$$

- Passive redundancy:

$$R_{PASSIVE}(m/n) = e^{-m*\lambda_{ON}*t}[1+\sum_{i=1}^{n-m}\frac{(1-e^{-\lambda_{OFF}*t})^i}{i!}\prod_{j=0}^{i-1}(j+m\frac{\lambda_{ON}}{\lambda_{OFF}})]$$

- The failure rate for non-operating components (λOFF) is assumed to be 1/10 of the failure rate (λON) for EEE components,
- For equipment with a duty cycle (α) other than 100%, an equivalent failure rate is calculated using the formula:

$$\lambda_{eq} = \lambda_{ON} * \alpha + (1 - \alpha) * \lambda_{OFF}$$

- Structural items (e.g. supports) and thermal insulation are assumed to have sufficient margins, and therefore a negligible probability of failure.

What's more,

- Consideration, for electronics, of realistic operational temperatures estimated using thermal models (category experience, thermal analyses with realistic margins) is possible,
- The reliability of the structural items is assessed using suitable methods and is presented in the file supplied to CNES Space Safety Office. The design rules used may be based on a reliability-oriented approach using suitable methods (e.g. Stress-Strength analysis) or on a deterministic approach with suitable safety margins (see ECSS-E-ST-32-10 "Structural factors of safety for spaceflight hardware").
- Items for which the probability of failure is disregarded must have design margins that must be presented in the analysis file.

Specific case of system designs with a low level of redundancy or the use of COTS-type electronic equipment, which is less robust than a high-level space standard (High Reliability).

For these system designs (in particular proposed for small 'NewSpace' platforms), the objective of 0.9 for electrical and fluid passivation may be difficult to achieve over the target mission duration. As a result, alternative or compensatory solutions or possibilities are being studied, such as those proposed below, which are not exhaustive:

- Watchdog-based solutions that enable passivation to be activated autonomously can substantially improve the reliability of successful disposal, as they do not require having the TM/TC system. If their robustness is demonstrated (by their design), the Technical Regulation does not require that activation of these sequences be demonstrated via TM reception (as required by *article 39* mentioned in §3.7.1 if the nominal passivation sequence is controlled via TC).
    - Note, however, that this watchdog system makes it possible to dispense with certain functional chains for calculating the reliability of electrical and/or fluid passivation operations, but reliability will still have to be demonstrated for de-orbiting if necessary.
- Autonomous, 'deterministic' passivation systems based on robust information can also be deemed

suitable solutions for low-redundancy electrical system designs.

- Demonstrating (by design and testing) the absence of debris generation for a non-passivated system (fluidic or electrical), under extreme conditions covering the environments encountered and their consequences (temperature, battery overcharging) after satellite loss of control, is an acceptable solution for the FSOA TR. Thus, the operator demonstrates that, given the design of the equipment in question, its design margin and its energetic state (fluid, electrical) at the end of the nominal mission duration, there is no risk of debris generation via internal explosion. The size (mass/surface) of the objects will be taken into account in the FSOA TR analysis.
- To justify the absence of risk of generating debris if the battery is not passivated, the operator may provide the following information:
  - Specifying the various protection systems implemented at cell level (venting device, PTC, CID, HRL, etc.).
  - Identifying in which SoC range the battery will remain at the end of its life.
  - Estimating the temperature ranges of the battery cells expected after disposal, and checking whether these ranges comply with the manufacturer's specifications (particularly in terms of charging/discharging).
  - Estimating the life (post-mission) of battery cells under charge level and temperature conditions.
  - Validating (or at least modelling) the behaviour of the EPS and battery charging-discharging in the medium or long term with representative solar panels illumination phases.
  - Ideally, providing a justification file with abuse tests on battery packs (including overcharging, short-circuit and overheating tests to ascertain the temperature at which thermal runaway occurs and the associated consequences).
  - IEC 62133-2:2017 certification can also provide additional relevant information.

It is also possible to demonstrate that even in the event of battery overcharging leading to an explosion, the debris would be contained inside the satellite (design of a "sarcophagus" to contain the debris).

4 LIMITING THE RISK OF CASUALTY WHEN A SPACE OBJECT RETURNS TO EARTH

Article 44: Quantitative objectives for human safety for return to Earth of a space object

1. With regard to the return of a space object, the quantitative safety objectives, expressed as the maximum probability of causing at least one casualty (collective risk) is 10^{-4}.

2. The provisions mentioned in 1 of this Article shall be evaluated by taking account of:

- *the atmospheric re-entry strategy (controlled or uncontrolled);*
- *the population on the intended date of re-entry;*
- *all phenomena leading to a risk of catastrophic damage;*
- *the trajectories before fragmentation;*
- *modelling of the scenarios covering fragmentation and the corresponding generation of debris on re-entry;*
- *dispersion of debris on the ground and evaluation of their effects;*
- *the reliability of the space object.*

3. These objectives comprise the risk associated with the nominal return of the object or fragments thereof as well as that associated with non-nominal cases. These objectives in no way prejudice the provisions of Articles 42 and 45 of this Order.

4.1 INTRODUCTION

During the return to Earth, a space object is exposed to aerothermal fluxes that can cause it to break up into fragments, which may then reach the ground and cause casualties. These fragments are produced by the rupture of various connections between the different space object components.

The trajectory and transformation of each fragment to the ground are calculated by a tool using as input the orbital conditions and a space object model based on sound knowledge of the structure, the mechanical strength and the thermal resistance (to aerothermal forces) of the different components and their connections to each other.

This model for an object-oriented tool (such as DEBRISK) defines these fragments by their shape, their mass, their dimensions and by the materials from which they are made.

The probability of causing at least one casualty is calculated by taking account of the properties of all fragments that reach the ground, the geographical distribution of the population and the type of re-entry.

This chapter describes good practices that can be used to help establish the minimum required elements in the Hazard Study chapter relating to the probability of causing at least one casualty during the return to Earth of a space object.

The contents of the Hazard Study, as requested in Article 15 of the order on documentation composition, in the section related to injury to persons during Earth re-entry, or that of the Impact Study, as requested in Article 16 of the order on documentation composition, must:

- Meet the quantitative objectives, expressed in maximum probability of causing at least one casualty (Article 44 and Article 48-2),
  - For random re-entries (uncontrolled re-entries) based on estimated incoming fragments,
  - For controlled re-entries, based on the estimated number of incoming fragments and the probability of failure of this re-entry method.
- Describe and demonstrate the components which may reach the ground,
- For uncontrolled re-entries, demonstrate that the choices of space object system design and materials are in line with the objective of limiting the number and energy (kinetic and explosive) of fragments that may reach the ground.
- For controlled re-entries: present the calculation of the estimated re-entry area and the operational procedures implemented with regard to the aviation and maritime authorities, as well as the risks of in-orbit collision associated with de-orbiting manoeuvres.

4.2 DEFINITIONS

Catastrophic damage: results in immediate or delayed loss of human life or serious injury to individuals resulting in irreversible damage to health, permanent disability and/or occupational illnesses.

Random re-entry (RA) or Uncontrolled re-entry (RNC): *Atmospheric re-entry of a space object for which it is not possible to predict the Earth impact zone for the object or fragments thereof.*

It must therefore comply with Article 44 of the TR, which requires a maximum probability of 1 x 10^{-4} of causing a casualty, as well as Article 48-2 of the TR for a megaconstellation.

Assisted Natural Re-entry (RNA) : De-orbiting method designed to limit the probability of casualties (FSOA compliance) without making a controlled re-entry, but limiting the possible re-entry area to a few orbits. This re-entry method must also comply with the requirement expressed in Article 44 of the TR, which requires a maximum probability of causing a casualty of less than 1 x 10^{-4} in the event of a failure, and potentially Article 48-2 of the TR for a megaconstellation. However, it does not necessarily have to comply with Article 46 of the TR.

Note that in the case of Assisted Natural Re-entry, the object must be able to carry out passivation operations, but these will not necessarily be required at the end of the mission, given the very short time in orbit at the end of the last return-to-Earth manoeuvre.

Controlled Re-entry (RC); Atmospheric re-entry of a space object with a predicted Earth contact or impact zone for the object or fragments thereof. A controlled re-entry may be a precision re-entry on a site, or by targeting a limited area with a certain level of confidence.

This re-entry must therefore comply with Art. 46 of the TR for which the Re-entry Area (ZdR) associated with a probability of 99.999% must not interfere with the territory, including territorial waters, of any State, unless agreed to by the latter, in addition to Art. 44 of the TR, which requires a maximum probability of causing a casualty of less than 1 x 10^{-4} in the event of a failure, and potentially Article 48-2 of the TR for a megaconstellation. In the case of re-entry to a site with precision, refer to Article 46-1 (see section 4.9).

The passivation requirement of paragraph 3 of Article 40 is not applicable to this type of re-entry, but as mentioned in paragraph 3.3 of this document, it is highly recommended to include systems allowing for passivation if controlled re-entry is no longer feasible due to a platform anomaly.

Initial RC manoeuvre: Manoeuvre performed at the start of Disposal following the decision to carry out an RC.

First RC manoeuvres: Manoeuvres performed after the decision has been made to carry out an RC from operational orbit to a stable orbit prior to the final manoeuvre.

Final RC manoeuvre: Final RC manoeuvre from a stable orbit to a re-entry orbit.

RC re-entry orbit: Orbit that ends with atmospheric re-entry.

SPOUA: South Pacific Ocean Uninhabited Area

Casualty: a person who has personally suffered catastrophic damage.

4.3 CALCULATING THE CASUALTY AREA

The practice recommended by this guide is to use the most recent authorised version of **the DEBRISK tool** (see §10.2). This software assesses the survivability of fragments of a vehicle re-entering the Earth's atmosphere, using an object-focused approach. This approach assumes that the re-entering vehicle (referred to hereafter as the parent vehicle) can be modelled as a set of several objects of basic geometric shapes:

- It calculates the trajectory and thermal properties of the vehicle as it re-enters the Earth's atmosphere,
- It includes the loss of solar generators at the assumed altitude of this event,
- It takes account of vehicle fragmentation at the assumed altitude of this event,
- For each object representing a fragment, it calculates, step by step, its trajectory, its temperature and any ablation based on incoming and outgoing fluxes.

This tool needs the initial kinematic conditions of the parent vehicle, its physical properties and a list of objects as input. This list represents the fragments of the vehicle under study, which may or may not be linked to each other by different types of relationship, which will arise from the main fragmentation altitude of said vehicle. This list is the responsibility of the operator producing it and the DEBRISK input file may be supplied as part of the request.

The first stage is therefore to establish and justify how fragmentation operates, because the DEBRISK software does not define it: this is a process that requires the skills of an engineer specialising in mechanics, structures and materials.

When assessing fragmentation, it is therefore necessary to carry out at least the following procedure:

- ***Representation of the integral space vehicle prior to fragmentation.***
- ***Breakdown into primary and secondary fragment objects, etc.***
- ***Knowledge of the materials that make up each item of the satellite.***

To do so, the operator must use documents such as:

- ***DJF: Design Justification Files***
- ***CIDL (Configuration Item Data List): Equipment configuration (parts list, S/S assemblies)***
- ***DML (Declared Material List): The materials used and their properties***
- ***DPL (Declared Process List): The processes used to assemble the items (bonding, soldering, etc.) and their properties (conduction, melting, etc.)***
- ***MICD: Part drawings, geometries***
- ***MCI report: Item masses***

- ***CAD*: Computer-Aided Design**

DEBRISK requires precise knowledge of all the fragments in terms of volume in order to perform realistic fragmentation. For example, the operator needs to know the components that make up the inside of a flywheel, the dimensions/weights (or thickness) of the shell of the electronics unit and its boards, the thickness of the skins and the NIDA of a sandwich panel, etc.

To use this tool, the operator will refer to its User Manual ***DBK-MU-LOG-0205-CNES*** and its user guide for satellite applications ***DBK-NT-LOG-0567-CNES*** [RD3].

Once the simulation has been completed, and the list of surviving fragments obtained by DEBRISK, the baseline calculation used for estimating the risk of a person being hit by an object reaching ground is that of the casualty area A_C. This surface describes the hazard potential of an object reaching ground in relation to the possible presence of a human being nearby. It is therefore specific to each object shape. This method is defined in Figure 4-1 such that:

$$A_C = \left(\sqrt{A_h} + \sqrt{A_d}\right)^2$$

where A_h represents the area of a disc with diameter of $D_h = 0{,}677m$, (average shoulder width of a human), and A_d represents the area of a disc equal to the mean projected area of the falling debris.

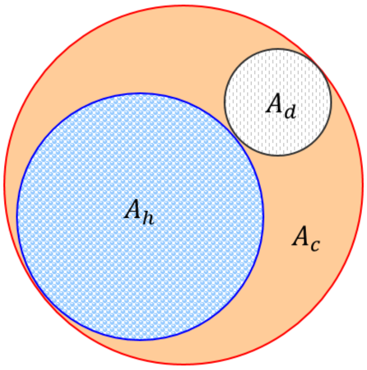


Figure 4-1- Casualty Area

4.4 LIMITING THE CASUALTY AREA VIA DESIGN FOR DEMISE

"Design for demise" is typically based on technological solutions aimed at:

1. Reducing the weight of components;
2. Replacing materials (lower melting temperature, lower specific heat capacity, lower infra-red emissivity, with possible lower oxidation, lower chemical reactivity, etc.) in the structure or equipment;
3. Modifying the geometry to increase the aerothermal flux received;
4. Putting in place a device for early break-up of the satellite structure or equipment.

In addition to checking the qualification of the considered technological solutions, it will be necessary to ensure that the benefit is taken into account when calculating the casualty area.

When using DEBRISK V3 software, the parameters that can be used are as follows:

1. Component weights and geometries;
2. The physical properties of the materials (melting temperature, emissivity, flaking);
3. The main break-up altitude of the satellite structure;
4. The satellite components separation temperature.

A technology which has "demisability" qualities that cannot be modelled by DEBRISK V3 can be justified by testing, in an environment representative of, or less severe than, the one expected upon re-entry.

It is essential to ensure that the casualty area for each of the separate components is zero (or significantly reduced) so as not to increase the total casualty area by adding incompressible areas.

Typical components concerned are: the structure (including balancing weights), tanks, flywheels, magneto-couplers, optical equipment (mirrors, support plate), batteries, large mechanisms and large electronic units, in particular those protected by the structure.

For hydrazine tanks, the residual quantity after passivation will heat up and break down. If the feed and/or pressurisation pipes have not ruptured, the tank will open under the combined effect of overpressure resulting from the adiabatic decomposition of the hydrazine and the loss of the tank's mechanical properties due to aerothermodynamic heating. It will be assumed that the tank does not fragment, but instead tears off and lands in a single part on the ground.

With identical equipment, the premature opening of the satellite (e.g. separation of the propulsion tray from the rest of the platform) can enable a significant increase in the heat flux for all the internal structures.

