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Inter-Agency Space Debris Coordination Committee

Support to the IADC Space Debris Mitigation Guidelines

Working Group 4

Action Items 32.1 & 33.2

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Document Information

I. Release Note

	Name	Function	Date	Signature
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II. Revision History

Issue	Revision	Date	Initials	Changed	Reason for Revision
1		2004-10-05	AK/JAXA	all	• Established
2	5.1	2009-03-26	SC/NASA		• First iteration of goals from IADC AI 26.2
2	5.2.	2012-06-04	HS/DLR	all	• Resolve formal deficiencies from previous versions • Accomplish goals of IADC AI 26.2 • Include comments received from CNES, ASI, JAXA on version 5.1 • Include comments received from SG on version 5.1 • Includes comments from IADC29 WG4 discussion (see minutes there) • Includes results from discussion on the usage of non-public references from IADC 30 (see minutes there)
2	5.3	2013-04-18	WG4	all	• Reflection of NASA comments • Inclusion of an executive summary of IT25.2 prepared by CNES • Correction of guidelines quotations and other editorial issues • Results of a review by the WG4 plenary
2	5.4a	2014-02-05	SG	all	• Editorial changes • Replacement of Figure 6 • Modifications to Table 4
2	5.4	2014-03-13	HK/ESA	all	• Editorial changes • Comments from WG 4 implemented • Exchange of Figure 6 against WG2 input
2	5.5	2014-05-12	WG4	all	• Implementation of DLR comments
3	5.6	2019-05-10	WG4	5.3.2	• Update of IADC-02-01 following AI 32.1 and AI 33.2
3	5.7	2019-12-16	SG & WG4		• Implementation of DLR and ISRO comments after the SG fall meeting of 2019 and the final approval of the *IADC Space Debris Mitigation Guidelines Rev. 2*; minor editorial changes

III. References

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IV. List of Abbreviations

Abbreviation	Description
ASI	Agenzia Spaziale Italiana (Italian Space Agency)
A/m	Area-to-mass ratio
CNES	Centre National d’Etudes Spatiales (French Space Agency)
CNSA	China National Space Administration
CoC	European Code of Conduct for space debris mitigation
C_R	Solar Pressure Coefficient
CSA	Canadian Space Agency
DAMAGE	Debris Analysis and Monitoring Architecture for the Geosynchronous Environment
DELTA	Debris Environment Long -Term Analysis tool (ESA)
DLR	Deutsches Zentrum für Luft-und Raumfahrt (German Aerospace Center)
DoD	US Department of Defense
ESA	European Space Agency
EVOLVE	Orbital environmental model developed by NASA/JSC
GEO	Geostationary Earth Orbit
GTO	Geostationary Transfer Orbit
HEO	High Earth Orbit
IDES	Integrated Debris Evolution Suite (orbital environmental model developed in UK)
I_{sp}	Specific Impulse
ISRO	Indian Space Research Organisation
ISS	International Space Station
ITU	International Telecommunication Union.
JSC	Johnson Space Center (NASA)
JAXA	Japan Aerospace Exploration Agency
LBB	Leak Before Burst
LEO	Low-Earth Orbit; orbit in the region below 2000 km altitude
LV	Launch Vehicle
MEO	Medium Earth Orbit; orbit in the region above LEO and below GEO
NASA	National Aeronautics and Space Administration
NASDA	National Space Development Agency of Japan
SSAU	State Space Agency of the Ukraine
PMD	Post Mission Disposal
ROSCOSMOS	Russian Federal State Space Corporation
S/C	Spacecraft
SSN	Space Surveillance Network (US)
SSS	Space Surveillance System (Russia)
STS	Space Transportation System (US Space Shuttle)
STSC	Scientific and Technical Subcommittee (for UNCOPUOS)
TBC	To Be Confirmed
TLE	Two-Line Element
UNCOPUOS	United Nations Committee on the Peaceful Uses of Outer Space

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VI. List of Tables

Foreword

This document provides the readers of IADC Space Debris Mitigation Guidelines (IADC-02-01 Revision 2, September 2019) [1] with the purpose, feasibility, practices, and tailoring guide for each recommendation addressed in the Guidelines. Much of this information was based on various documents, research papers, and opinions that were introduced by IADC member agencies.

Table 1 depicts the category of typical debris, their causes, and recommendations from IADC. Several national and international organisations of the space-faring nations have established Space Debris Mitigation Standards or Handbooks to promote efforts to deal with space debris issues. The contents of these Standards and Handbooks may be slightly different from one another, but their fundamental principles are the same as the IADC Guidelines: (1) preventing on-orbit break-ups, (2) removing spacecraft and orbital stages that have reached the end of their mission operations from the densely populated orbital regimes, and (3) limiting the objects released during normal operations.

Table 1. Category of typical debris, their causes, and recommendations from IADC

Category	Causes	Recommendation
Mission-related objects	**Objects released intentionally**	**Mitigation design**
	Objects released unintentionally	**Design robustness**
Fragments	**Intentional destruction**	**Refrain from intentional destruction**
	Accidental break-ups during operation	**Mission assurance**
	Break-ups after mission termination	**Mitigation design**
	On-orbit collisions	**Collision avoidance and shielding**
Mission-terminated spacecraft and rocket bodies	**Inadequate disposal manoeuvre**	**Re-orbit or de-orbit manoeuvre to avoid interference with useful orbital regions**

In this document, the following information typically will be given for each recommendation:

(a) **Purpose**: rationale for the guideline;

(b) **Practices**: recommendations on how to cope with the guideline, applicable methods, and justification of the numerical values;

(c) **Tailoring guide**; and

(d) Feasibility, definition of parameters, technical information, applicable references, and examples.

> Literal Quotes from IADC Space Debris Mitigation Guidelines [1] are provided as boxed text (grey shaded).

1. Scope of the document

The IADC Space Debris Mitigation Guidelines describe existing practices that have been identified and evaluated for limiting the generation of space debris in the environment. The Guidelines cover the overall environmental impact of the missions with a focus on the following:

(1) Limitation of debris released during normal operations

(2) Minimisation of the potential for on-orbit break-ups

(3) Post-mission disposal

(4) Prevention of on-orbit collisions.