4.5 CHOOSING THE RE-ENTRY METHOD

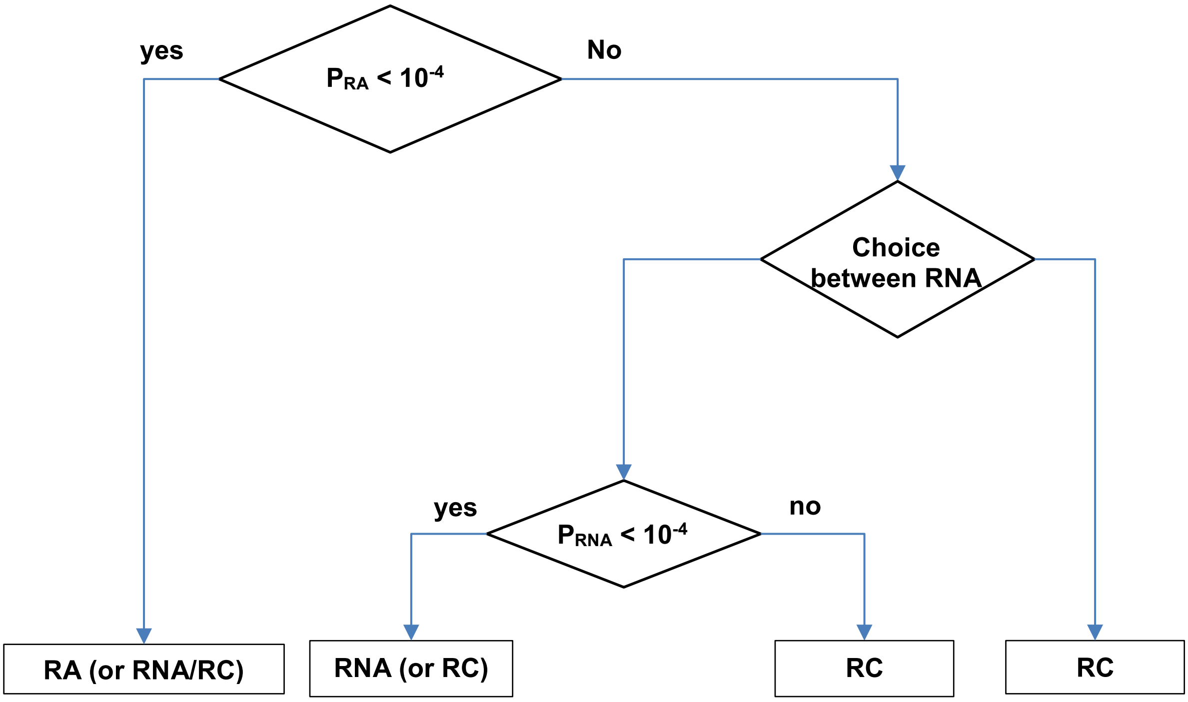


Figure 4-2: Flow chart for choosing the type of re-entry

A Controlled Re-entry (RC) consists of one or more manoeuvres/thrusts, the last of which takes the vehicle into a re-entry orbit, involving an immediate return to Earth (excluding any failures) in less than half an orbit. For controlled satellite re-entries, the area that must be targeted is the **SPOUA.**

Assisted Natural Re-entry (ANR) consists of a series of manoeuvres/thrusts to bring the vehicle into an orbit that is not yet a re-entry orbit, but from which it is possible to predict the re-entry area with a dispersion of around just a few orbits (i.e. a lifetime from just a few hours to a few days between the end of the last manoeuvre and atmospheric re-entry).

4.6 CALCULATING THE RISK OF HUMAN CASUALTY

4.6.1 Definitions and acronyms

ZdR	Re-entry Area Area into which the debris will fall in the event of an RC.
ODR	Re-entry orbits Orbits from which final re-entry will take place during an RNA.
P_{RA}	Probability of at least one casualty in the event of an RA. It covers the following cases: • Case of an initial RA choice; • Inability to perform an RC or RNA at the end of the mission; • Case of failure during the first RC or RNA manoeuvres; • Case of failure during the final RC manoeuvre, which would result in a non-re-entering orbit. • Case of a failure during the last RNA manoeuvres that would result in a non-ODR re-entry. Risk calculated for a given re-entry date (for satisfactory consideration of population densities) corresponding to the decision date for the nominal disposal strategy (by convention, because in reality the re-entry date depends on the different cases).
P_{RNA}	Probability of causing at least one casualty in the event of an RNA.
P_{RC}	Probability of causing at least one casualty in the event of an RC (see dedicated flow chart).
P_{RCI}	Probability of being able to engage the initial manoeuvre on the mission end date for the RC or RNA. Calculated based on the duration of the mission up to the date of the initial RC or RNA manoeuvre
P_{RCF}	Probability of being able to engage the final manoeuvre for the RC or RNA, in the knowledge that the RC or RNA has been engaged. Calculated between the date that the initial RC or RNA manoeuvre was activated and the activation date of the final manoeuvre. This duration depends on the de-orbiting strategy, operational constraints and delay risks.
P_{PNR}	Probability of failure during the final RC manoeuvre resulting in a non-re-entering orbit. Calculated between the start of the final manoeuvre and the time corresponding to the last failure case resulting in a non-re-entry orbit.
P_{OR}	Probability of causing at least one casualty following a failure during the last RC manoeuvre resulting in a re-entry orbit outside the ZdR.
P_{ZDR}	Probability of reaching the re-entry area (ZdR) during the final RC manoeuvre. Calculated between the time corresponding to the last failure case that did not result in a re-entry orbit and the end of the manoeuvre.
P_{ODR}	Probability of reaching the re-entry orbits during the final RNA manoeuvres.

Table 3: Definitions and acronyms relating to the risk during return to Earth

4.6.2 Calculating the probability of casualties in random re-entry

The calculation method is presented in the chapter dedicated to the ELECTRA software, see paragraph 10.3.

The table below enables the operator to estimate, based on the fall-back year and the inclination of the re-entry orbit, the total casualty area possible in order not to exceed the risk threshold of the Technical Regulation.

This is an estimate based on the assumption of a single piece of debris. A full ELECTRA calculation is recommended for casualty area values close to the thresholds in this table.

	2021	2022	2023	2024	2025	2030	2035	2040	2045	2050	2055	2060	2065	2070	2075	2080	2085	2090	2095	2100
0	9.06	8.83	8.61	8.4	8.18	7.26	6.47	5.79	5.21	4.72	4.24	3.82	3.44	3.09	2.79	2.51	2.26	2.03	1.83	1.65
5	9.7	9.52	9.34	9.16	8.99	8.19	7.49	6.85	6.28	5.76	5.28	4.83	4.43	4.06	3.72	3.41	3.12	2.86	2.62	2.40
10	6.85	6.73	6.61	6.49	6.37	5.84	5.35	4.91	4.5	4.13	3.79	3.48	3.19	2.93	2.69	2.47	2.26	2.07	1.90	1.75
15	6.4	6.29	6.18	6.07	5.97	5.49	5.07	4.69	4.36	4.05	3.76	3.49	3.24	3.01	2.79	2.59	2.41	2.23	2.07	1.92
20	6.64	6.56	6.47	6.38	6.29	5.9	5.56	5.24	4.96	4.71	4.45	4.21	3.99	3.77	3.57	3.38	3.20	3.03	2.86	2.71
25	4.95	4.89	4.83	4.77	4.71	4.46	4.24	4.06	3.9	3.76	3.61	3.46	3.33	3.19	3.07	2.95	2.83	2.72	2.61	2.51
30	4.74	4.69	4.64	4.59	4.54	4.32	4.13	3.97	3.83	3.7	3.57	3.44	3.32	3.20	3.08	2.97	2.87	2.76	2.66	2.57
35	4.36	4.32	4.27	4.23	4.19	4.01	3.85	3.72	3.61	3.51	3.41	3.30	3.20	3.11	3.01	2.92	2.83	2.75	2.67	2.59
40	4.69	4.65	4.6	4.56	4.51	4.32	4.15	4.01	3.89	3.8	3.68	3.57	3.47	3.37	3.27	3.17	3.08	2.99	2.90	2.81
45	5.3	5.25	5.2	5.16	5.11	4.9	4.73	4.57	4.43	4.31	4.18	4.05	3.93	3.81	3.70	3.58	3.48	3.37	3.27	3.17
50	5.79	5.75	5.7	5.65	5.6	5.4	5.24	5.09	4.97	4.87	4.75	4.64	4.53	4.42	4.31	4.21	4.11	4.01	3.92	3.82
55	6.16	6.12	6.07	6.02	5.97	5.77	5.6	5.45	5.33	5.23	5.11	5.00	4.89	4.78	4.67	4.57	4.47	4.37	4.27	4.18
60	6.84	6.78	6.73	6.67	6.61	6.38	6.18	6.01	5.86	5.74	5.60	5.46	5.33	5.20	5.08	4.96	4.84	4.72	4.61	4.50
65	7.52	7.45	7.39	7.32	7.26	6.99	6.76	6.56	6.4	6.26	6.09	5.93	5.78	5.64	5.49	5.35	5.21	5.08	4.95	4.83
70	8.01	7.94	7.87	7.8	7.73	7.44	7.19	6.97	6.79	6.63	6.45	6.28	6.11	5.95	5.80	5.64	5.49	5.35	5.21	5.07
75	8.37	8.3	8.23	8.15	8.08	7.77	7.5	7.27	7.08	6.91	6.72	6.54	6.36	6.19	6.02	5.86	5.70	5.55	5.40	5.25
80	8.62	8.55	8.47	8.4	8.32	8	7.72	7.48	7.28	7.11	6.91	6.72	6.53	6.36	6.18	6.01	5.85	5.69	5.54	5.38
85	8.77	8.69	8.62	8.54	8.46	8.13	7.85	7.61	7.4	7.22	7.02	6.82	6.64	6.45	6.28	6.11	5.94	5.78	5.62	5.46
90	8.82	8.74	8.66	8.59	8.51	8.18	7.89	7.65	7.44	7.26	7.05	6.86	6.67	6.49	6.31	6.14	5.97	5.80	5.64	5.49
92	8.81	8.73	8.66	8.58	8.5	8.17	7.89	7.64	7.43	7.25	7.05	6.85	6.67	6.48	6.30	6.13	5.96	5.80	5.64	5.48
94	8.79	8.71	8.63	8.56	8.48	8.15	7.87	7.62	7.41	7.24	7.03	6.84	6.65	6.47	6.29	6.12	5.95	5.79	5.63	5.47
96	8.75	8.67	8.6	8.52	8.44	8.11	7.83	7.59	7.38	7.2	7.00	6.81	6.62	6.44	6.26	6.09	5.93	5.76	5.61	5.45
98	8.69	8.62	8.54	8.46	8.39	8.06	7.78	7.54	7.34	7.16	6.96	6.77	6.58	6.40	6.23	6.06	5.89	5.73	5.57	5.42
100	8.62	8.55	8.47	8.4	8.32	8	7.72	7.48	7.28	7.11	6.91	6.72	6.53	6.36	6.18	6.01	5.85	5.69	5.54	5.38
102	8.54	8.46	8.39	8.31	8.23	7.92	7.65	7.41	7.21	7.04	6.84	6.65	6.47	6.30	6.13	5.96	5.80	5.64	5.49	5.34
104	8.43	8.36	8.28	8.21	8.13	7.82	7.55	7.32	7.13	6.96	6.76	6.58	6.40	6.23	6.06	5.90	5.74	5.58	5.43	5.28
106	8.31	8.24	8.17	8.09	8.02	7.71	7.45	7.22	7.03	6.86	6.67	6.49	6.32	6.15	5.98	5.82	5.67	5.51	5.37	5.22
108	8.17	8.1	8.03	7.96	7.88	7.58	7.33	7.11	6.92	6.76	6.57	6.39	6.22	6.06	5.90	5.74	5.59	5.44	5.29	5.15
110	8.01	7.94	7.87	7.8	7.73	7.44	7.19	6.97	6.79	6.63	6.45	6.28	6.11	5.95	5.80	5.64	5.49	5.35	5.21	5.07

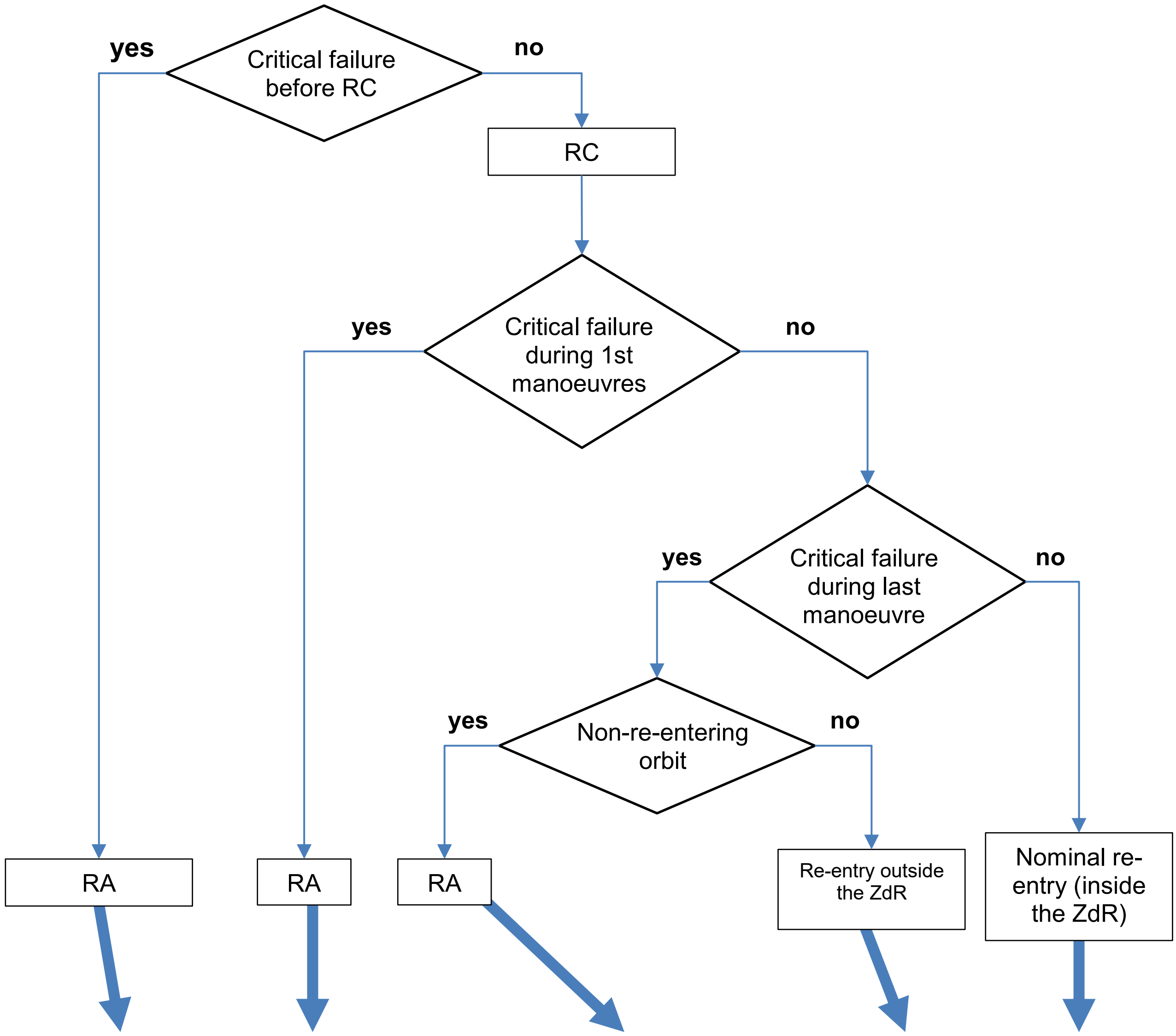
Table 4: Maximum casualty area (in m²) resulting in a risk of $1x10^{-4}$, based on fall-back year and orbit inclination.

Table 4 is created using the GPW 4.11 tables, based on 2015 and 2020 population data, then extrapolated.

Note: Article 44 mentions that the 1×10^{-4} requirement is also to be demonstrated in the event of a non-nominal re-entry, typically in the event of a premature random re-entry due to injection by the launcher into an orbit that does not allow the operator to reach its operational orbit. If the risk associated with this launcher failure were 1%, the risk of human casualty resulting from such a premature re-entry would be weighted by a factor of 1×10^{-2}.

The risk of a satellite failure, based on the nominal launch vehicle injection orbit, causing it to remain in an orbit resulting in a random re-entry to Earth, will be estimated by the operator and taken into account in the same way as estimating the risk of casualty associated with this kind of premature random re-entry.

4.6.3 Calculation of probability of a casualty in controlled re-entry in zone



$$(1 - P_{RCI}) * P_{RA} + P_{RCI} * \{(1 - P_{RCF}) * P_{RA} + P_{RCF} * [P_{PNR} * P_{RA} + (1 - P_{PNR}) * (1 - P_{ZDR}) * P_{OR} + \sim 0]\}$$

Figure 4-3: Risk calculation flowchart for controlled re-entry

Note: The above formula results from the calculation flowchart. It can subsequently be simplified as follows:

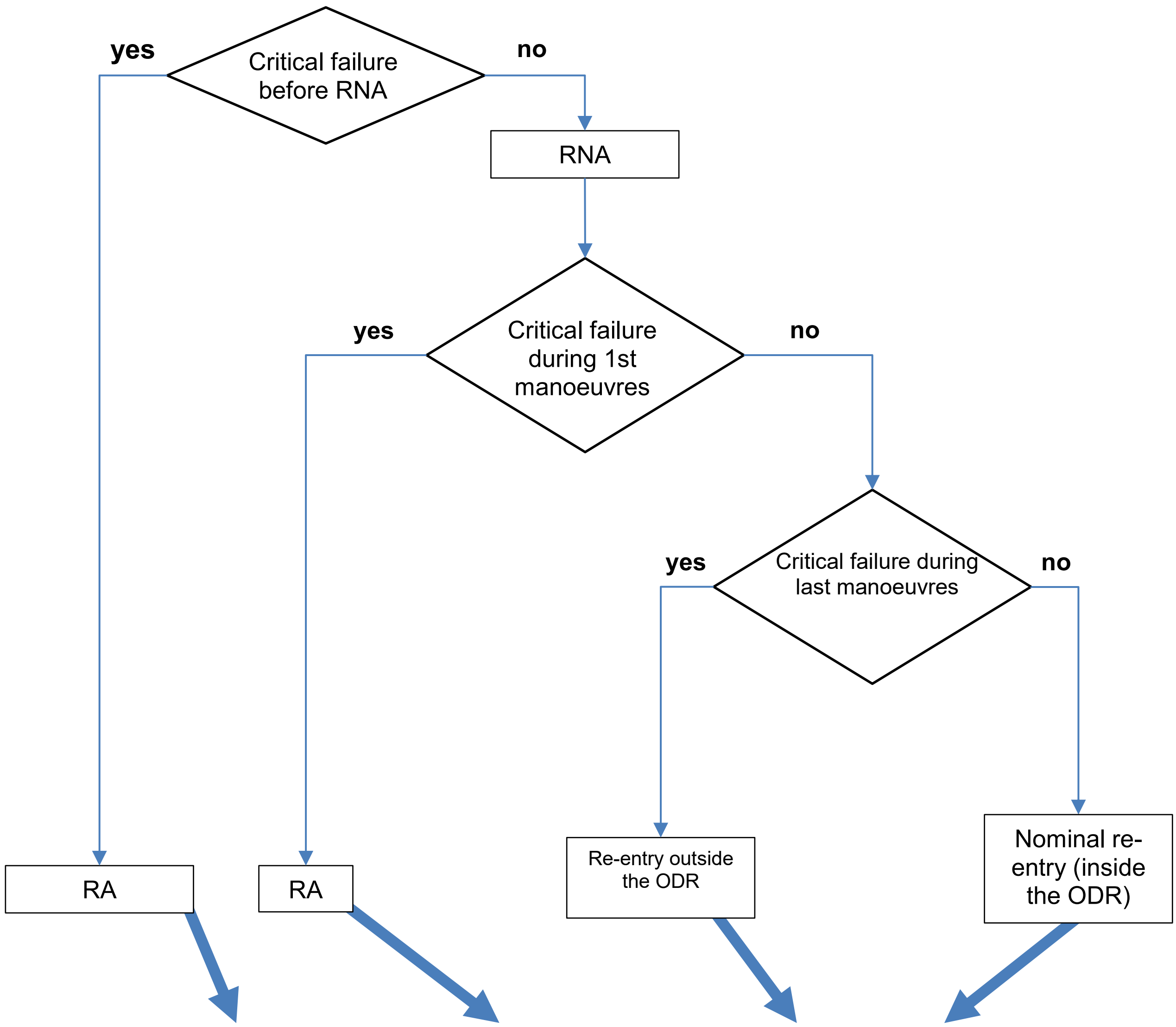
$$(1 - P_{RCI} * P_{RCF}) * P_{RA} + P_{RCI} * P_{RCF} * [P_{PNR} * P_{RA} + (1 - P_{PNR}) * (1 - P_{ZDR}) * P_{OR} + \sim 0]$$

The contents of the square brackets in the second member of this equation can be calculated directly by the Electra tool using the RC mode and the option to take account of the RA risk for non re-entry failures.

4.6.4 Calculation of the probability of casualties in controlled re-entry to a site

The calculation of the probability of casualties in the event of a controlled re-entry to a site is presented in paragraph 4.9, having defined the concepts necessary for this type of re-entry.

4.6.5 Calculating the probability of casualties in assisted natural re-entry



$$(1 - P_{RCI}) * P_{RA} + P_{RCI} * \{(1 - P_{RCF}) * P_{RA} + P_{RCF} * [(1 - P_{ODR}) * P_{RA} + P_{ODR} * P_{RNA}]\}$$

Figure 4-4: Risk calculation flowchart for assisted natural re-entry

Note: Unlike the RC, there is not really a major final manoeuvre. Depending on the design of the strategy, the "last manoeuvres" may correspond to one or more manoeuvres.

4.7 ESTIMATING THE RE-ENTRY AREA FOR CONTROLLED RE-ENTRY

Article 46: Prevention of risks arising from fall-back of the space object or fragments thereof during a controlled re-entry.

1. The operator shall demonstrate that there is no risk of on-orbit collision with manned stations following the de-orbiting and return to Earth manoeuvres.

2. The operator shall determine the fall-back zones of the space object and fragments thereof for any controlled atmospheric re-entry to Earth, associated with a probability of 99% and 99.999% respectively. These fall-back zones shall take account of the uncertainties linked to the re-entry parameters.

3. The fall-back zone, associated with a probability of 99.999%, shall not impinge on the territory, including the territorial waters, of any State, without its agreement.

In the event of a fall-back zone being situated in a region with heavy maritime or air traffic or in which fixed and manned oil platforms are located, a special analysis shall be carried out, pursuant to Article 15 of the above-mentioned Order of February 23rd, 2022.

Controlled re-entries are generally subject to several successive manoeuvres, in order, for example, to initially lower the perigee to an altitude that is still compatible with the AOCS's capabilities.

A final boost is then used to aim for a perigee close to zero to guarantee re-entry into the target zone. The operator will therefore have to demonstrate that the orbits crossed and the final trajectory can under no circumstances result in a risk of collision with manned stations, or that it will be capable at all times of managing a risk of collision with these manned stations by means of clear operational methods and processes. This collision avoidance strategy must be presented in the technical request file and then at the milestone preceding the start of the disposal manoeuvres to make sure the risk of collision with objects of interest will be tackled, by showing that, during the operations, the operator will be able to geometrically guarantee that there will be no risk, which seems feasible in the short term.

The re-entry area for the debris from a vehicle that disintegrated in the atmosphere must also be estimated with a probability of 99.999%. This zone, more commonly referred to as the "10^{-5} zone", will be calculated assuming nominal re-entry (i.e. no failures cases) that is still subject to dispersion. The dispersion items resulting in the definition of this zone will be at least:

- Uncertainty about the direction of thrust.
- Uncertainty about atmospheric density.
- Uncertainty about the mass and frictional surface of the object.
- Possibly, consideration of residual DV (Delta-v) following fragmentation and/or explosion.

In the specific case of *DV controlled thrust* (based, for example, on accelerometers or on-board propulsion models) the dispersion items taken into account will be:

- Uncertainty about this DV.
- Uncertainty about the level of thrust. Note that this uncertainty does not replace uncertainty

about the DV because, even if the DV is perfectly executed, over-thrust or under-thrust will imply a shift in the predicted impact zone.

In the case of *time-controlled thrust* (based, for example, on a timer), uncertainty about DV or thrust level.

The impact zone can be calculated:

- Either via the Monte Carlo method for which it will be necessary to justify that the number of draws is sufficient (for example by showing that the change in the size of the zone converges).
- Or by considering the causes of dispersion one by one and then grouping them together quadratically (assuming that these dispersions are uncorrelated). This will enable the estimation of the size of the impact zone. Its position will then have to be correctly adjusted according to the initial orbital conditions.

As the aim is to calculate the limits of an impact zone, one can limit the study, after fragmentation, to debris with "extreme" ballistic coefficients, i.e., corresponding to the shortest and longest trajectories. Note that fragments can also be taken into account with lift-to-drag ratio.

Note: Estimating the re-entry areas for space vehicles performing a controlled re-entry and operated by CNES (ATV or SWOT type) is based on the use of the DOORS software (created for ATV needs, inspired by Russia), which calculates the manoeuvring strategy and the impact area, with a scaled approach based on estimating the upstream/downstream distances in relation to the nominal impact point, to take account of the different dispersions associated with controlled re-entry. ELECTRA can also be used in "nominal dispersed" mode. Other methods are also used, for example for the fall-back from the upper stages of VEGA, Soyouz or AR6.

4.8 DECLARING RE-ENTRY AREAS ON EARTH TO THE RELEVANT AUTHORITIES

Article 46: Prevention of risks arising from fall-back of the space object or fragments thereof during a controlled re-entry:

4. The organisation and resources put in place by the ~~launch~~ operator shall enable the Chairman of the CNES:

- *to inform the competent authorities in charge of air and maritime traffic control of the fall-back zones in a nominal situation, specifying the zones receiving 99% of these fall-backs;*
- *to transmit to the competent authorities the information concerning the fall-back zone of elements, so that the authorities of the states concerned can be warned as early as possible of any degraded situation;*
- *to provide all useful information at its disposal so that the necessary response plans can be determined and implemented by the competent authorities.*

Note: The process for declaring nominal and non-nominal orbital re-entry areas is based directly on the one already in place at Europe's Spaceport (CSG) for the fall-back (nominal and non-nominal) of stages and elements from launchers operated from the spaceport.

Definitions

Operational authority: The operational authority for orbital systems is the CNES Space Surveillance Service structure. This structure is familiar with the operational requirements for collision avoidance activities.

The operator must provide CNES Space Safety Office with a description of the organisation and facilities in place for creating and passing on the information required and up-to-date to define the warning notices (NOTAM and AVURNAV) relating to the space object.

1) Provision by the operator of data on calculated re-entry areas

The operator must provide CNES Space Safety Office with estimates (fragments and re-entry areas) when requesting authorisation for the space object. This data must be confirmed or possibly reassessed (for example, following a technical event during the space object's mission) at latest by the FSOA briefing before the controlled re-entry is initiated (and at least 1.5 months before the planned re-entry date).

The data supplied by the operator must indicate:

- The re-entry area defined by :
  a. The coordinates of the nominal fall-back point
  b. The coordinates of the 4 points of the quadrilateral encompassing the 99% confidence impact area
  c. The 99.999% confidence impact area

  The coordinates (longitude/latitude) will be provided in degrees and in the WGS84 reference system.
- The start and end times of the nominal fall-back of the items, indicated in Universal Time Coordinated (UTC), as well as the associated margins (including back-up slots).

- A complete list of the coordinates of the areas showing the fall-back ellipse in details for both probability levels.

This information must be sent to the operational authority (l-astreinte-ssa@cnes.fr) and to CNES Space Safety Office (bureaulos.systemesorbitaux@cnes.fr) upon each modification, until the end of the controlled re-entry and until the high-risk zones are cleared.

CNES Space Safety Office ensures that the data supplied by the operator is correct, with the support of CNES experts, and then checks that the re-entry operation complies with the Technical Regulation.

If the launch operator manages the publication of warning notices (NOTAMs and AVURNAVs) for which the description covers the re-entry of the space object, the operator must provide evidence of this to CNES Space Safety Office. In this case, CNES does not manage the publication of warning notices.

2) *A hazard area declaration note* is drawn up in English by the operational authority for use by the aviation and maritime authorities. The operational authority then ensures that NOTAMs/AVURNAVs are issued correctly.

3) The operator must cooperate with CNES Space Safety Office and send all useful information required to refine the re-entry area and impact time forecasts: relevant observables, actual duration and orientation of the last thrust and object PVT (Positions Velocities and Times) at the end of this thrust.

4) After confirmation that the event has taken place (based on the operator's scaled estimates or the means used to observe the event), the hazard zones can be cleared with a pro-forma clearance note describing the completion of the event and the clearance of the hazard zone. This note, like the previous ones, is issued and forwarded by the operational authority.

> ***Article 47: Non-nominal re-entries***
> *In the case of premature or accidental re-entry, the operator as a priority implements all measures such as to reduce the risk on the ground.*

The aim here is to make operators aware of the need to cooperate with space surveillance systems, for re-entries that could be considered at high-risk due to fragments falling back to earth.

Based on the criticality of this kind of non-nominal re-entry, a crisis unit may be set up by *the operational authority.*

The operator's contribution is at least:

- To inform the LOS office and the *operational authority* of the risk of premature re-entry as soon as possible,
- To provide the on-board status of the space object, ephemeris and manoeuvring plan if applicable,
- To estimate the re-entry area, potentially with the help of the *operational authority* and any experts it deems useful to involve.

4.9 CASE OF RE-ENTRY TO A SITE

Article 46-1: Controlled re-entry to a site

If a space object is performing a controlled re-entry to a French or foreign site designed for that purpose, said object shall be designed, produced and implemented such as to ensure compatibility with the systems and procedures of the landing site in question. It may only land on this site once authorised by the authorities responsible for the landing site.

If the object performing re-entry to a site has separated from a service module beforehand, the risks of any casualties caused by fall-back of fragments of this latter shall be less than 10^{-4}, including for the orbital composite in the event of non-separation.

For the object performing re-entry to the site, the operator shall demonstrate that the risk of casualties on the ground is less than $2x10^{-5}$.

For the return and landing phase, the operator shall identify the failure scenarios at the origin of abnormal situations leading the orbital vehicle to become a hazard, in particular in the following cases:

- *deviation from the predetermined re-entry corridor;*
- *dangerous fall-back and recovery phase for those elements designed to detach;*
- *non-nominal behaviour of landing flight control.*

The operator shall qualitatively and quantitatively deduce the need or not for on-board systems allowing neutralisation of the orbital vehicle before the moment at which the impact zone is, in full or in part, within a territory placed under the sovereignty of any State encountered along its nominal trajectory, including its territorial sea.

Definitions:

- *"Re-entry vehicle"*: vehicle that performs the final landing.
- *"Resource module(s)"*: the module(s) forming part of the orbital system performing the de-orbiting manoeuvre(s) but which are subsequently separated from the re-entry vehicle.
- *"Composite"*: the above vehicles, connected (orbital phase)
- Note: if there is no resource module, the composite must be understood as the re-entry vehicle.
- *MSA*: Monitoring, Safety and Alert.
- *MSI*: Monitoring Safety and Intervention (near field)

To calculate the risk of causing casualties on ground as a result of a failure during the de-orbiting phase of the composite, as well as during the atmospheric re-entry phase, this risk will be broken down as follows:

1. Consideration of a failure before or during the composite de-orbiting manoeuvre(s) resulting in a random re-entry;
2. Consideration of a failure during the last de-orbiting manoeuvre **of the composite** resulting in a direct but non-nominal re-entry;
3. Consideration, following a nominal or degraded de-orbiting sequence, of non-separation between the re-entry vehicle and its resource module(s) if applicable;
4. Consideration of the risk of casualty caused by the controlled re-entry of the resource module(s) (see §4.6.3) *if its resources are used following separation with the site re-entry vehicle.*
5. Consideration a failure during the atmospheric phase of the **re-entry vehicle** which would result in fall-back with possible explosion and/or fragmentation; Consideration of a possible release (shield) during or at the end of this phase. This phase corresponds to the MSA phase, during which the operator and/or the landing site safety authority have on-board and trajectory information on the vehicle.
6. Consideration of a failure during the MSI phase from which landing site safety is able to neutralise the **re-entry vehicle.**

The following flowchart only starts when the last de-orbiting manoeuvre is performed. For failures prior to this event, refer to the flowchart for controlled re-entry in the zone (see §4.6.3).