Purpose: The major sources of space debris are categorised in Table 1. The Guidelines recommend feasible and important measures to deal with debris sources identified by bold type letters in Table 2.

Table 2. Debris sources

Main Categories	Causes	Debris Sources
Mission- related objects **(Parts Released during Mission Operation)**	**objects released by design**	**operational debris** (fasteners, covers, wires, etc.)
		objects released for experiments (needles, balls, etc.)
		tethers designed to be cut after experiments
		others (released before retrieval)
	unintentionally released objects	**fragments caused by ageing** (flakes of paints and blankets resulting from degradation)
		tether systems cut by debris or meteoroids
		objects released before retrieval to ensure safety
		liquids (released from nuclear power systems, etc.)
		particles ejected from solid motors
On-orbit break-ups	**intentional destruction**	**destruction for scientific or military experiments** (including self-destruction, intentional collision, etc.)
		destruction prior to re-entry in order to minimise ground casualty
		destruction to ensure security of on-board devices and contained data
	accidental break-ups	**explosion caused by failure during mission operation**
		explosion caused by command destruct systems, residual propellants, batteries, etc., after mission termination
	on-orbit collisions	**fragments caused by collision with catalogued objects**
		fragments caused by collision with un-catalogued objects
Mission-terminated space systems		**systems left in near-GEO, GTO, LEO, and HEO**

2. Application

The IADC Space Debris Mitigation Guidelines are applicable to mission planning and the design and operation of spacecraft and orbital stages that will be injected into Earth orbit.

Organisations are encouraged to use these Guidelines in identifying the standards that they will apply when establishing the mission requirements for planned spacecraft and orbital stages.

Operators of existing spacecraft and orbital stages are encouraged to apply these guidelines to the greatest extent possible.

- **Purpose**

  The IADC Space Debris Mitigation Guidelines demonstrate the international consensus on space debris mitigation activities and constitute a baseline that can support agencies and organisations when they establish their own mitigation standards. Figure 1 shows the structure of a document system related to the IADC Guidelines.

  Some space agencies throughout the world have developed or are developing their own debris mitigation standards to preserve and improve the orbital environment. Refer to the References section of this document for a list of the mitigation standards.

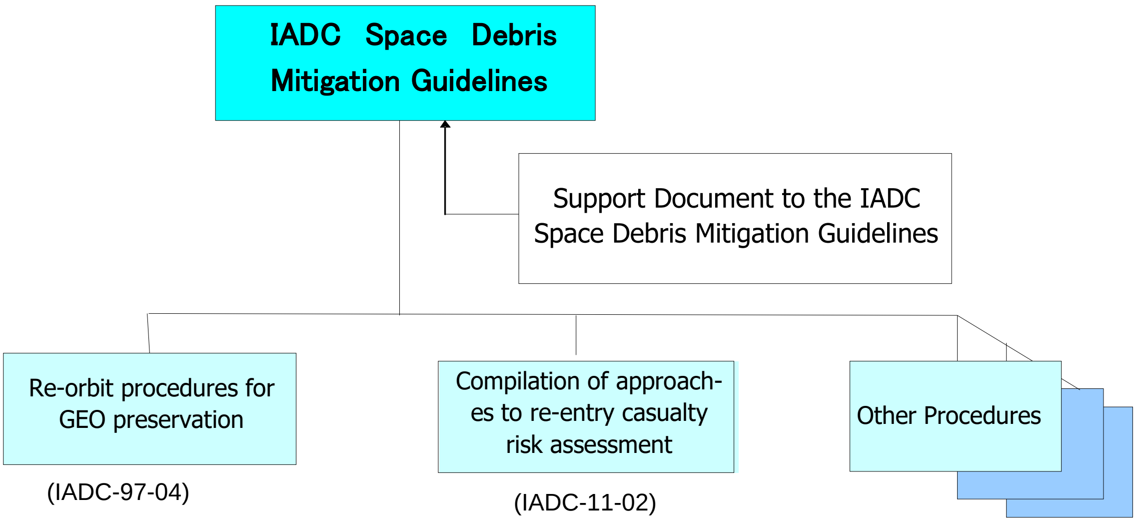


Figure 1. IADC document system for debris mitigation guidelines

3. Terms and definitions

The following terms and definitions are added for the convenience of the readers of this document. They should not necessarily be considered to apply more generally.

3.1 Space Debris

Space debris are all man-made objects including fragments and elements thereof, in Earth orbit or re-entering the atmosphere, that are non-functional.

Reference

The term of space debris was defined in more detail as below in *Technical Report on Space Debris*, 1999, by UN/COPUOS/STSC [6].

> "*Space debris are all man-made objects, including their fragments and parts, whether their owners can be identified or not, in Earth orbit or re-entering the dense layers of the atmosphere that are non-functional with no reasonable expectation of their being able to assume or resume their intended functions or any other functions for which they are or can be authorized".*

Detail

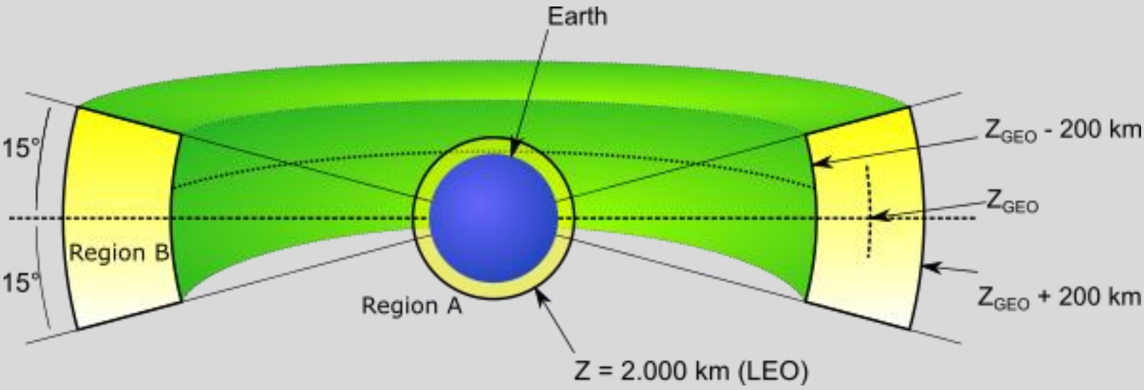
As explained in Table 2, fluids can also constitute a type of debris, such as NaK released from nuclear power systems.