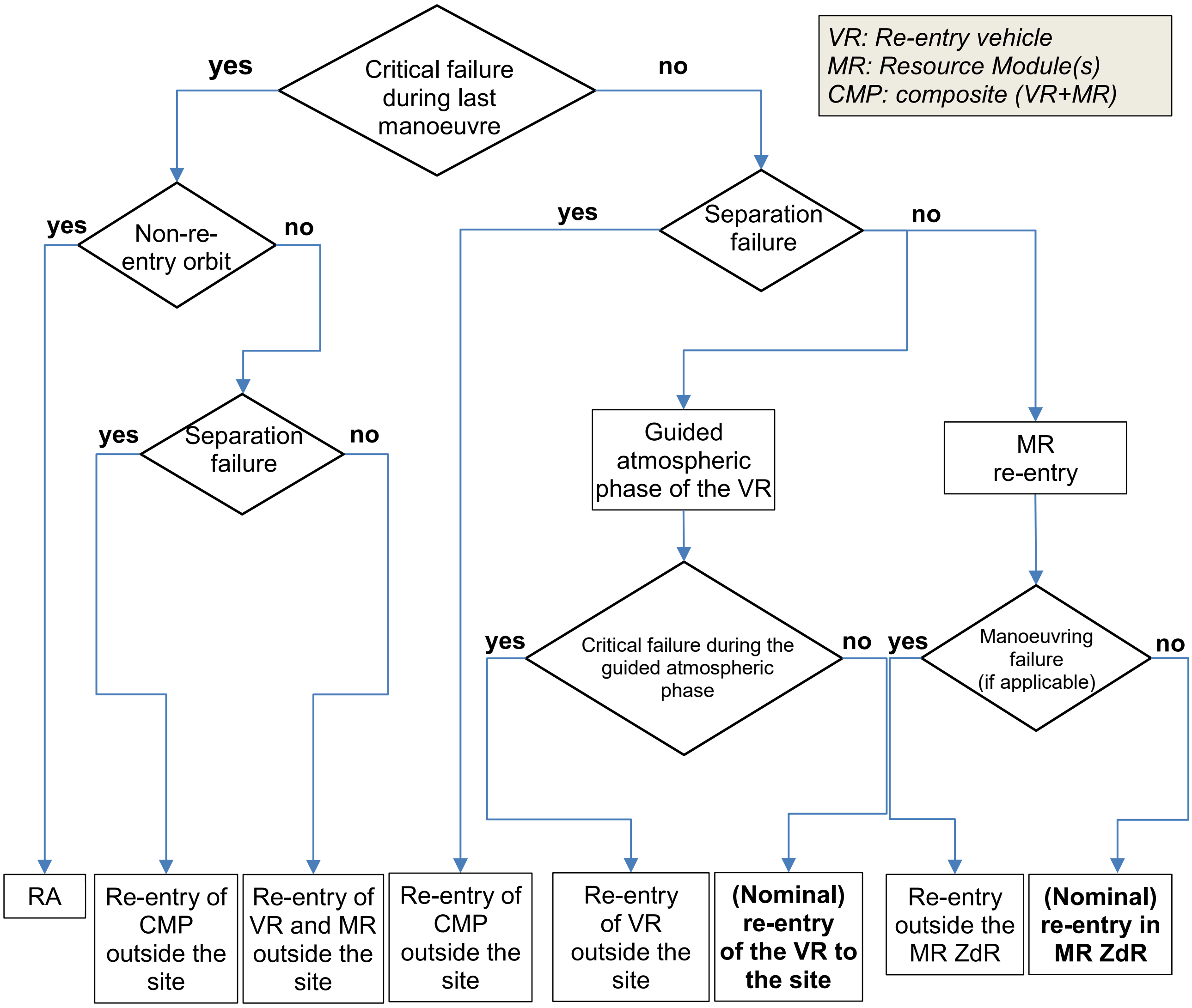


Figure 4-5: Flow chart showing the risk contributions of a re-entry method

Note: to date and at Europe's Spaceport, the near-field safety processes ensure that in the event of neutralisation, the fragments fall back into zones that are not dangerous for the site. Neutralisation must not result in fragments falling back onto land.

The re-entry area must be declared to the aviation and maritime authorities concerned by the on-site re-entry corridor, in accordance with the procedures described in §4.8 (declaring re-entry areas on Earth to the relevant authorities) of this guide.

Finally, and as per article 38-1 of the TR (inspection plan during on-orbit control, §3.7.2), the two key points below will be established:

- An 'ON-BOARD STATUS' milestone to assess the vehicle's ability (state of systems, redundancies, etc.) to carry out a controlled re-entry to a site following its orbital mission and to confirm the operational qualification of flight procedures and ground facilities.

- An 'OPS' milestone shortly before the final de-orbiting manoeuvre. The purpose of this milestone is to guarantee the availability of all the systems and facilities (on-board and ground) involved in the re-entry to a site, and also to confirm the collision 'clearance' with manned stations, in particular with regard to the slot selected for the re-entry to a site.

If an on-board neutralisation mean is required, it can be activated by a telecommand order or automatically via an on-board algorithm.

5 REDUCING AND TRACKING THE IMPACT ON THE EARTH ENVIRONMENT

Article 45: Requirements concerning uncontrolled re-entry of a space object foreseen at its end-of-life
The systems shall be designed, produced and implemented so that the elements which manage to reach the surface of the Earth entail no unacceptable risk for property, public health or the environment, in particular through pollution of the environment by hazardous substances.

5.1 FOOTPRINT

The description of each object likely to reach ground must include:

- An explicit name (for example, *Xenon tank*, or *primary mirror*) and the weight of the initial object (before re-entry).
- The post-ablation weight, derived from the re-entry and ablation calculation (calculation also requested), size and shape.
- The materials it is composed of, and likely to fall to the ground.

The propellant mass and tank pressure at launch and at the end of the operation will also be provided.

Materials containing substances of known toxicity (chemical, radiation, etc.) to humans and the environment must be explicitly declared. The technical data sheet for high-risk substances will be attached to the application file. These items must be identified as early as the satellite preliminary design phase.

5.2 ENVIRONMENTAL TOXICITY: METHOD AND CRITERIA

A method for assessing the environmental risks of satellite fall-back has been developed by CNES in conjunction with the French National Institute for Industrial Environment and Risks (INERIS). This makes it possible to provide quantitative criteria (dependent on the main properties of the fall-back fragments, i.e. material, mass and surface area) guaranteeing the absence of an unacceptable risk for humans and the Earth environment.

This method is not mandatory for the operator, who may use another methodology to assess the impact of incoming objects on the environment, provided that this method is recognised, relevant and justified.

The choice of method and its level of details can be adapted to suit the size of the satellite (a small satellite is likely to have less impact on the environment).

The various stages of the CNES/INERIS method are:

1. Inventory of substances:
   This stage consists of drawing up an exhaustive quantitative inventory of the substances contained in the fragments reaching ground (list of fragments with materials, mass and composition).

2. Estimate of the hazardous substances contained in the satellite and the potential for pollution:
   This stage involves assessing the unwanted effects that each substance may cause. Toxicological

reference values (VTRs) and Predicted No Effect Concentration (PNEC) values are calculated at this stage, or retrieved from databases (WHO, INERIS, etc.).

3. Selection of substances to be assessed:
   The substances will then be prioritized in order to decide which should be analysed in detail. To do this, the ratio "Mass of substance in the fragment/*VTR or PNEC*" will be calculated and ranked in descending order. The choice of substances selected must be justified if the operator proposes not to assess all the substances.

4. In-depth assessment of the hazards of so-called priority substances and assessment of the dose-response relationship of the substances emitted:
   During this stage, the VTRs and PNECs can be assessed in greater detail than in stage 2, using a number of methods set out in the documentation available upon request (in French only).

5. Exposure assessment:
   This stage involves assessing the concentrations of chemical substances in the various potentially contaminated receiving compartments (depending on the type of re-entry). Examples include air (atmosphere), soil, freshwater (lake, river), marine water (coastal zone and out at sea), sediments (freshwater or marine) and humans. Exposure levels (PEC) are calculated for each of the selected substances.

6. Risk characterisation:
   For each substance and each compartment, the "PEC/PNEC" ratio is calculated. If it is greater than 1, i.e. if the level of exposure is higher than the threshold for which an effect on the environment is expected, the substance is considered to be a cause for concern, in which case the assessment must be refined or the risk reduced (by reducing the quantities present in the satellite, for example).
   If the re-entry area is not known, an overall risk can be calculated, based on the distribution of environments on the surface of the globe. If the calculated overall risk is greater than 1, it is considered unacceptable for the environment.

The documents (in French) describing this method and enabling it to be implemented can be supplied by CNES Space Safety Office at the request of the operator subject to the FSOA. It includes details of the calculations, as well as PNEC and VTR values for certain substances.

6 SPECIFIC REQUIREMENTS

6.1 CYBERSECURITY

Article 39-3: Cybersecurity *The operator shall adopt a cybersecurity plan to ensure that no unauthorised or unauthenticated remote command that could compromise compliance with these regulations, can be received and executed by the on-board systems.*

All operators will at least have to take measures in terms of authentication and replay (the action of re-transmitting a signal identical to one already sent by ground), except for a non-manoeuvrable satellite that is already operating in a re-entry orbit that complies with article 41.9 and that is unlikely to generate debris in the absence of electrical passivation.

A cyber hygiene guide (see [RD8]) drawn up in collaboration with the CNES cybersecurity experts and operators involved in a cybersecurity approach (space and other) includes a series of recommendations applicable to any space project, covering the entire project approach.

6.2 RADIO EMISSIONS

Article 41-14: Radio electric emissions *The operator shall comply with the applicable radiofrequency regulations from its operational orbit and shall conduct in-flight coordination with the other operators to avoid all radio interference.*

To meet this requirement, the operator may, for example, demonstrate that it has obtained a frequency authorisation.

7 ON-ORBIT SERVICING

Warning: As on-orbit servicing is not yet fully mature, the requirements set out below will be refined over the coming years, particularly in light of these new practices. Many of the proposals below are nevertheless inspired by ATV experience.

A diagram showing the different phases of an on-orbit servicing vehicle's mission is included below (*inspired by ISO 24330 - Rendez-vous and Proximity Operations (RPO) and On-Orbit Servicing (OOS) programmatic principles and practices*). The relevant definitions are included in Article 1 - Definitions, of the Technical Regulation.

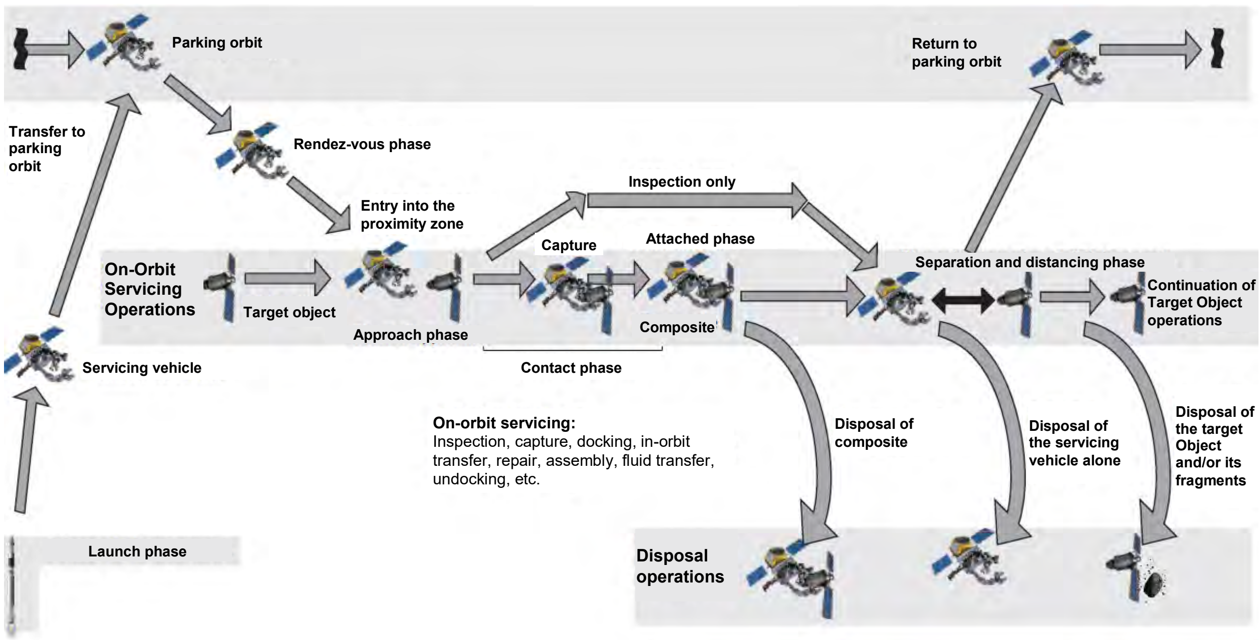


Figure 7-1: Different phases associated with on-orbit servicing

> ***Article 39-4: Case of an on-orbit service for a vehicle for which control has already been authorised***
> *An operator wishing to benefit from an on-orbit service shall ensure and demonstrate that the servicing vehicle complies with the specific requirements described in Chapter V.*

This article suggests that satellite operators wishing to benefit from on-orbit servicing should include the considerations associated with these activities and described in this chapter in its interface document with the operator of the selected servicing vehicle.

Note that On-Orbit Servicing performed for a satellite already authorised under the FSOA modifies the terms of the authorisation and must be covered by a dedicated declaration.

If the servicer is French (subject to the FSOA), a dedicated declaration will still have to be drawn up, but demonstration of compliance with Chapter V will not necessarily be required (as the servicer will in theory have applied for FSOA authorisation).

7.1 REQUIREMENTS FOR ALL PHASES

Recommendations on trajectory safety:

The approach and distancing strategies with respect to the target vehicle must be designed to constantly place (excluding the docking phase) the servicing vehicle in "passively safe" orbits. A passively safe orbit is such that any inability to manoeuvre does cause a risk of collision within a fixed period (typically 12hr, 24hr or 48hr). This period must be compatible with the ability to carry out additional safety operations, if necessary, on one or the other vehicle.

In addition, the approach and distancing strategies with respect to the target vehicle must be designed in such a way as to ensure that no sub-phase is initiated without having the assurance that the satellite is operating correctly (GO NOGO with possible interruption by ground).

These holding points (with GO NOGO) can be:

- fixed points in relation to the target: stable points without thrust, or forced holding points (maintained with continuous or almost-continuous thrust)
- forced translational motion (with continuous or almost-continuous thrust)
- drifting positions (excluding manoeuvres), for example in coelliptic orbits

These holding points (with GO/NOGO) must comply with the criterion of a passively safe orbit, regardless of when the loss of manoeuvring capability occurs.

For very critical missions, recommendations may be made for this criterion to be observed also during all manoeuvres carried out in the proximity zone. In this case, any propulsion failure during each manoeuvre must leave the vehicle in a passively safe orbit.

Article 47-1: Collection of debris created
If the on-orbit servicing operation entails compromising the integrity of the target object, the operator of the servicing vehicle shall collect the intentionally created debris of 1 mm or more along its largest dimension, in compliance with the other provisions of this chapter, so that it is not released into outer space.

In relation to Article 40 1. Intentional release of debris. The aim is not to release debris larger than 1 mm into outer space.

This refers only to debris intentionally generated as part of the operational concept of the service , and not to any debris that might be released in a non-nominal situation.

Note that the notion of environmental benefit (e.g. an ADR mission that de-orbits a large piece of debris but generates a few small pieces of MLI in flight has an obvious environmental benefit) has been studied but is difficult to specify and implement in the context of this regulation. These impacts must be assessed on a case-by-case basis.

The impact of potential detumbling of the target by the action of the servicer's thrusters on it should also be considered from this perspective.

Article 47-2: Survival and collision *The on-board systems of the servicing vehicle shall be designed and implemented such that triggering of survival mode by said servicing vehicle leads to no risk of collision with the target object.*

The use of passively safe trajectories makes it possible to meet this requirement during the rendez-vous and distant approach phases.

In order to make proximity phases safer, from collision risk perspective, some FDIRs that are not critical for this phase may be deactivated or their thresholds relaxed.

If the servicing vehicle still enters survival/safe mode, an active escape manoeuvre can be implemented to avoid collision with the target object.

Article 47-3: Compatibility of target object *The servicing vehicle shall demonstrate that its design and operational concept are compatible with the systems of the target object, or if the target object is space debris, with its condition.*

The mentioned compatibility applies to the composite approach and/or operations concept (in the flight dynamics meaning), as well as in terms of interfaces between the two objects, and by ensuring, for example, that the capture mechanism of the servicing vehicle is compatible with the mechanical loads that can be withstood by the target Object.

Furthermore, electrostatic and electromagnetic compatibilities between the two objects are not to be taken into account under this requirement as these are the subject of article 47-17.

Article 47-4: Mission impact on a third party *The on-orbit servicing operation shall be conducted without prejudice to or interference with the operations of third parties not involved in this operation.*

The aim here is to ensure sufficient communication and coordination with entities that have operational space objects in the vicinity of the servicing operation, so as to guarantee the safety of operations. Close approaches with active space objects other than the Target Object should also be minimised, as should any interference (electromagnetic, optical, radio frequency, etc.) with other space activities.

To meet this requirement, the operator must describe the operational strategy it intends to implement, during the preparation and execution of the servicing operation, to check for the absence or presence of third parties in the vicinity and ensure that there is no harm or interference to these third parties.

To this end, listing/describing the means aimed at ensuring the absence of third parties in a zone defined by the operator is recommended, in line with the servicing operation (e.g. volume/box defined in relation to the position of the servicer) and taking account of the orbital propagation of the various third party objects during a period covering the entire duration of the servicing operation, or the duration of each phase dependent on this prior check in its GO/NOGO criteria. Verification means can typically be provided by one (or more) external space surveillance systems (CSPoC, EUSST, private SSA providers, etc.) and supplemented by any on-board means (e.g. cameras, rangefinders, sensors, etc.).