3.2 Spacecraft, Launch Vehicles, and Orbital Stages

Spacecraft	An orbiting object designed to perform a specific function or mission (e.g., communications, navigation or Earth observation). A spacecraft that can no longer fulfil its intended mission is considered non-functional. (Spacecraft in reserve or standby modes awaiting possible reactivation are considered functional.)
Launch vehicle	Any vehicle constructed for ascent to outer space, and for placing one or more objects in outer space, and any sub-orbital rocket.
Launch vehicle orbital stages	Any stage of a launch vehicle left in Earth orbit.

3.3 Orbits and Protected Regions

Equatorial radius of the Earth	The equatorial radius of the Earth is taken as 6,378 km, and this radius is used as the reference for the Earth's surface from which altitudes and orbit regions are defined.
Protected regions	Any activity that takes place in outer space should be performed while recognising the unique nature of the following regions, A and B, of outer space (see Figure), to ensure their future safe and sustainable use. These regions should be protected regions with regard to the generation of space debris.
	(1) Region A, **Low Earth Orbit** (or LEO) **Protected Region** – spherical region that extends from the Earth's surface up to an altitude (Z) of 2,000 km. **<u>Note</u>**: The orbital region used for manned flights, of special concern due to risks of in-orbit casualties, is included in the Region A, Low Earth Orbit Region.
	(2) Region B, the **Geosynchronous Protected Region –** a segment of the spherical shell defined by the following: • lower altitude = geostationary altitude minus 200 km • upper altitude = geostationary altitude plus 200 km • −15 degrees ≤ latitude ≤ +15 degrees • geostationary altitude (Z_{GEO}) = 35,786 km (the altitude of the geostationary Earth orbit)



Protected regions

Geostationary Earth Orbit (GEO)	Earth orbit having zero inclination and zero eccentricity, whose orbital period is equal to the Earth's sidereal period. The altitude of this unique circular orbit is close to 35,786 km.
Geostationary Transfer Orbit (GTO)	An Earth orbit which is or can be used to transfer spacecraft or orbital stages from lower orbits to the geosynchronous region. Such orbits typically have perigees within LEO region and apogees near or above GEO.

3.4 Mitigation Measures and Related Terms

Passivation	The elimination of all stored energy on spacecraft or orbital stages to reduce the chance of break-up. Typical passivation measures include venting or burning excess propellant, discharging batteries and relieving pressure vessels.
De-orbit	Intentional changing of orbit for re-entry of a spacecraft or orbital stage into the Earth's atmosphere.
Re-orbit	Intentional changing of a spacecraft or orbital stage's orbit
Break-up	Any event that generates fragments, which are released into Earth orbit. This includes: (1) An explosion caused by the chemical or thermal energy from propellants, pyrotechnics and so on (2) A rupture caused by an increase in internal pressure (3) A break-up caused by energy from collision with other objects However, the following events are excluded from this definition: • A break-up during the re-entry phase caused by aerodynamic forces • The generation of fragments, such as paint flakes, resulting from the ageing and degradation of a spacecraft or orbital stage.

3.5 Operational Phases

Launch phase	Begins when the launch vehicle is no longer in physical contact with equipment and ground installations that made its preparation and ignition possible (or when the launch vehicle is dropped from the carrier-aircraft, if any), and continues up to the end of the mission assigned to the launch vehicle
Mission phase	The phase where the spacecraft or orbital stage fulfils its mission. Begins at the end of the launch phase and ends at the beginning of the disposal phase.
Disposal phase	Begins at the end of the mission phase for a spacecraft or orbital stage and ends when the space system has performed the actions to reduce the hazards it poses to other spacecraft and orbital stages.

4. General Guidance

During an organisation's planning for and operation of a spacecraft and/or orbital stage, it should take systematic actions to reduce adverse effects on the orbital environment by introducing space debris mitigation measures into the spacecraft or orbital stage's lifecycle, from the mission requirement analysis and definition phases.

In order to manage the implementation of space debris mitigation measures, it is recommended that a feasible Space Debris Mitigation Plan be established and documented for each program and project. The Mitigation Plan should include the following items:

(1) A management plan addressing space debris mitigation activities

(2) A plan for the assessment and mitigation of risks related to space debris, including applicable standards

(3) The measures minimising the hazard related to malfunctions that have a potential for generating space debris

(4) A plan for disposal of the spacecraft and/or orbital stages at end of mission

(5) Justification of choice and selection when several possibilities exist

(6) Compliance matrix addressing the recommendations of these Guidelines.

- **Purpose**

Space debris mitigation measures should be taken into consideration from the very early phases of project planning. Also, adequate decision-making is expected in each of the planning, design, operation, and disposal phases. Section 4 recommends that space debris mitigation activities be included in phased planning, and that organisational and systematic actions be taken according to the authorised plan.

- **Practices (Phased Planning)**

System concept, mission planning, launch configuration, operation planning, and disposal procedures should be developed with consideration for their effects on the orbital environment. It may be noted that major mitigation procedures should be fixed in the very early phases (mission definition and conceptual design phases), and the issues relevant to debris generation should be identified in the preliminary design review and be solved by a detailed design review. (NASA and JAXA standards formally define two design reviews, PDR (Preliminary Design Review) and CDR (Critical Design Review), to assess the mitigation actions.) A Mitigation Plan should be developed to control these activities.

The disposal phase should be clearly considered in mission planning.

- **Practices (Mitigation Plan)**

  Space debris mitigation issues should be identified and dealt with in a project like several other issues, such as safety. It is therefore suggested to include this issue in the scope of the Product Assurance manager of the project. It should not be necessary to issue a large amount of documentation:

  - a plan for control of debris mitigation during the development of the project and the operations, including the disposal and passivation of the spacecraft, and the necessary technical documentation answering to this plan and identifying the measures to limit debris generation and the assessment of the spacecraft or orbital stage's disposal and its operational aspects.

  Of course, the compliance status of any recommendations is addressed via standard practices. Moreover, it would be desirable for the Mitigation Plan to include the following elements.

  (1) **Concept:** The Mitigation Plan could include management organisation, major event, schedule, potential for generating debris, assessment plan, related documents, and the results of design tailoring.