However, if the presence of active space objects in the vicinity is nominally envisaged for performing the servicing operation, the operator must show either that its operation does not harm or interfere with these third-party objects, that these impacts are negligible, or that it has the agreement of the concerned third-party operators.

Finally, this operational strategy must enable compliance with article 41-6 by continuously guaranteeing that avoidance operations (in the event of a collision alert with a catalogued object) take priority over mission accomplishment.

7.2 PROXIMITY ZONE REQUIREMENTS

Article 47-5: Proximity zone volumes and corridors

In the proximity zone, the operator of the servicing vehicle shall define the volumes around the target object in which the servicing vehicle can move and those which it shall not enter.

The approach corridors in particular shall be defined by the servicing vehicle operator.

The systems of the servicing vehicle shall be designed, produced and implemented such that any deviation from these corridors in flight is continuously monitored and triggers a back-up solution enabling the servicing vehicle to be placed in a state or initiate movement which does not compromise the safety and integrity of the two objects.

For ground surveillance, this article requires that visibility be maintained at all times during this proximity phase. This requires a suitable network of stations, or even space relays (GEO satellite, for example). In addition, in the proximity zone, the servicing vehicle will be able to have autonomous and segregated (independent) on-board trajectory monitoring of the guidance, navigation and control chain, so that it can enable the implementation of suitable measures, particularly if it leaves its corridor.

For inspection without capturing the object, this exclusion volume could, for example, consist of a safety sphere centred on the target object, with a sufficiently large radius to be compatible with the implementation of collision avoidance measures in the event of breaching this volume.

Approach corridors must also be defined in such a way that a manoeuvre can be implemented in the event of a breach.

Article 47-6: GO/NOGO criteria

For the purposes of the approach phase and in order to initiate separation, the operator of the servicing vehicle shall define holding or passage points in the operational concept. For these points, the minimum required on-board and ground configurations (states) and the absolute and relative orbital configurations (position, speed, attitude, angular velocity) permitting the continuation or abortion of operations shall be defined in advance and for each object. These verification points are mandatory before entering the various volumes of the proximity zone.

The operator will be able to meet this requirement in its proximity mission analysis.

The concept of operations should specify the expected states (on-board and dynamics) for each object, agreed between the various control centres. It is desired that these configurations will be assessed and shared in flight between the operational centres and will lead to respective cross GOs for the continuation of operations.

Note that these Go/NoGos may be automated and do not necessarily require intervention from ground.

Article 47-7: Coordination of control centres

The control centres of the servicing vehicle and the target object shall be perfectly coordinated, with the *following principles:*

- *sharing of all the data and telemetry needed to ensure the safety of the operations;*
- *for each phase, identification of the control centre (servicing vehicle or target object) with the decision-making authority for the joint operations in the proximity zone, including during the attached phase, and the control centre which controls the composite in the attached phase.*

The above provision does not apply if the space object is a space debris.

The decision-making authority should be well defined so that there are no conflicting decisions when it comes to deciding, for example, whether to initiate an escape or emergency manoeuvre.

Handovers between control centres must therefore be clearly defined in the concept of operations. This operating principle is used in the ISS programme for visitor vehicles.

An exchange channel between the control centres of the servicing vehicle and the control centre of the target object could be set up to facilitate coordination.

Article 47-8: Vehicle/ground communications

Continuous vehicle/ground communications and surveillance shall be implemented in order to maximise the safety of the critical phases of the on-orbit servicing operations.

The contact phase, up to capture, the operations considered to be critical in the attached phase and the separation shall be performed with continuous telemetry/telecommand visibility.

In the proximity zone and during the approach and distancing phases, continuous telemetry/telecommand visibility is not required if an operational concept with sufficient autonomy in terms of operations safety can be demonstrated.

In order to meet this requirement, one can demonstrate that the critical phases have been designed so as to provide, in real time:

- An analysis of potential events or incidents,
- The possibility of taking emergency action (including via autonomous mechanisms for operations in the proximity zone and during the approach and distancing phases) if the safety of operations is threatened

Article 47-9: Secure on-board service communications

The on-board and ground systems of the servicing vehicle shall be designed, produced and implemented such that vehicle/ground and vehicle/vehicle communications are secure and therefore resilient to all corruption with the potential to compromise the safety of the operations.

The aim here is to avoid cybersecurity threats, as well as any interference (not necessarily malicious). Communications security requires compliance with the cybersecurity requirements of article 39-3 at the very least.

The actual need for this security is in the proximity zone or during the attached phase, but as, by design, the application is immediate to the other phases, the requirement is deliberately extended to all phases of the mission.

Article 47-10: Vicinity check
The operator of the servicing vehicle shall, for all operations performed in the proximity zone, ensure that only those objects taking part in the ongoing operation are in its vicinity in order to avoid any collision. The operational concept shall thus define the safety zone within which the presence of a third party shall be a reason for the ongoing operation not to be carried out or to be aborted.

The aim is to prevent critical operations from being carried out when a third party not involved in the operation is in the vicinity and could jeopardise its safety or that of the Servicing Vehicle and the Target Object.

The aim here is to obtain confirmation from the operator that it is able, using its own systems or those of a Space surveillance system (e.g. EUSST) with which it is working in close collaboration, to detect any intrusion into its vicinity by a third party, and to be able, if necessary, not to engage in the operation or to be able to implement an escape manoeuvre. The operator may refer to the good practices already indicated to satisfy article 47-4.

Article 47-11: Emergency avoidance capability
In the proximity zone, during the approach phase and after separation, the servicing vehicle's on-board systems shall be able to evaluate the risk of collision between the servicing vehicle and the target object in real time.

These systems shall be able to autonomously trigger an avoidance manoeuvre which should place the vehicles on relative trajectories ensuring no conjunction with the other for a time frame compatible with total control of the combined mission being restored, to guarantee the required level of safety.

During a Servicing operation, close approach may be desired due to proximity operations being carried out. This is therefore a different case from a conventional risk of collision.

A collision avoidance capability is thus a capability intrinsic to the concept of operations: an on-board CAM engaged based on state or dynamic criteria specific to the operation itself to avoid non-nominal contact that could be described as a collision.

Furthermore, a low-speed collision may not generate any debris, but may render one of the two objects inoperative, which would subsequently become debris.

The risk of collision between the two objects can be assessed using on-board equipment (e.g. cameras) to estimate relative positions and velocities. The estimate can also be made by an external space surveillance type system. However, in this case, the operational loop must be compatible with the implementation of an avoidance manoeuvre, and continuous visibility with the ground segment must be guaranteed.

Article 47-12: Good operating tests of the servicing vehicle

The operator of the servicing vehicle shall perform good operating tests on the equipment needed for the on-orbit service operations and their safety, except for non-reversible operations, at least before initiating the first servicing and in conditions which represent no danger for any other space object.

This article specifically refers to equipment that would not have been used in orbit for routine operations prior to the approach phase (including equipment required for an autonomous escape manoeuvre). It is then necessary to perform periodic health check of redundant equipment to guarantee its performance if needed. Pre-launch ground tests do not meet the requirement expressed in this article.

Article 47-13: Plume effect prevention

In the proximity zone, the servicing vehicle shall be designed, produced and implemented to avoid causing damage by contamination of the target object as a result of the jet effects from its propulsion system.

The above provision does not apply if the space object is space debris.

The design of the servicing vehicle, and the approach for selecting actuators in the proximity zone, must take account of the relative geometry between objects, and the design of the target object, to prevent propellant gases being discharged onto vulnerable items of the target object (star tracker, solar panels, docking connectors, etc.).

If the space object is debris (ADR-type mission), this requirement is not applicable, but it is still necessary to check, under article 47-1, that the plume effect of the servicing vehicle's thrusters does not damage the object in such a way that it generates debris then released into outer space.

7.3 APPROACH AND CONTACT PHASE REQUIREMENTS

> ***Article 47-14: Qualification of approach and docking concepts***
> *Any new approach, docking or undocking concept or technology for the servicing vehicle shall be qualified. Qualification shall include:*
>
> - *a ground demonstration in all cases;*
> - *if the ground demonstration cannot be shown to be representative of the hazards inherent in the operation, an in-flight demonstration by successful docking with a target object in an orbit below 600 km, above region B, or between regions A and B.*

This requirement applies not only to a capture operation, but also to any approach operation.

Qualification of the approach and docking concepts and technologies is achieved by a first production servicing vehicle carrying out this demonstration in a dedicated orbit. For a new vehicle in the same series, this requirement may not be applied, but only if there is no change in the concepts and technologies in question. In the event of a change, the absence of a dedicated in-orbit test must be justified.

The specific orbit in which this flight demonstration is carried out must meet the following criteria:

- in the LEO zone, a sufficient safety distance (in terms of altitude) from manned stations (typically 50 km) and from areas with a high density of satellites (constellations), typically 20 km.
- in the GEO graveyard zone, above zone B, in an orbit that complies with the criteria linked to the GEO satellite end-of-life requirement, *so a little higher than zone B.*

If the decision is made not to carry out an in-orbit demonstration, the operator must provide evidence of the representativeness of its ground qualification, such as: the use of Monte Carlo simulations, in-depth tests on the sensors used for approach and docking, GNC performance simulation, ground facilities of sufficient quality (simulator with a high level of representativeness, tests involving the satellite platform), etc.

If representativeness of the test vehicle is only partial, the file must specify the limitations of the demonstration coverage and the measures taken (additional in-flight tests) to ensure correct operation during the first operational mission.

> ***Article 47-15: Inspection before docking***
> *Any docking with a target object shall be subject to prior in-flight inspection of said target object and, if possible, of the servicing vehicle, in order to check that no interference – mechanical in particular – could lead to failure of docking, or disrupt relative navigation. The servicing vehicle shall remain at a holding or parking point until such time as the evaluation of the inspection allows the operation to continue.*

Note that a visual inspection (camera) fully meets this requirement. When carrying out this operation, it is important to ensure that no object interferes with docking or corrupts the measurements of the approach sensors, or to ensure, when the target object is a space debris, that its rotation speeds are as expected and compatible with the operations of the servicing vehicle.

Article 47-16: Performance for approach phase safety.
The systems of the servicing vehicle shall be designed, produced and implemented to guarantee, in the approach phase, a probability of violation of the flight corridors defined in the approach and docking operational concepts, and thus a risk of collision between the 2 vehicles, of less than 1% per approach, and less than 5% over the entire orbital lifetime of the servicing vehicle.

A probabilistic approach is favoured over a Fail-Operational/Fail-Safe approach, which could over-limit the on-board design.

Any servicing operation planned at the time the request is submitted will be taken into account to meet this requirement. Any servicing operation not planned for at the time of the request, and which will therefore have to be the subject to a dedicated declaration, must update this estimate, taking account of past and future servicing operations.

For example, Monte Carlo simulations can be performed to ensure, with a sufficient level of confidence, that flight corridors are not breached. However, potential failures of relative navigation systems and/or emergency avoidance measures should also be considered, in addition to the handling of nominal cases.

Article 47-17: Electrostatic and electromagnetic compatibility at contact
The servicing vehicle shall be designed and produced with the necessary protections, so that during the contact phase, it cannot create any ESD (electrostatic discharge) and EMC (electromagnetic compatibility) damage.

The design of the servicing vehicle must address the issue of managing the risk of any electrostatic or electromagnetic damage to any target object.

High resistance (of several kΩ) in the interface between the capture system and the body of the servicing vehicle may help meet the requirement related to ESD-induced damage.

7.4 ATTACHED PHASE REQUIREMENTS

Article 47-18: Control of the composite in the attached phase
It must be possible to attitude and orbit control the composite in particular in order to retain collision avoidance capability.

For a joint operation between two distinct entities, the entity in charge of controlling the composite shall be identified.

This entity shall be in charge of collision avoidance manoeuvres, as necessary. It shall take all necessary steps to ensure compliance with the provisions required in sub-section 3 of Chapter III of Section II of Part three of this Order.

To comply with this article, it will be necessary to define, for each situation in the attached phase, which object/vehicle is the master and which is the slave, and to ensure that one of the two objects is capable of controlling the composite in terms of performing collision avoidance manoeuvres in compliance with the other provisions of this regulation.

7.5 SEPARATION AND DISTANCING PHASE REQUIREMENTS

Article 47-19: Separation reliability *The calculated probability of successful nominal separation and distancing from the servicing vehicle outside the proximity zone shall be evaluated and maximized.*

This requirement applies not only to separation, but also to any distancing operation in the proximity zone, whether or not contact has been made with the target object.

To calculate this probability, inspiration may be drawn from the methods used to calculate the reliability of space object disposal (see paragraph 3.10), as well as from the use of Monte-Carlo simulations to ensure that the planned trajectories permit risk-free distancing from the proximity zone.

Article 47-20: Integrity of target object at separation *The systems of the servicing vehicle shall be designed, produced and implemented such that, at separation of the composite, the servicing vehicle does not definitively degrade the vital functional capabilities of the target object, in particular its attitude control and disposability.* *The above provision does not apply if the space object is space debris.*

The operator must identify all risks associated with separation that could damage the Target Object, and demonstrate that they have been taken into account in the design and concept of operations of the Servicing Vehicle, and are managed via suitable risk reduction measures.

Article 47-21: Separation dynamics *The systems of the servicing vehicle and of the target object shall be designed, produced and implemented such that separation enables the two objects to move apart along a trajectory where any drift creates no risk of collision between them over a time frame compatible with implementation of a collision avoidance manoeuvre.*

8 CONSTELLATIONS

Definitions

- **Constellation**: Group of space objects consisting of at least 10 operational space objects working together for a common mission, with a predefined orbital deployment plan.
- **Satellite train**: several satellites in the same orbit but with staggered PSOs (by a few seconds or a few minutes.). Example *A Train, etc*.
  A train of 10 or more satellites belonging to the same operator is considered a constellation.
- **Megaconstellation**: Constellation containing at least 100 space objects.

Note: each satellite in a constellation must comply with the requirements of the applicable TR and the associated recommendations and practices set out in the other chapters of this guide.

8.1 REQUIREMENTS APPLICABLE TO ANY CONSTELLATION

Article 48-1: Probability of disposal of the satellites of a constellation
Each satellite in a constellation shall have a probability of success of the disposal operations (including the passivation operations and the disposal manoeuvres) with the following rule:

- *constellation in which the number (N) of satellites is less than 50: P > 0.9 + N x 0.001;*
- *constellation in which the number (N) of satellites is greater than or equal to 50: P > 0.95.*

Where N is the number of satellites in the constellation, N greater than or equal to 10.

This requirement has been introduced to take account of the scale factor associated with the constellations.

The number N of satellites is taken to be the maximum number of satellites in the constellation (including spare satellites).

Regarding calculation of the probability of successful disposal, reference may be made, as for a single satellite, to the methods described in paragraph 3.10.

Article 48-3: Incorporation of experience feedback
All experience feedback resulting from the in-flight failure of a satellite belonging to a constellation undergoing deployment and, more generally, from any incident or technical event affecting the conditions of the space operation as authorised, shall be taken into account for the launch of the subsequent satellites.

Following an in-flight anomaly on the first satellite(s) deployed, the operator must demonstrate that there is no impact on the launch of subsequent satellites (constellation deployment plan) or take corrective measures so that the initial authorisation file is not called into question.

Article 48-4: Intra-constellation collision after disposal
Satellites in the same constellation shall be decommissioned such as to guarantee a risk of intra-constellation collision of less than 10^{-3} until their atmospheric re-entry, or for 100 years in the graveyard region approved for constellations located outside region A.

This threshold of 1×10^{-3} needs to be consolidated via simulations using a suitable tool, on a debris population consisting solely of the population of satellites disposed from the constellation. The calculation will be based on the total number of satellites disposed.

To comply with this article, the operator must present an analysis setting out the disposal strategy implemented to limit the risks of intra-constellation collision after disposal.

For the disposal *of a single satellite* (which would be replaced in the constellation), the safest way to manage the risk of intra-constellation collision is to lower the apogee of the satellite's orbit at EOL to be below the perigee of the operational orbit. The operator will ensure that this configuration is valid for the osculating values, regardless of the disturbances withstood over the orbital duration after disposal, i.e. a maximum of 25 years in zone A and a maximum of 100 years in zone B.

In the short term, this guarantees that there will be no crossover, and in the long term, the lower orbit should descend faster, so the gap will increase.

If the constellation is small (a few dozen satellites) and that disposal involves removing all the satellites, a stacked approach applying the above principle should enable the requirement to be fully met.

Article 48-8: Separation of intra-constellation planes
The geometry of a constellation shall be defined such as to ensure sufficient separation between the satellites of this constellation with the aim of guaranteeing robustness to the collision risk.

This separation will be carried out preferentially in altitude (a few km) with respect to relative orbital nodes or with comfortable margins (a few dozen seconds) for phasing, in order to manage the risk of collision between satellites in different orbital planes.

The operator will explain its strategy, for example in the constellation positioning mission analysis, and must demonstrate that the separation selected can withstand contingencies, in particular the loss of control of a satellite.

8.2 REQUIREMENTS SPECIFIC TO MEGACONSTELLATIONS

> ***Article 48-2: Probability of causing casualties on the ground***
> *The quantitative safety objective including all returns to Earth by the satellites of a mega-constellation, expressed as a maximum allowable probability of causing at least one casualty (collective risk), is 10^{-2}.*

To address this article, reference may be made to chapter 4.

To comply with the 1×10^{-2} requirement, the sum of the individual contributions of each satellite in the constellation launched during its deployment will be considered, as well as the identified spares.

> ***Article 48-5: Collision avoidance capability for mega-constellations***
> *Each satellite in a mega-constellation shall have an on-board propulsion system so that it is able to perform effective collision avoidance manoeuvres in due time, up until the end of its disposal.*

The objective here is to be able to guarantee the management of collision risks within the constellation itself but also with any objects external to it. The operator may refer to the information presented in paragraphs 3.5 and 3.6.

> ***Article 48-6: Vital system tests before reaching operational orbit for mega-constellations***
> *Before a satellite of a mega-constellation reaches its operational orbit, good health checks shall be run, from an intermediate orbit, on the subsystems of its platform needed for disposal.*
>
> *For satellites operating in region A, this intermediate orbit shall allow natural re-entry in less than 5 years and shall have an apogee below the perigee of the operational orbit.*

This requirement, which could apply to any satellite, is all the more justified for a megaconstellation, since the same operator deploys a large number of satellites over the same orbital zone (generally at the same altitude, potentially with staggered planes) and this measure prevents leaving ded-on-arrival satellites (hence debris) in an operational orbit. This requirement is complementary to the disposal reliability requirement: the regulator is reassured not by an estimated figure but by an in-orbit test.

After injection, the equipment (nominal and redundant) required for disposal must at least be checked.

Note that the re-entry duration from this intermediate orbit can be calculated by taking account of the panels deployed.

Article 48-7: Maximum duration of disposal for the satellites of a mega-constellation
For each satellite of a mega-constellation operating in region A, the maximum presence in orbit after disposal shall be limited to:

- *5 years for mega-constellations in which the total number of satellites is less than 1,000;*
- *2 years for mega-constellations in which the total number of satellites is greater than or equal to 1,000.*

For further details, please refer to the STELA user guide in [RD5], as well as to the use of the STELA tool (§10.1).

Article 48-9: Separation between mega-constellations
The geometry of a mega-constellation shall not intercept the geometry of another mega-constellation already in orbit, guaranteeing adequate radial separation, up until the beginning of disposal of the mega-constellation.

If it is not possible, and duly justified, to guarantee adequate radial separation, the operator shall demonstrate robustness with regard to the risk of collision between its satellites and those of the other mega-constellation.

<u>Definition of radial separation</u> (proposed by ISO 6434 - Design, Testing and operation of a spacecraft large constellation): Radial separation is defined as the distance between constellation orbits in the radial direction within a common latitude range, irrespective of right ascension of ascending node and timing (nodal regression and in-track motion).

A radial separation of 25 km between the constellations geometries is an acceptable order of magnitude to limit the risk of collision between the two constellations.

If radial separation is impossible, the operator must justify its choice of orbit and demonstrate the robustness of its choices with regard to the risk of collision between the satellites of the two megaconstellations, considering both nominal and degraded operation.

Article 48-10: Limitation of optical disruptions by the satellites of a mega-constellation.
Each satellite of a mega-constellation shall be designed, produced and implemented with the objective of attaining an apparent magnitude of 7 or more in order to minimize optical disruptions for astronomical observations from the ground or space.

The sheer number of satellites that make up a megaconstellation can have a major impact on optical astronomical observations.

The operator must quantify the optical impact (light pollution) of each of the satellites in the megaconstellation for an observer on the ground.

Apparent magnitude: measurement of the brightness of a celestial object at a given distance. It is relative to a reference object of "zero magnitude" (historically the Vega star).

$$m - m_{réf} = -2.5\,log_{10}\left(\frac{E}{E_{réf}}\right)$$

where E: illuminance (W/m2)

Note that objects with an apparent magnitude of 6 or less are visible to the naked eye.

As there is currently no standardised method for estimating the illuminance of a satellite, the operator may select or develop the method best suited to its situation.

It will justify the relevance of the method used by setting out the assumptions made and the steps resulting in the final result of the apparent magnitude calculation. It will also describe, if necessary, the measures taken to minimise the reflectivity of its satellites and therefore the optical disturbances caused for an observer on the ground.

These measures can be design measures and/or operational measures. Examples include, but are not limited to: application of light-absorbing materials (e.g. dark reflectivity-limiting paint), use of physical barriers to block sunlight on reflective surfaces, management of the orientation of the satellite and/or solar panels to minimise reflection back to Earth (including specular diffusion towards astronomical observatories), etc.

9 MISSION EXTENSION

Article 49-1: Conditions for mission extension
If extension of the mission beyond the initially authorised duration is intended, the operator shall demonstrate that such mission extension does not compromise compliance with the operational provisions of the third part of this Order.

In addition, with respect to the hazard study, the feared events specific to the mission extension shall be identified and managed.

The contribution of a servicing vehicle intervening during this mission extension shall be evaluated with regard to the provisions of this Order.

Some operators wish to extend the operational life of their satellite beyond the period granted by the authorisation order. A formal request must be made to the French Ministry in charge of Space, which will then be able to make its decision, based in particular on CNES's opinion, on the technical aspects of the request.

The purpose of this paragraph is to help operators draw up the technical file accompanying the request, which must show that the proposed extension does not jeopardise compliance with the applicable Technical Regulation.

9.1 REQUIREMENTS TO BE RE-ASSESSED AS PART OF A MISSION EXTENSION

This section provides details on the requirements that should, at the very least, be reassessed in the context of a mission extension. The considerations presented in this guide may be used, as well as the additional information provided by the table below.

Generally speaking, if the mission extension results in one or more changes to the nominal strategy as defined in the initial request file, the operator must declare these changes along with the extension request and demonstrate compliance with the associated articles.

The documents requested at the time of the initial request, under the composition order (see [DA3]), must, if necessary, be updated and resubmitted at the time of the extension request (such as the compliance notice, hazard study, etc.).

Article	RT article title	Re-assessment requested
Chapter II: Quality system requirements		
35-1	Quality and management system	The operator must provide details of any changes to the system declared at the time of the initial authorisation.
35-2	Expertise, means and organisation	

Article	RT article title	Re-assessment requested
38	Co-contractors and subcontractors	
35-3	Conservation undertaking	It will simply be necessary to reformulate the undertaking made when the initial request was submitted
36	Technical and organisational events	
37	Technical reviews	
38-1	Inspection plan during on-orbit control	
Chapter III, Section 1: Requirements related to the performance of operations		
39	Ability to control the space object	It is essential to re-demonstrate the capability of controlling the object if there is a mission extension request. The operator must confirm that all ground and organisational means will be kept in order to continue satellite operations for the whole duration of the extension. This means that the ground systems are still functional and available, and that there is a correct number of operational personnel qualified for the operations. In this context, the operator will be able to: • rely on the state of the platform's equipment (see section 9.2), • possibly reinforce on-board and ground surveillance. Good practice requires suitable basic surveillance to avoid any risk of being unable to carry out disposal operations. (See section 9.3.2). If the satellite report shows any specific damage or failures, the operator will be able to strengthen the operational precautions already in place. This may involve trend analysis, establishing thresholds or warnings, etc. • establish an analysis of the risk of not being able to carry out the disposal (see section 9.3.2)
39-2	Propellant management	For manoeuvrable satellites, the operator will present an updated estimation of the propellant budget (see §3.9), enabling it to guarantee the propellant required at the time of the new planned disposal date. Note that this Good Practice Guide is not intended to specify a calculation method for re-estimating the propellant budget, which is left to the operator's discretion.
39-3	Cybersecurity	Any changes to the cybersecurity system declared at the time of the initial authorisation must be described.

Article	RT article title	Re-assessment requested
Chapter III, Section 2: Prevention of fragmentation		
40	2. Accidental break-up	It should be demonstrated that the high-risk items identified initially are still qualified during the extension so that the considerations included in the initial file are still valid. If this is not the case, a low risk of disintegration will need to be proven.
40-1	Intentional destruction	It will simply be necessary to reformulate the undertaking made when the initial request was submitted
Chapter III, Section 3: Prevention of collisions		
41	Prevention of the risks of collision with manned objects	If the new flight envelope for the duration of the extension involves crossing the orbits of manned objects, details must be provided of the measures taken to limit the risk of collision with these objects.
41-3	Probability of collision with a space object	The cumulative risk must be re-assessed, taking account of the initial lifetime and the mission extension, including the updated orbital population.
41-5	Coordination in the event of a collision alert between two operators controlling manoeuvring space objects	The operator can simply reformulate the coordination undertaking made when the initial file was submitted.
41-6	Trigger threshold for collision avoidance manoeuvres	If the probability of collision threshold is modified in relation to the initial request, the new threshold must be provided and justified.
Chapter III, Section 4: Prevention of saturation of orbits		
41-12	Reliability of disposal operations	Details on the reliability reassessment are given in section 9.2.
41-14	Radio electric emissions	It will simply be necessary to reformulate the undertaking made when the initial request was submitted
Chapter IV: Specific technical requirements for the return of a space object		
44	Quantitative objectives for human safety for return to Earth of a space object's	For assisted natural re-entry (ANR) or controlled re-entry (RC), the risk on ground could be increased by a degradation in the reliability of the equipment involved in these operations during the mission extension. In this case, compliance with this requirement should be re-demonstrated.
46	Prevention of risks arising from fall-back of the space object or fragments thereof during a controlled re-entry.	The potential impact on populations must be reassessed under articles 46.2 and 46.3.

Article	RT article title	Re-assessment requested
46-1	Controlled re-entry to a site	The probability of causing a casualty is certainly dependent on the reliability of the systems implemented, and must be re-demonstrated.
Chapter V: Specific technical requirements for On-orbit servicing *Note: most of the requirements relating to On-Orbit Servicing are not specific to a mission extension, but they will need to be re-demonstrated via a Technical Event in the event of a new concept of operations compared with the one(s) described in the initial request file.*		
47-16	Performance for approach phase safety	Details on the reliability reassessment are given in section 9.2.
47-19	Separation reliability	
Chapter VI: Technical requirements specific to Constellations		
48-1	Probability of disposal of the satellites of a constellation	Details on the reliability reassessment are given in section 9.2.
48-2	Probability of causing casualties on the ground	For assisted natural re-entry (ANR) or controlled re-entry (RC), the risk on ground could be increased by a degradation in the reliability of the equipment involved in these operations during the mission extension. In this case, compliance with this requirement should be re-demonstrated.
48-9	Separation between megaconstellations	If robustness with regard to the risk of collision initially demonstrated is jeopardised based on new adjacent megaconstellations, compliance with this requirement should be reconsidered.

Table 5: Requirements to be re-assessed as part of a mission extension

9.2 RE-ESTIMATION OF IN-FLIGHT RELIABILITY

The most relevant criteria for guaranteeing successful disposal are:

- Re-estimated calculation of the probability of successful disposal (a potential extension of the qualification could be carried out on equipment requiring it).

- **Health report and fault prediction:** Using the telemetry provided by the satellite to monitor and track the performance and behaviour of a number of items of equipment, and assessing future changes to performance/margins.

The health report is a qualitative criterion, which objective is to use the telemetry provided by the satellite to monitor and track the performance and behaviour of a number of items of equipment, particularly those on the platform required for end-of-life operations.

To this end, weekly, annual or multi-year reports can be produced as part of the in-orbit support activities, providing indicators and criteria for assessing and justifying the possibility of continuing the mission, or even extending its duration.

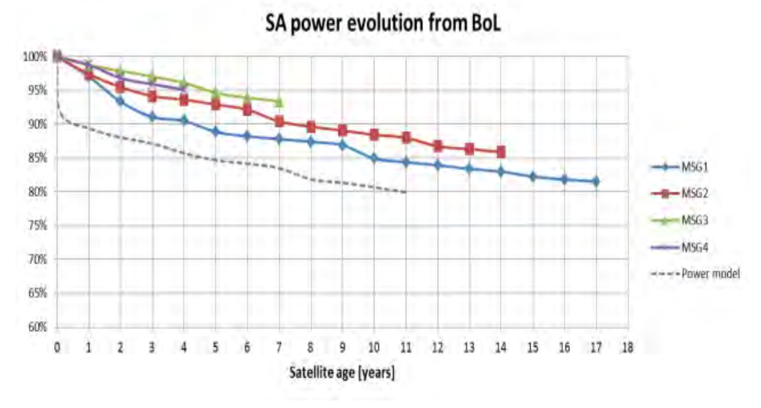
Where possible, the operator should use an analysis to assess the residual margins of the equipment (cycling/cumulative durations/radiation, etc.) in relation to its design. This is done by referring to the system design and justification files, which must always be available for the operator. A life extension may then be granted, even if the qualification margin for certain equipment has been dipped into.

In fact, as long as there are positive margins and performance is within the norm, it is reasonable to consider that the mission can continue. On the other hand, in the event of degraded health of one or more items of equipment required for end-of-life operations, it would be riskier to continue the mission.

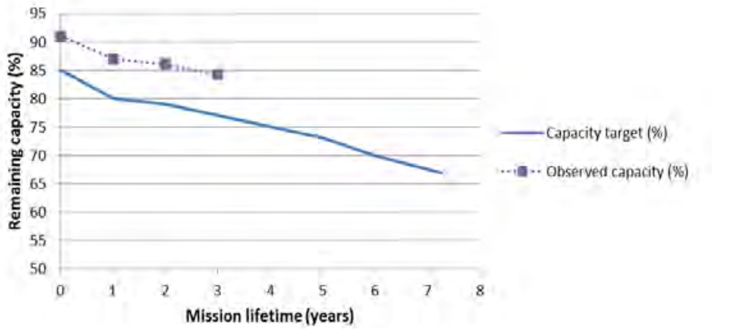
It is also necessary, first of all, to identify the degradation phenomena, determine their causes and influencing factors, and determine the observables enabling to monitor changes over time. It is then possible to compare the current state with that required for end-of-life operations.

The most common observables and criteria include the remaining propellant and power budgets. In the first case, different methodologies can be used to estimate propellant consumption and therefore the remaining mass, which can then be compared with the requirements for mission continuation (e.g. station-keeping, collision avoidance, end-of-life manoeuvres, etc.). In the second case, one need to determine whether the power available on board, generated by the solar panels or supplied by the batteries, is still sufficient to power the equipment needed to continue the mission.

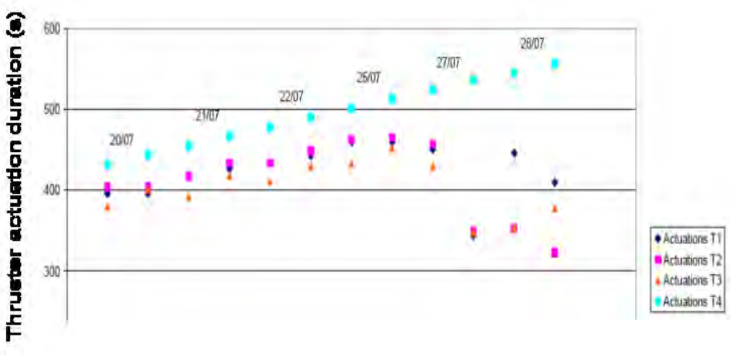
In addition to this, other observables, whether direct or derived, can/must be used to make end-of-life decisions. Some examples are given below:



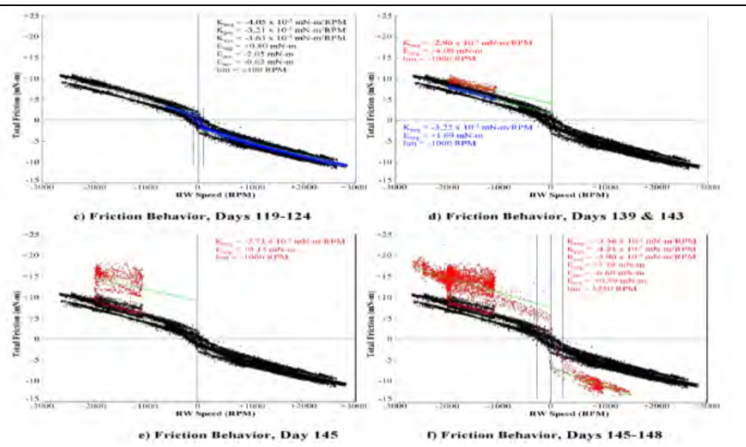
This figure shows the change in the power generated by the solar panels of 4 GEO satellites from the same family based on their age. It shows that the degradation in relation to the power available at the start of life is much lower than that estimated before launch (grey dotted curve). These satellites are therefore performing better than expected, which gives good confidence for the rest of the mission, as the necessary power will still be available.