  (2) **Organisation**: Each agency (and its contractors) may assign a group or individual bearing responsibilities to study, plan, implement, and review space debris mitigation activities. The assigned group or individual should be provided with enough authority and resources required to accomplish and fulfil this duty and should report the progress status to the project manager. Usually, such a role would be assigned to a Safety & Mission Assurance department.

  (3) **Management**: Major events and schedule, potential debris sources, disposal plan, assessment plan, and related documents would be helpful.

  (4) **Mitigation measures:** The technical basis for mitigation measures corresponding to each debris source and disposal plan should be described.

  (5) **Compliance matrix:** In each design phase, compliance among system requirements, design, manufacturing, and the operation plan should be reviewed and recorded in a compliance matrix. If some requirements or recommendations are tailored, the facts should be recorded as specified immediately below.

- **Tailoring guide**

  The recommendations in this document can be tailored before being applied. The results of tailoring, however, should be agreed upon among the departments responsible for each project and should be submitted and reviewed by the responsible review committee.

  The facts of tailoring and the basis for such should be recorded in the Space Debris Mitigation Plan. Typical examples for tailoring are as follows:

  (1) for space systems already in progress in their development phase to some extent, only practically feasible recommendations would be applied, and

  (2) comprehensive studies for various conditions including economical, technical, and other issues concerned with debris mitigation measures would identify the practically feasible range of recommendations to be applied.

5. Mitigation Measures

5.1 Limit Debris Released during Normal Operations

In all operational orbit regimes, spacecraft or orbital stages should be designed not to release debris during normal operations. Where this is not feasible any release of debris should be minimised in number, area and orbital lifetime.

Any program, project or experiment that will release objects in orbit should not be planned unless an adequate assessment can verify that the effect on the orbital environment, and the hazard to other operating spacecraft or orbital stages, is acceptably low in the long term.

The potential hazard of tethered systems should be analysed by considering both an intact and severed system.

- **Purpose**

Approximately 7% of the current catalogued objects are debris released during normal operations. The release of fasteners, yo-yo end masses, nozzle covers, lens caps, and multiple payload mechanisms should be kept to a minimum.

In the past, deliberate activities detrimental to the space environment have taken place. Large numbers of needles were scattered in-orbit for a communications experiment in the 1960's.

- **Feasibility**

It is relatively easy, both technically and economically, to take mitigation measures against these objects. Many agencies have already reported to be taking such action.

Satellite manufacturers usually avoid intentional debris generation, since this debris might remain very close to the satellite and become a danger to the satellite itself (blocking mechanisms, obstructing the field of view, etc.). It is therefore a sound requirement for spacecraft manufacturers to preclude intentional debris generation during normal operations.

- **Practices**

The number of objects released during nominal operations to become orbital debris should be minimised by design. The following are examples of these objects.

(1) Launch vehicle connectors and fasteners: separation bolts, clamp bands, etc.

(2) Fairings: fairings and adapters for launching multiple payloads, etc.

(3) Covers: nozzle closures, etc.

(4) Others: yo-yo masses and lines, etc.

Apogee motor cases or engines should not separate or be left in an orbit passing through the protected regions. If this is not possible, they should be left so as not to interfere with the protected regions, and they should be passivated.

Note: Solid Rocket Motors release solid particles during and after burning. The precise nature of the amount and distribution of the ejecta are unclear, and the improvement of solid propellants and motor insulation to minimise the number of released objects is recommended.

- **Practice (tethers)**

Tethers several thousand meters in length and a few millimetres in diameter have a large probability to be severed by small debris or meteoroids. New multi-strand tether designs can reduce the risk of severing. At the end of missions, it is recommended that tethers be retracted to reduce the probability of collision with spacecraft or orbital stages. The IADC has investigated the benefits and risks of electrodynamic tethers for spacecraft disposal [7].

- **Tailoring guide**

(1) **Fairings:** support structural elements left in orbit during a multiple payload mission may be released, if there are no feasible alternative measures. Fortunately, when released at low altitude, their orbital lifetimes can be relatively short if their area-to-mass ratios are high.

(2) **Orbital lifetime:** released objects whose orbital lifetime is short (less than 25 years, for example) could be assessed as allowable.

(3) **Mission requirements to release objects:** missions that require releasing objects should be submitted to the review board of the agencies to assess their necessity and their effects on orbital environment.

(4) **Paint flakes and other objects released by degradation:** paint, surface materials, and possibly deployment devices can deteriorate and generate fragments from exposure to the space environment (ultraviolet radiation, atomic oxygen, thermal cycling, and micro-particle impacts). However, further research is required to present standards or recommendations with regard to how many years materials should withstand the space environment.

(5) **Tethers:** tethers can exacerbate the debris environment, but can also be used to reduce orbital lifetime. In the planning of tether systems, these advantages and disadvantages should be assessed.

5.2 Minimise the Potential for On-Orbit Break-ups

> On-orbit break-ups caused by the following factors should be prevented using the measures described in 5.2.1 – 5.2.3:
>
> (1) The potential for break-ups during mission should be minimised
>
> (2) All space systems should be designed and operated so as to prevent accidental explosions and ruptures at end-of-mission
>
> (3) Intentional destructions, which will generate long-lived orbital debris, should not be planned or conducted.

- **Purpose**

The most common source of space debris is on-orbit break-ups of spacecraft or orbital stages. At the time of writing, more than half of catalogued objects, and the vast majority of all space debris larger than 5 cm in diameter stem from on-orbit break-ups. The contributors to the space debris population are regularly updated in the NASA Orbital Debris Quarterly News. This section recommends efforts to prevent their generation.

According to the NASA database provided by the NASA/JSC Orbital Debris Program Office, as of 1 January 2014 more than 280 orbital fragmentations (excluding aerodynamic break-ups) have occurred. Intentional destruction has been the major cause for spacecraft break-up, while the propulsion system is the major responsible for rocket body break-up. No spacecraft has yet been observed to have broken up as a result of liquid propulsion failure, and no rocket body as a result of battery failure.