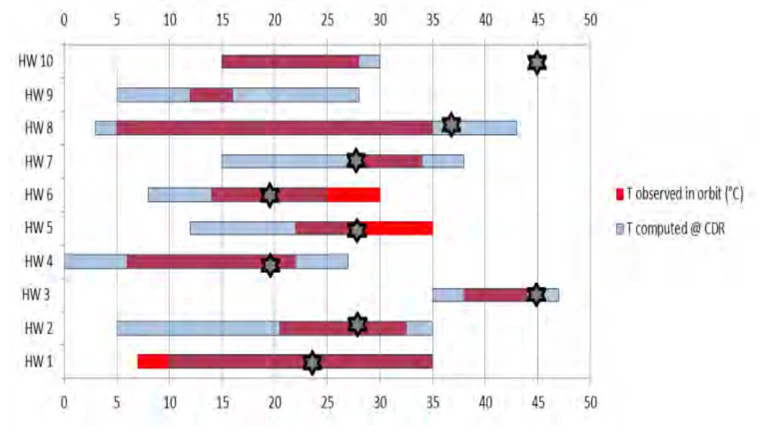
This figure shows the change in the remaining capacity of a battery observed during the initial years of this mission, compared with the actual need (blue curve). In this case too, there are positive margins that go even further than initially envisaged.



This figure shows that some chemical thrusters are becoming degraded, forcing others to be used longer. This phenomenon must therefore be taken into account, not only in the propellant budget, which may be impacted (e.g. overconsumption), but also in the reliability model.



This example shows how telemetry from a reaction wheel revealed a non-nominal increase in friction torque. This was later associated with an early warning sign of a failure. This can result in reconfiguration of the satellite or early end of life if the phenomenon affects all the equipment.



This figure compares the temperature range actually observed for certain electronic equipment on a satellite with that estimated during the design phase. The actual maximum temperatures are often lower, with a limited number of exceptions. It is also important to note that the mean temperature used in the reliability model (star) is sometimes too pessimistic.

The health report therefore provides criteria and indicators that are essential for making the right decision about whether or not to continue/extend the life of a satellite.

Failure prediction analysis allows to go even further in estimating positive margins. The aim is to assess future performance/margin changes.

This analysis thus provides additional elements for better decision-making on continuation of the mission, as it enables the remaining lifetime of the equipment to be estimated (RUL: Remaining Useful Lifetime) once a threshold is crossed, as illustrated in the following figure:

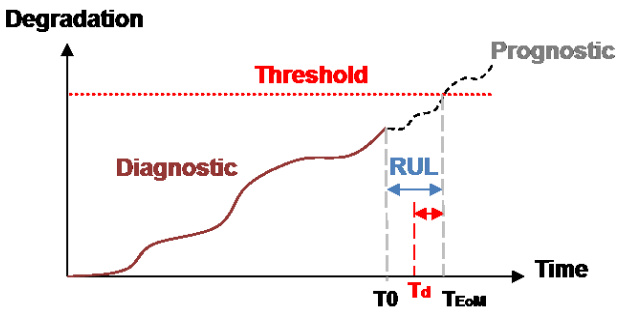


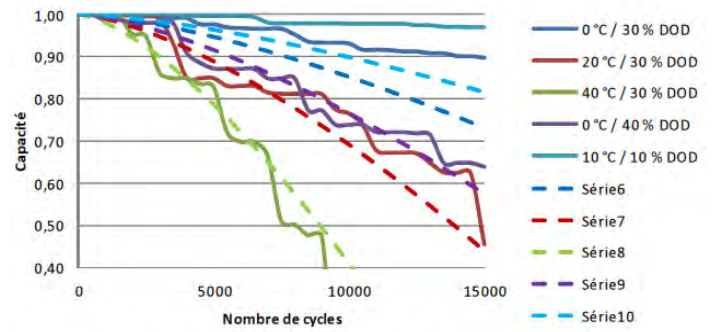
Figure 9-1: Remaining lifetime of equipment and associated threshold

In addition, by ascertaining the time required to carry out end-of-life operations, knowing the RUL enables us to decide when they should be started (Tdisposal) to ensure success before the satellite's end-of-life (TEoM).

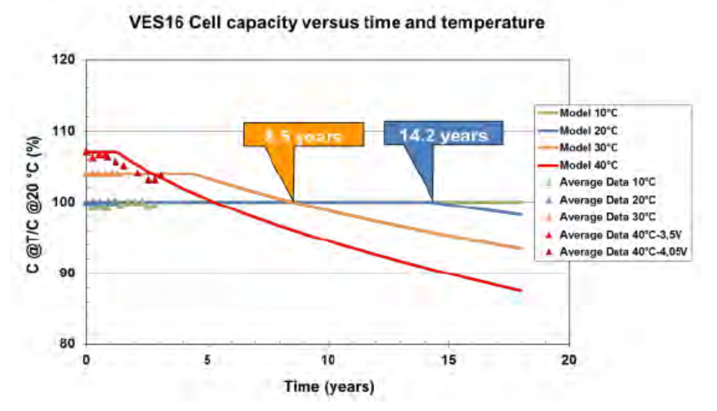
There are various approaches to this method, which can be based on:

- mathematical models
- engineering models/tools
- or data analysis (Machine Learning or Artificial Intelligence)

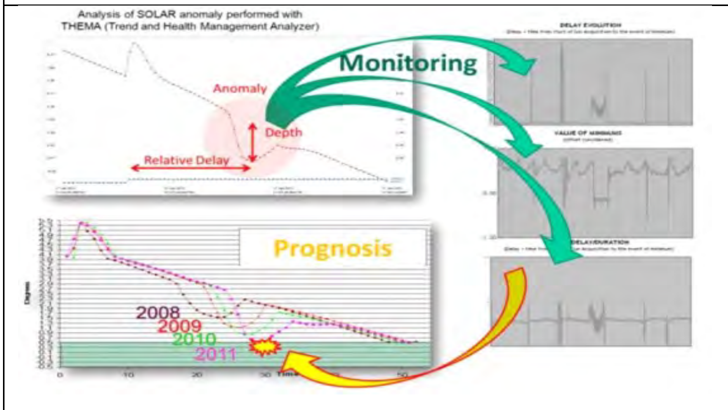
Each method has its advantages and disadvantages. Examples are given below for each of these three types of failure prediction:



In this example, taken from the literature and based on simulated rather than actual data, a Gamma process was used to determine the future degradation of batteries in terms of loss of capacity based on their operating conditions. This was then used to link it to the probability of having enough power to continue the mission.



In this example of a prediction based on engineering models, an electrochemical model, developed by a battery manufacturer and validated using test and orbit data, was used to monitor the current performance of a mission and, more importantly, to estimate future performance based on actual operating conditions.



In this example of a prediction based on data and in particular on Machine Learning methods, it was possible to monitor the degradation of this equipment and, above all, to predict the failure occurrence date (or at least when the equipment could no longer provide the functions necessary to continue its mission).

Although more complex, failure prediction is the most reliable and relevant approach for proving a satellite's ability to continue its mission, including end-of-life operations. Although not always perfect, estimating the remaining lifetime gives greater confidence as regards the possibility of extending the mission, especially when compared with the approaches described in the previous paragraphs. In addition, this information can be taken into consideration in the reliability models, which also enable a more realistic probability calculation to be made, so that decisions can be made at the end of the mission by assessing compliance with one or more quantitative criteria.

In addition, these results can also be used for reliability calculations and therefore for quantitative criteria.

This is because:

- depending on the change to the margins identified in the analysis, updated redundancy diagrams must be considered in the reliability model (e.g. the loss of more solar generator strings may be accepted with respect to the initial assumptions if a greater power margin than expected is available).
- in the event of operating conditions that differ from those estimated prior to launch (e.g. lower operating temperature, lower number of ON/OFFs or cycles, shorter operating time, etc.), equipment failure rates and/or utilisation rates must be reconsidered.

9.3 RISK ANALYSIS

Feared events specific to mission extension must be identified and managed. A few examples of risks are presented below, although they are not intended to be exhaustive.

9.3.1 Risks associated with using on-orbit servicing

The operator will ensure that any On-Orbit Servicing operation carried out with the aim of extending the mission duration of a Target Object will not pose an increased risk to the space environment (in particular will not compromise the object's ability to be disposed, nor pose a risk of increased accidental disintegration due, for example, to a tank filling leading to an excessively high operational pressure) or an increased risk of causing a casualty on ground in the event of a planned atmospheric re-entry at the end of the orbital life.

9.3.2 Risk of not being able to carry out the disposal as planned in the initial file

The experience gained in operating satellites of the CNES fleet has led to the systematic availability, as soon as the initial authorisation request is made, of a note on the *analysis of urgent end-of-life situations*. This note provides a basis for the operator to report on the robustness of the satellite PF in the event of a failure. This type of document must be created (if it does not already exist) when applying for an extension, as this is one of the bases on which the operator will be able to demonstrate that the risk of not being able to carry out disposal operations (as provided for in the initial file) is controlled.

The 'consumption' of redundancies during the nominal mission is a very relevant piece of information to include in the extension request, since, in the event of failure of a redundant item of equipment, switching to a redundancy enables to keep the disposal capability.

More generally, the robustness of the various sub-systems (AOCS, Propulsion, etc.) as regards a (new) failure will be reviewed at the time of the extension request.

Note that this robustness does not depend solely on redundancies, but also on any countermeasures that might be put in place to make up for on-board equipment failure. For example, attitude control equipment may fail, but the satellite could do without it by establishing new AOCS modes that do not make use of the equipment initially identified as necessary.

9.3.3 Risk of leaving the satellite in its operational orbit

The risk of leaving the satellite in its operational orbit will also have to be assessed:

- Given the condition and design of the PF: remaining propellant and pressure in the tanks, risks of generating debris outside the satellite casing if the batteries are overcharged or overheated.
- Given the satellite's operational orbit. Particularly if it is already in a re-entry orbit compatible with the FSOA TR requirements.

The need is to assure the regulator that there is no risk of the satellite exploding, *given its condition at the time of the extension request.*

9.3.4 Risk of generating debris due to collision

Finally, the risk of debris generation due to collision will be reassessed taking account of the orbital debris population at the time of the extension request.

10 SOFTWARE TOOLS

Warning: This chapter describes the tools recommended by CNES, explaining how to use them: input data, settings and results provided. The aim is therefore to guide operators through the method for making a calculation. User manuals for these tools are included in the installation package.

The STELA software is the tool developed and used by CNES in the frame of the FSOA TR to check the long-term evolution of orbits and compliance with protected areas in the LEO (<2,000 km) and GEO (latitude ±15 deg and altitude of 35,786 km ± 200 km) regions.

The DEBRISK and ELECTRA software can be used to identify surviving objects or fragments during atmospheric re-entry and to quantify the associated risks on ground, to meet the requirements of the applicable TR.

CNES software can be downloaded from **https://www.connectbycnes.fr/los**.

The MASTER software, developed by the ESA, is used to estimate the probability of collision with a given catalogue of debris, in an orbital 'space-time'. This ESA software can be downloaded from https://sdup.esoc.esa.int

10.1 STELA

The STELA (Semi analytic Tool for End of Life Analysis) software is the tool used by CNES to verify the long-term evolution of orbits within the framework of the FSOA. The User Guide - see RD5 - gives a more detailed description of its model, its functionalities and its scope of use.

The latest version of the tool recommended for FSOA use is available on the website referenced in §10.

Figure 10-1: STELA logo

10.1.1 Tool/method presentation

STELA is an orbit propagator based on semi-analytic integration of the space object centre of gravity movement equations. The dynamics equations were averaged to only retain medium and long-term effects of perturbations on the orbital parameters. These equations can therefore be integrated with a major step (greater than the orbital period) to gain in calculation time. The main short periods are then analytically added to calculate the osculating parameters for the required dates.

The dynamic model used is adapted to each type of orbit. It can therefore be different for LEO, GEO and GTO orbits.

STELA integrates the average parameters, in coherence with the dynamic modelling used.

STELA produces in particular a summary file of the orbit extrapolation performed (file in "_sim.txt" format containing the description of inputs, outputs and calculation parameters, and indicating the compliance with FSOA TR criteria).

The content of this "_sim.txt" file must be given in the FSOA application file in addition to the corresponding file in "_sim.xml" format.

STELA also proposes iterative utility programmes used to determine the end-of-life orbit and a tool to calculate the average surface. If the latter is used to determine the average surface, the corresponding descriptor file ("_shap.xml" format file) must be provided.

10.1.2 Physical parameters and constants

- Physical constant values used by STELA:
  - Earth radius used to check FSOA TR criteria and calculate apogee and perigee altitudes: **6,378 km**
  - Potential model, Earth radius and Earth oblateness coefficients used to calculate the dynamics and the geodetic altitude for the atmospheric model, the state vector type conversions: those of the **Grim5-S1 model**

- An astronomical unit (AU): **1.49598022291 10^{11} m**
- Solar radiation pressure at 1UA: **0.45605 10^{-5} N/m^2**
- The Sun's gravitational constant: **1.32712440018 10^{20} $m^3s^{-2}kg^{-1}$**
- The Moon's gravitational constant: **4.9027779 10^{12} $m^3s^{-2}kg^{-1}$**

- Using STELA **and its default settings** (atmospheric model, Cx, "equivalent constant" solar activity, etc.) to extrapolate the orbit **ensures compliance with the TR**.
- Additional information required for the use of STELA in the context of the FSOA is available in document [RD5].

10.2 DEBRISK

This section briefly describes the DEBRISK tool and its associated method. A full user guide is supplied with the software for satellite applications - see RD3.

The latest version of the tool recommended for FSOA use is available on the website referenced in §10.

DEBRISK®

Figure 10-2: DEBRISK logo

10.2.1 Tool/method presentation

DEBRISK is a tool for assessing the survivability of fragments of a vehicle re-entering the Earth's atmosphere, using an object-focused approach. This approach assumes that the incoming vehicle (referred to hereafter as the parent vehicle) can be modelled as a set of several objects, using the basic geometric shapes available. This tool therefore needs the initial kinematic conditions of the parent vehicle, its physical properties and a list of objects as input. This list represents the fragments of the vehicle under study, which may or may not be linked to each other by different types of relationship, and which will arise from the main fragmentation altitude of said vehicle, or during the disappearance of the parent object containing them. This list is the responsibility of the operator who produces it. The geometry of all the fragments is identified using the shapes already available in the software.

Using all this information, DEBRISK can calculate the trajectory and thermal properties of the vehicle re-entering the Earth's atmosphere, and take account of its fragmentation at the assumed altitude of this event. From this event, each object representing a fragment is simulated step by step, via its trajectory, its temperature and any ablation based on incoming and outgoing fluxes.

More precisely, at each time step and for each object, DEBRISK models:

- The Earth's atmosphere to define local flow conditions,
- The equations of motion in an inertial reference frame - **modelling the trajectory**,
- The drag coefficient based on the local flow - **aerodynamic modelling,**
- Heat flux based on the local flow - **aerothermodynamic modelling**,
- The temperature rise of the object - **thermal modelling**,
- Material ablation and calculation of new dimensions - **ablation modelling**.

10.2.2 Physical modelling

Trajectory modelling and digital propagation use the CNES's Patrius library.

The calculation of aerodynamic forces only considers drag forces. Aerodynamic reference coefficients and surfaces are defined for each shape and for each flow regime. The flow regime is based on the Knudsen number, itself calculated using a reference length that depends on the geometric properties of each object.

The heat flux on each object includes the contribution of the following different heating modes:

- Convection transfer, which applies to the thermal reference surface,
- Oxidation transfer, which applies to the thermal reference surface,
- Radiation: losses due to wall radiation; applied to the total surface area of the object exposed to the outside,
- Transfer via contact: transfer of energy between two objects by means of a contact coefficient applied to the interaction surface between these objects.

The drag coefficient of the object and the **heat absorbed** depend on its shape, dimensions, flow conditions, and the attitude of the object. Wall temperature is calculated based on heat flux, specific heat and object mass. The amount of ablated mass is determined by integrating the fluxes once the melting temperature has been reached. Finally, integrating the equations of motion depends on the ballistic coefficient and the local flow conditions. These same conditions depend on the movement of the object and the Earth's atmosphere.

The aerodynamic, thermal and total reference surfaces of the object exposed to the outside depend directly on the shape in question: sphere, cylinder, box, plate, complex, etc.

The temperature of each object is considered uniform in the material, which assumes that conduction in the material is infinite. When the melting temperature of an object is reached, the energy transferred to the object no longer causes the temperature to rise, but the material melts, reducing its mass and external dimensions.

The mass of material ablated at each time step is calculated using the ratio of the total heat absorbed by the object to the material's melting enthalpy. The way in which an object is ablated depends on its geometric properties.

The object is deemed destroyed if it activates one of the following criteria, see UM (***DBK-MU-LOG-0205-CNES)***:

- The mass reaches a minimum limit value set by default in the software.
- The thickness reaches a minimum limit value set by default in the software.

- Deceleration reaches a maximum limit value set by default in the software.
- The kinetic energy reaches a minimum limit value set by default in the software.

Ablation is the process of an object losing mass throughout its re-entry.

Fragmentation is of different types (4 identified):

- Main fragmentation is the process that designates the moment when the satellite "explodes" and gives rise to all the items pre-listed by the user (i.e., the children).
- Fragmentation of the solar panels is the "automatic" process of the solar panels separating from the vehicle, which takes place either at 95 km or at the main fragmentation altitude if the latter is greater than 95 km.
- Fragmentation (without specifying "main" or "of the solar panels") is the classic birth process:
    - of a child from inside the parent, and which is carried out automatically when the parent has disappeared in the sense of DEBRISK (disappearance criterion activated, as seen above)
    - of a component, carried out automatically when the separation temperature set by the user is reached.

10.2.3 Breakdown of the DEBRISK Method

From a macroscopic point of view, here is the breakdown of the method to be implemented to analyse the survivability of the objects that make up a space vehicle.

- The initial kinematic conditions of the parent vehicle must be defined.
- The main fragmentation altitude of the parent vehicle is defined using the methodology recommended in the full user guide supplied with the software - see RD3.
- Each fragment, whether it comes from the breakdown of the parent vehicle, or relates to the parent vehicle itself, must be described as follows:
    - Explicit name (with definition of acronyms),
    - Quantity (this only concerns fragments resulting from the breakdown of the parent vehicle)
    - The type of relationship with other fragments using the methodology recommended in the full user guide supplied with the software - see RD3,
    - The shape chosen for modelling, using the methodologies recommended in the full user guide supplied with the software - see RD3. Reference should be made to the following, in particular:
        1. Geometric properties: external and internal dimensions, aerodynamic and thermal masses,
        2. Physical properties:
            - Conduction coefficients (see RD3),
            - Materials (see RD3).

To use the tool's various functionalities, the operator can also refer to the DEBRISK user manual (supplied with the software).

10.3 ELECTRA

This section briefly describes the ELECTRA tool and its associated method. A full user guide is supplied with the software for satellite applications - see RD4.

The latest version of the tool recommended for LOS use is available on the website referenced in §10.

Figure 10-3: ELECTRA logo

10.3.1 Tool/method presentation

The ELECTRA (Launch and Re-Entry Safety Analysis tool) method is used to estimate the collective casualty risk related to the fall-back of fragments from a space object:

- Risk of casualty in uncontrolled re-entry (i.e. risk of casualty related to the natural re-entry to Earth of a satellite) ⇨ **RA mode**.
- Launch casualty risk (i.e. casualty risk associated with flying over inhabited land during a launch) ⇨ **RL mode** (not addressed here)
- Controlled re-entry casualty risk (i.e. casualty risk associated with the active de-orbiting of a satellite) ⇨ **RC mode**
- Final orbits casualty risk (i.e. casualty risk associated with the imminent natural re-entry to Earth of a space object a few days to a few hours before its fall-back) ⇨ **RF mode**.

Note: The ELECTRA method concerning the Risk during Launch (RL) or the Risk during Controlled Re-entry (RC) estimates the risk of causing casualties related to a space operation in the event of a system failure.

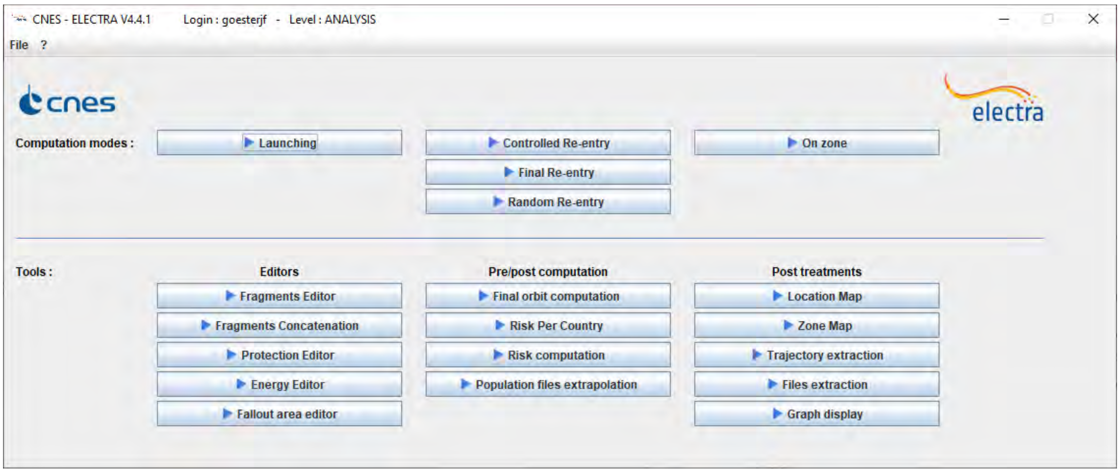


Figure 10-4: Banner for selecting the mode or tool to be used

10.3.2 Risk of a casualty during uncontrolled re-entry

Assessment of the "impact" risk during Uncontrolled Re-entry is calculated in a specific way because the debris re-entry area is, in principle, not known. The potential re-entry area corresponds to the area of the Earth's surface between latitudes +i and –i (i being the inclination of the space object's orbit). Performing a simplified calculation, the casualty risk will be directly proportional to the average density on the [+i, -i] latitude band.

The ELECTRA tool performs a more precise calculation by discretising the [+i, -i] latitude band into N latitude bands correlated with the population grid, taking the following elements into account:

- The population density is variable along the latitude band considered amongst the N bands.
- The probability of falling in a latitude band depends on the latitude of this band. The periods of time spent in each latitude band, for an object in a circular orbit, are in fact not equal.

10.3.3 Risk of a casualty during controlled re-entry

The risk of a casualty following a controlled re-entry is based on Monte Carlo type simulations and takes the following aspects into account:

- The probabilities of failures resulting in space object propulsion shutting down,
- The probability of failures resulting in over or under thrust during the de-orbiting manoeuvre of the space object,
- Fragmentation scenarios for the space object,
- Fragments of the space object falling back to ground,
- Determination of the fragment trajectories and the points of impact,
- Consideration of the population in the re-entry area,
- Population density and vulnerability to debris fall-back.

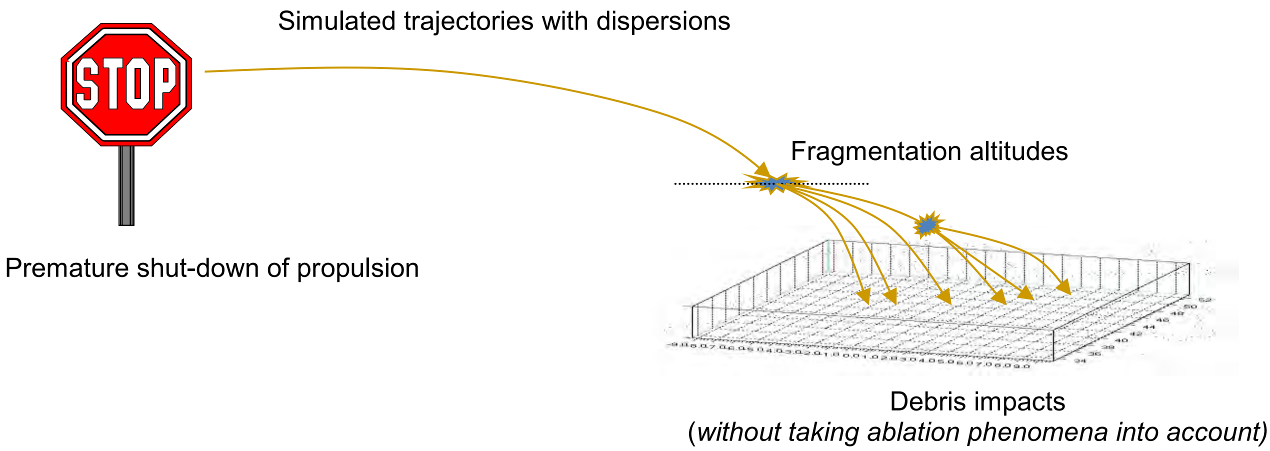


Figure 10-5: Monte Carlo simulations for RC mode

10.3.4 Risk of a casualty in final orbits

In contrast to an Uncontrolled Re-entry, it is possible a few hours or even a few days before re-entry to determine with greater "precision" the re-entry area, or at least the orbits on which re-entry will take place. Provided there is a set of possible entry points (for which a tool is available with the ELECTRA package), it will be possible to calculate the risk of a casualty with respect to:

- The probability of occurrence for each of the entry points

And as for controlled re-entry:

- Fragmentation scenarios for the space object,
- Fragments of the space object falling back to ground,
- Determination of the fragment trajectories and the points of impact,
- Consideration of the population in the re-entry area,
- Population density and vulnerability to debris fall-back.

10.3.5 Additional tools

ELECTRA also comes with a number of additional tools, the main ones being listed below:

- Fragment editor: used to read/modify lists of fragments,
- Protection and power file editor: used to read/modify protection and/or power levels,
- Display on a planisphere (2D/3D),
- File extraction for exporting to other environments,
- Calculation of risk by Country: recalculates the risk by country without re-simulating Monte Carlo draws,
- Calculation of posterior risk: recalculates risk without re-simulating Monte Carlo draws,

- Population extrapolation: used to extrapolate population densities for a given year,
- Calculation of entry points: an essential tool when using the RF mode.

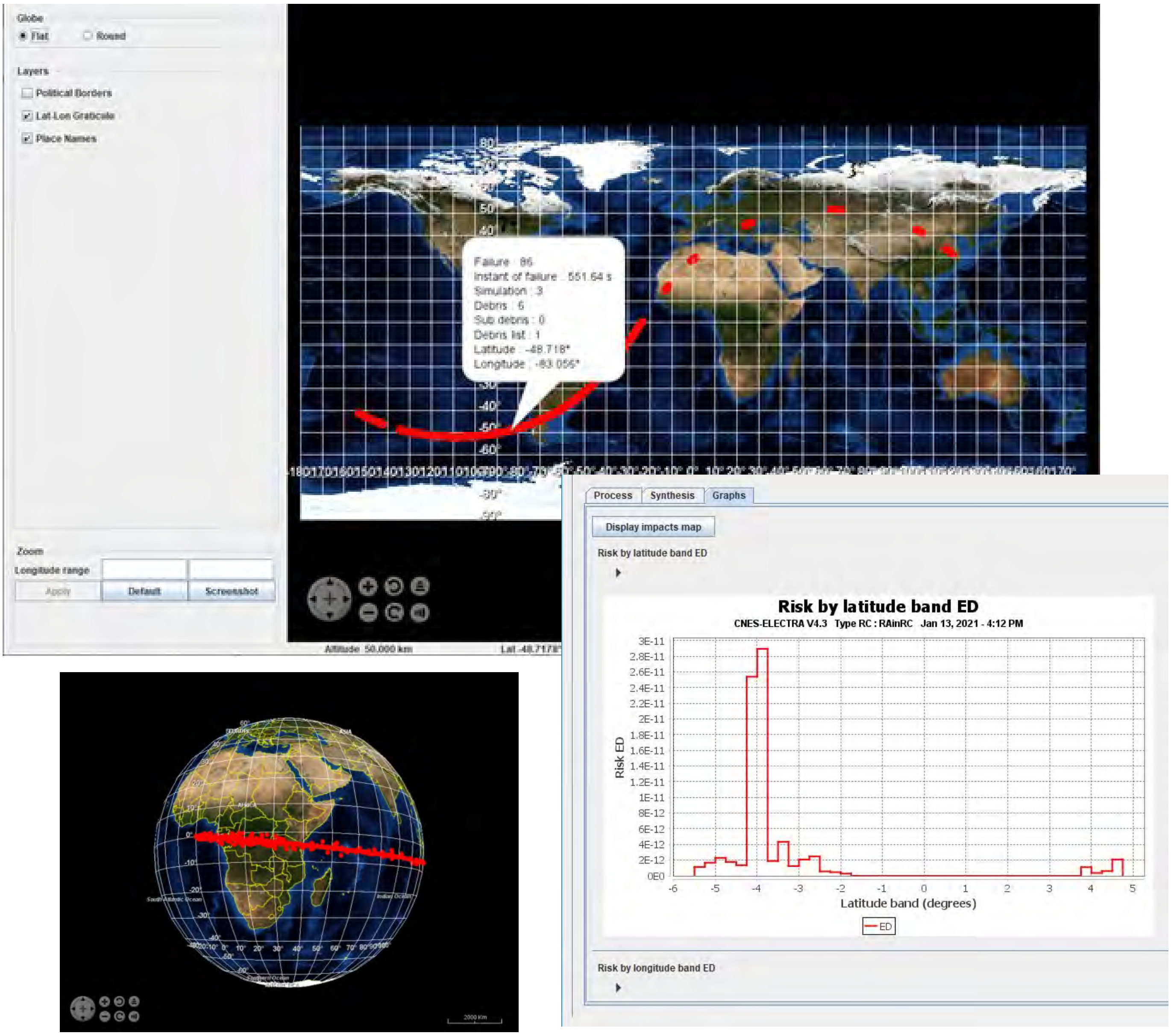


Figure 10-6: ELECTRA plot types

10.4 MASTER

MASTER is a combination of several space debris and micrometeroid population models and software developed by the ESA/ESOC to exploit these models.

MASTER models are briefly described in the MASTER Software User Manual (https://sdup.esoc.esa.int).

For space debris, MASTER (version 8) uses a reference population from 1 November 2016 consisting of objects larger than 1 µm of the following types:

1) Objects related to launches/missions
2) Fragments from explosions or collisions
3) Nuclear reactor cooling products in orbit (Sodium-Potassium, NaK)
4) Slag and dust created by solid rocket motors (SRM)
5) Particles from paint degradation (flaking)
6) Fragments from debris impacts on the surfaces of space objects
7) Fragments of multilayer insulation

The largest objects are taken from measurement catalogues. The smallest objects are the result of simulations.

The initial population changes over time using the "DELTA 4" model, which simulates the evolution of the population and long-term debris fluxes using the Monte Carlo method, and takes account of objects larger than 1 mm of types 1 to 4. Several scenarios including changes to space traffic and protection measures are considered to define the mean evolution scenario. The models use an energy threshold of 40 J/g to determine catastrophic collisions.

For micrometeroids, MASTER (version 8) proposes the Divine-Staubach (1993) and Grün (1985) mean environment models (with or without Taylor velocity distribution (1990)) taken from the literature. The seasonal meteorite flux models available are the Cour-Palais (1969) and Jenniskens/McBride (1994) models.

♦♦♦♦♦ END OF DOCUMENT ♦♦♦♦♦

CNES Space Safety Office

FSOA GOOD PRACTICE GUIDE FOR ORBITAL SYSTEMS

This guide is intended to help operators
submitting a **F**rench **S**pace **O**perations **A**ct compliance file.
It contains proposals for meeting
all the technical requirements of the Technical Regulation.

Studio Graphique CNES, 2025-110