5.2.1 Minimise the potential for post mission break-ups resulting from stored energy

> In order to limit the risk to other spacecraft and orbital stages from accidental break-ups after the completion of mission operations, all on-board sources of stored energy of a spacecraft or orbital stage, such as residual propellants, batteries, high-pressure vessels, self-destructive devices, flywheels and momentum wheels, should be depleted or safed when they are no longer required for mission operations or post-mission disposal. Depletion should occur as soon as this operation does not pose an unacceptable risk to the payload. Mitigation measures should be carefully designed not to create other risks.

- **Purpose**

The most important and effective measure is the prevention of break-ups. Expenditure of residual propellants and high-pressure fluids and the switching-off of battery charging lines are typical measures. More detailed recommendations are addressed below.

(1) Residual propellants and other fluids, such as pressurants, should be depleted as thoroughly as possible, either by depletion burns or venting, to prevent accidental break-ups by over-pressurisation or chemical reaction.

- **Purpose**

Residual propellant is the most common cause of on-orbit break-ups. Many accidental break-ups have been caused by orbital stages possessing hypergolic propulsion systems with common bulkhead tanks. But even cryogenic propulsion systems have apparently ruptured as a result of propellant evaporation and resulting over-pressurisation.

The above recommendation can prevent such propulsion-related break-ups. However, it is sometimes difficult to know the exact amount of remaining propellant, since sensors can give incorrect information, for example at the end of life of a satellite.

- **Practices in design and operation of LV**

Accidental mixing of hypergolic propellants should be prevented by design. For example, the common bulkhead or the lines having a path between the oxidiser and fuel feeding systems, that would increase the risk of mixing of oxidiser and fuel, should be properly designed and used. In cases where a common bulkhead tank system is designed, the pressure of the inner tank should be kept higher than the outer tank in order to prevent a rupture of the common bulkhead. This effort to keep differential pressure should also be applied during the final venting or burning operation to prevent bulkhead breakage.

Even in the case of a monopropellant or cryogenic propellant system or a separated tank system, residual propellant should be vented or burned at the end of mission. Venting lines should be designed to prevent blockage from freezing propellants.

Consequently, an adequate sequence of valve operation, sufficient electric power to sustain vent-valve operation, and a monitoring system to sense complete depletion are recommended. The sequence of events should be planned and reviewed.

- **Impact on the operating spacecraft**

Depletion burns and venting may generate impulses that will disturb the attitude of spacecraft or rocket bodies. Especially in the case of venting propellants, a specific design (torque-free venting system) or operation may be required to cancel the impulse.

- **Tailoring guide**

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

(2)	Batteries should be adequately designed and manufactured, both structurally and electrically, to prevent break-ups. Pressure increase in battery cells and assemblies could be prevented by mechanical measures unless these measures cause an excessive reduction of mission assurance. At the end of operations battery charging lines should be de-activated.

- **Purpose**

Historically, more than ten accidental satellite break-ups have been caused by battery ruptures. The above guideline recommends considering measures during design, manufacturing, and operation to prevent such malfunctions.

- **Practices**

The main causes of battery break-ups are inadequate design and manufacturing in both structural and electrical aspects, as well as operational errors. Usually, battery cases have enough strength to withstand the increase of inner pressure under normal conditions and will not cause a satellite break-up. However, system qualification for long periods can be difficult. In addition, there is a break-up risk in case of hypervelocity impact. Shutting-off charging lines and discharging the battery to a safe level will substantially reduce the break-up risk.

Relays (and the command line) to shut off the charging lines and heaters or other high power loads to discharge batteries are recommended.

In any case, there are electrical and chemical events able to generate gas inside the cells, and then cause a pressure increase beyond structural limits. The space debris mitigation should rely on electrical protection, rather than on battery mechanical re-enforcement, for example,

- in case of a potential leakage current, the implementation of a resistor between battery and structure might be recommended, or
- a high depth of discharging (DOD) may lead to a cell being inversely polarised if the cell is not homogeneous.

It is therefore recommended to perform a specific power subsystem study aimed at defining an adequate architecture that would be able to cope with end-of-life electrical passivation needs for the various families of satellites.

- **Tailoring guide**

For the passivation itself, some documents recommend the implementation of a relay or relays for disconnection from the charging lines and the associated command line. From French experience, such a disconnection capability was implemented on the SPOT platform (and this command was used for the disposal of SPOT 1), but it is usually not implemented on Telecommunication satellites or many small satellites. An erroneous command to a system employing a solitary relay could be a single point of failure, which is often considered unacceptable in satellite design. An alternative would be to install independent relays in parallel.

Pressure relief valves for battery cells might reduce reliability. Such measures have been taken for the battery cells and assemblies on some launch vehicles (e.g., Ag-Zn batteries), but less often for spacecraft.

> (3) High-pressure vessels should be vented to a level guaranteeing that no break-ups can occur. Leak-before-burst designs are beneficial but are not sufficient to meet all passivation recommendations of propulsion and pressurisation systems. Heat pipes may be left pressurised if the probability of rupture can be demonstrated to be very low.

- **Purpose**

This recommendation is mainly applied to regulated systems that consist of an upstream high-pressure vessel and a downstream, regulated-pressure vessel.

- **Practices**

(1) Blow down system: The upstream pressurant should be vented at least to less than the mean operational pressure of the downstream vessel.

(2) Tanks with a bladder: Tanks in which fuel and pressurant are separated by a bladder should contain a mechanism for totally venting gases. In cases where such a mechanism is not implemented, enough safety margin to prevent break-up under expected solar heating should be adopted.

(3) LBB design: Leak-before-burst (LBB) designs are beneficial but not sufficient in preventing potential break-up scenarios. They are normally effective when the rise in pressure is gradual. On the other hand, the cause of the significant 1996 Pegasus HAPS break-up has been assessed to be the rapid over-pressurisation and failure of the main propellant tank (which had a leak-before-burst design) when a regulator between the propellant tank and pressurant tank failed.

- **Tailoring guide**

Although helium bottles of launch vehicles sometimes do not have vent mechanisms, a bleed valve of the pressure regulator will gradually decrease the inner pressure to avoid unsafe levels.

In some propellant tanks with a bladder and no vent valve, the pressurising gas might be trapped in the tanks and cannot be vented. Usually the pressure will decrease during normal operations to safe levels (less than one tenth of initial pressure), but enough margin should be taken for the case that some failure would keep the initial pressure, e.g., main engine failure.

Heat pipes are highly pressurised and, therefore, a source of stored energy. However, in the usual design process, they have enough structural integrity to prevent such accidents. NASA notes in its standard that sealed heat pipes [and passive nutation dampers] need not be depressurized at end of mission.

(4)	Self-destruct systems should be designed not to cause unintentional destruction due to inadvertent commands, thermal heating, or radio frequency interference.

- **Purpose**

  Unintentional triggering of self-destruct systems can produce break-ups.

- **Practices**

  - Unintentional activation of self-destruct systems is a complex topic and many sources may trigger it, for example, static electricity discharge, impact, etc.
  - Destruction command receivers should be turned off as soon as they are no longer needed.
  - Thermal insulation should protect the explosive charge to keep its temperature less than its cook-off temperature.

(5)	Power to flywheels and momentum wheels should be terminated during the disposal phase.

- **Tailoring guide**

  Usually no action will be required if the batteries have been discharged. Flywheels and momentum wheels will usually stop shortly after cutting off the power supply due to friction.

(6)	Other forms of stored energy should be assessed and adequate mitigation measures should be applied.

- **Purpose**

  “Other forms” covers all other possible sources of break-ups that have not been mentioned above. Such forms might be design-dependent and should be assessed; adequate mitigation measures should then be applied.

- **Practices**

  A list of all elements with stored energy (mechanical, thermal, chemical, etc.) should be established and subjected to assessment on each project. Examples are as follows:

1. chemical experimental devices,
2. mechanical devices that might retain a large amount of stress or kinetic energy,
3. thermal devices, and
4. pyrotechnic devices.

5.2.2 Minimise the potential for break-ups during operational phases

> During the design of spacecraft or orbital stages, each program or project should demonstrate, using failure mode and effects analyses or an equivalent analysis, that there is no probable failure mode leading to accidental break-ups. If such failures cannot be excluded, the design or operational procedures should minimise the probability of their occurrence.
>
> During the operational phases, a spacecraft or orbital stage should be periodically monitored to detect malfunctions that could lead to a break-up or loss of control function. In the case that a malfunction is detected, adequate recovery measures should be planned and conducted; otherwise disposal and passivation measures for the spacecraft or orbital stage should be planned and conducted.

- **Purpose**

  Mission assurance is not explicitly a space debris issue. However, considering the effect of on-orbit break-ups, an intentional decrease in reliability that is induced by cost reductions, lack of technology, or time-saving should be avoided for the sake of other operating spacecraft and orbital stages and the orbital environment.

- **Practice**

It is standard practice on satellites, even on the cheapest ones, to identify potential failure modes and their effects and to monitor on-board or on-ground (depending on the needed reaction delay) the technological parameters indicating that

(1) a failure has occurred and is likely to propagate to other functions of the vehicle, or

(2) a failure is likely to occur (indicated by parameter drift).

Monitoring then allows the ground or the on-board satellite management to take all necessary passivation measures, in order to eliminate the risk of failure propagation.

A primary recommendation would then be to make sure that all necessary measurement points are implemented on-board to monitor the physical characteristics (pressure, temperature, current, etc.) and their drift, in order to detect failures with the potential to lead to debris generation.

Concerning propulsion, depending on the selected architecture, these actions may consist of closing or opening some valves to isolate the critical section.

5.2.3 Avoidance of intentional destruction and other harmful activities

> Intentional destruction of a spacecraft or orbital stage, (self-destruction, intentional collision, etc.), and other harmful activities that may significantly increase collision risks to other spacecraft and orbital stages should be avoided. For instance, intentional break-ups should be conducted at sufficiently low altitudes so that orbital fragments are short lived.

- **Purpose**

  Intentional destructions have been conducted for the purpose of engineering tests, experiments, or security assurance (data and technology security) for on-board information. Such activities should be avoided whenever possible.

  When conducted, intentional destruction or potentially harmful activities should be assessed for possible damage to other spacecraft.

- **Tailoring guide**

  In rare cases, destruction may be planned to reduce the risk to people on Earth from re-entering debris objects, but this should be conducted at low altitude, e.g., lower than 90 km. However, keeping the destruct devices in-orbit during mission operation could increase the risk of an on-orbit explosion, even if the mission duration is short. Also, to control the destruction in low altitude may not be easy because of difficulty in attitude control, protection from aero-heating, and the maintenance of command lines.

5.3 Post Mission Disposal

5.3.1 Geosynchronous Region

Spacecraft that have terminated their mission should be manoeuvred far enough away from GEO so as not to cause interference with spacecraft or orbital stage still in geostationary orbit. The manoeuvre should place the spacecraft in an orbit that remains above the GEO protected region.

The IADC and other studies have found that fulfilling the two following conditions at the end of the disposal phase would give an orbit that remains above the GEO protected region:

1. A minimum increase in perigee altitude of:

$$235\ km + (1000 \cdot C_R \cdot A/m)$$

where C_R	is the solar radiation pressure coefficient
A/m	is the aspect area to dry mass ratio ($m^2 kg^{-1}$)
235 km	is the sum of the upper altitude of the GEO protected region (200 km) and the maximum descent of a re-orbited spacecraft due to luni-solar & geopotential perturbations (35 km).

2. An eccentricity less than or equal to 0.003.

Other options enabling spacecraft to fulfil this guideline to remain above the GEO protected region are described in the "Support to the IADC Space Debris Mitigation Guidelines" document.

The propulsion system for a GEO spacecraft should be designed not to be separated from the spacecraft. In the case that there are unavoidable reasons that require separation, the propulsion system should be designed to be left in an orbit that is, and will remain, outside of the protected geosynchronous region. Regardless of whether it is separated or not, a propulsion system should be designed for passivation.

Operators should avoid the long term presence of launch vehicle orbital stages in the geosynchronous region.

- **Purpose**

  To preserve the GEO environment, where the removal of objects by natural forces normally will require extremely long periods, objects should be moved to a higher region when no longer useful.

- **Definitions**

A/m: Aspect Area (in m^2) over Dry Mass (in kg):

Aspect area, A (m^2), is the effective cross-sectional area of the spacecraft in the condition when it is sent to an orbit above the GEO protected region, usually with solar arrays and antennas in their deployed positions. The NASA Standard [1] on limiting orbital debris provides guidance for determining the cross-sectional area for a tumbling vehicle.

Mass, m (kg), is the actual mass at the time that the spacecraft is sent to an orbit above the GEO protected region. Usually this can be considered equal to the dry mass, if all fluids have been burned or released.

C_R (Solar Pressure Radiation Coefficient):

The actual value of C_R depends on the surface characteristics (insulators, solar arrays, radiators, antennas, etc.), their relative areas, and the vehicle attitude with respect to the sun. There will be some difference between the case of the golden colour of aluminised Kapton and the black Kapton, but the total value of C_R will not vary significantly because of the large area of the solar panels and other components. So C_R may be in the range of about 1.2 to 1.5. In addition, the value is typically expected to decrease with ageing, but usually the value at the beginning of life will be used as a conservative measure.

- **Practice**

The IADC Space Debris Mitigation Guidelines include a recommendation to re-orbit objects that have reached the end of their useful life, to an orbit that will remain above the GEO protected region. This can be achieved by combining an increase in perigee altitude with an appropriate eccentricity vector. The minimum increase in perigee altitude is derived from consideration of the GEO protected region and the influence of orbital perturbations on a typical near-circular GEO spacecraft. It is illustrated in Figure 2.

Consideration also needs to be given to the eccentricity vector (magnitude and direction) of an object when it is re-orbited above GEO. The main factors influencing the evolution of the eccentricity are solar radiation pressure and luni-solar perturbations. Solar radiation pressure gives an annual variation in eccentricity that is already addressed in the formula describing the minimum increase in perigee altitude (1000 · CR · A/m). Luni-solar gravitational perturbations result in a sinusoidal variation in eccentricity, which has a period of many years and an amplitude that is dependent on the magnitude of the initial eccentricity.

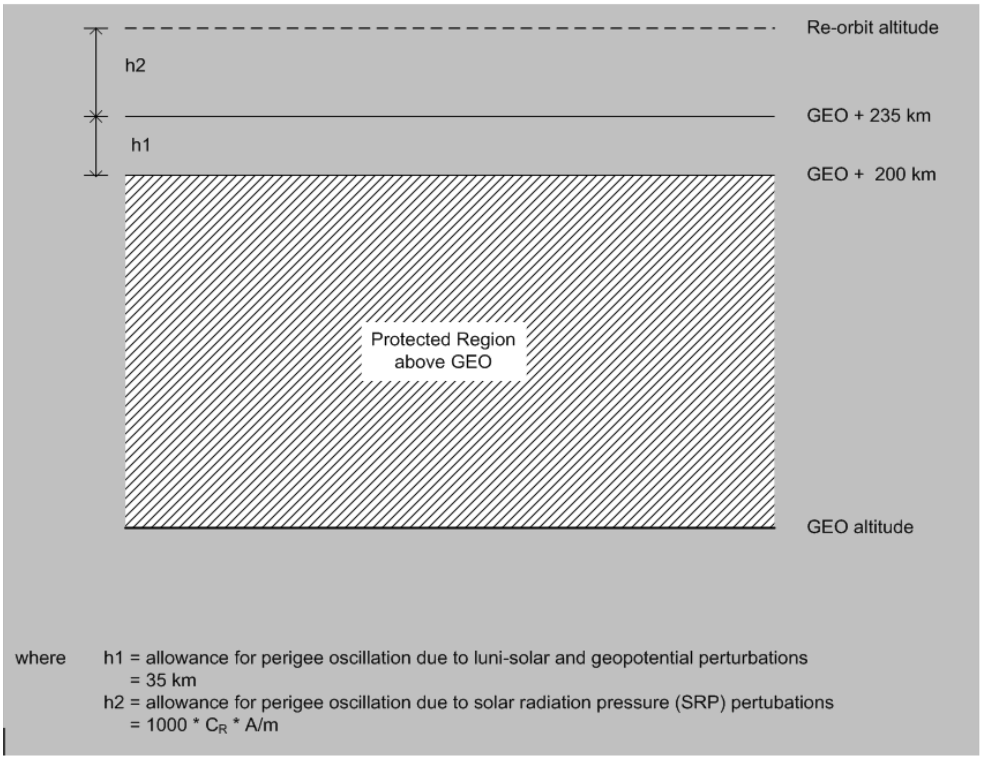


Figure 2. Schematic showing the basis for the formula describing the recommended minimum increase in perigee altitude

The objective of the IADC guideline is to ensure that objects re-orbited above GEO do not subsequently interfere with the GEO protected region. To achieve this, a perigee increase above the geostationary altitude needs to be combined with control of the initial eccentricity / eccentricity vector of the disposal orbit. Technical studies performed suggest that the initial eccentricity / eccentricity vector could be selected such that:

- The initial eccentricity of the orbit should be lower than ~ 0.003, or
- The eccentricity vector should be pointed such that $\Omega + \omega \approx 90$ or 270° (i.e. towards the summer or winter solstice), with the magnitude of the eccentricity set to ensure that the perigee of the orbit does not drop into the protected region.

This is illustrated in **Figure 3**, which provides an example of the initial eccentricity vectors that will successfully establish a stable disposal orbit, i.e., one that remains above the GEO protected region in the long-term.

Combining the recommended increase in perigee altitude with an initial eccentricity limit is one method of achieving a disposal orbit that will not re-enter the GEO protected region in the long-term. There are other solutions that will achieve the purpose of the IADC guideline and in developing a re-orbit strategy it should be noted that:

- Proper pointing of the eccentricity vector is not a sufficient condition to achieve a stable disposal orbit, i.e. one that remains outside the GEO protected region, unless the value of the eccentricity is suitably bounded (see Figure 4).

- If the eccentricity magnitude is less than ~ 0.003 then the disposal orbit does not violate the protected region regardless of the direction of the eccentricity vector, assuming that the recommended minimum perigee altitude increase is adopted.
- Given the sensitivity of the pointing direction of the eccentricity vector to disposal epoch, if the eccentricity is to be greater than ~ 0.003 then the long-term evolution of the disposal orbit should be studied on a case-by-case basis.
- For small eccentricities, sun-pointing can give a more stable orbit as it reduces the variations in perigee height due to solar radiation pressure. This can mean that a smaller perigee increase is acceptable, thus requiring less delta-velocity (ΔV) for the disposal manoeuvre.

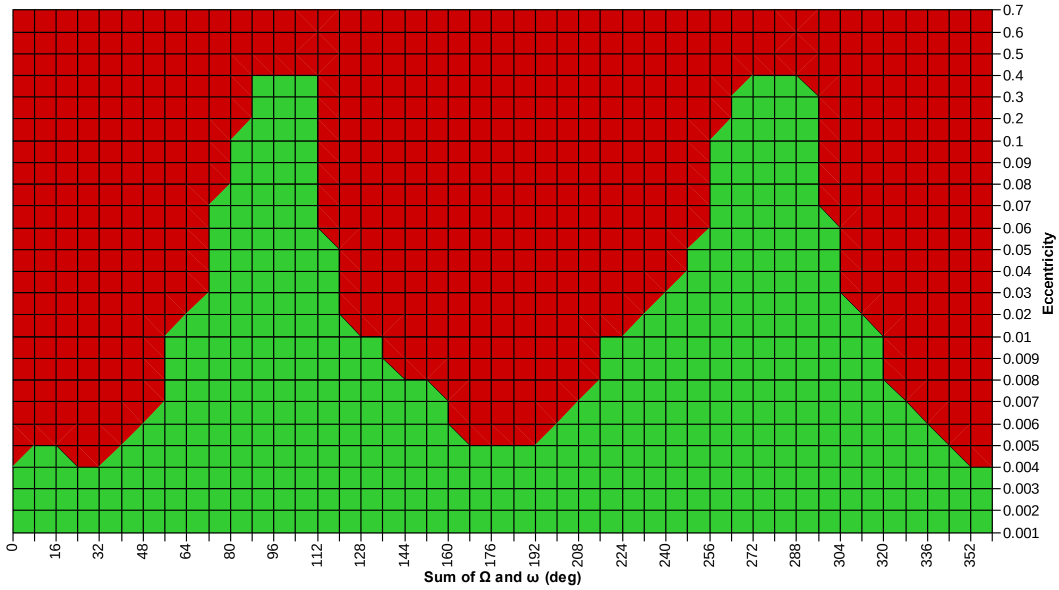


Figure 3. Example combinations of Ω and ω that will cause an orbit to re-enter the GEO protected region over 40 years

N.B.: for various initial eccentricities, assuming the minimum increase in perigee altitude and an initial inclination of 0.04°. Green indicates a stable orbit (i.e. no violation of the protected region) and red indicates orbits that will re-enter the GEO protected region. For higher inclination orbits (6°) the advantage of pointing the eccentricity vector in a given direction is not as pronounced.

For all re-orbit strategies, it is beneficial to propagate a proposed disposal orbit over several decades (sufficient to capture the periodic variation in eccentricity due to luni-solar and geopotential perturbations) to assess its suitability.

Careful planning of a re-orbit manoeuvre can reduce the required ΔV for the manoeuvre (and therefore the cost). However, the uncertainty in determining the remaining fuel mass for a mission reaching the end of its useful life cannot be neglected. Figure 4 shows typical values for the required ΔV for re-orbit manoeuvres.

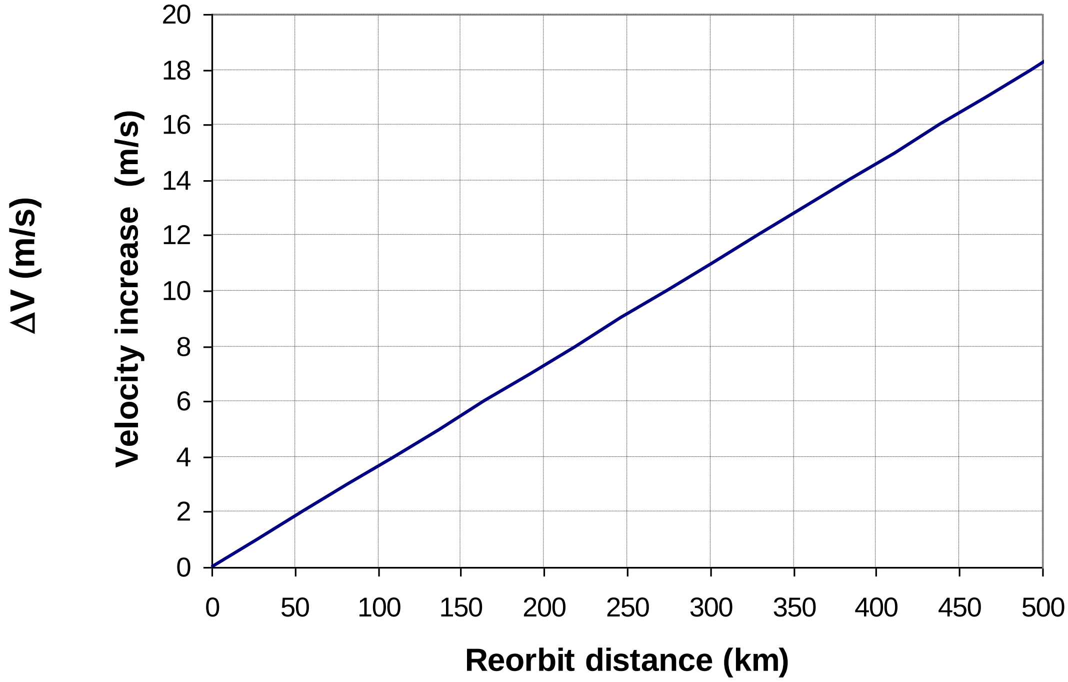


Figure 4. ΔV requirements as a function of re-orbit distance above GEO

- **Practice (Apogee Propulsion System)**

  In the past, some types of spacecraft have separated their apogee propulsion systems to obtain better characteristics and efficiencies in terms of attitude control, thermal control and field of view. Liquid engines are more hazardous than solid motors, particularly in the event that they separate while containing residual propellants as sources of break-up energy. Such residual propellants should be vented or burned before separation. Otherwise specific devices (to control venting or burning and to provide energy to open the valves), should be required to vent or burn shortly after separation.

  If unavoidable reasons arise that require separation, the propulsion system should be designed to be left in a higher orbit as recommended for spacecraft that have terminated their mission in GEO.

  It is noted that current and proposed satellite designs do not usually include separable propulsion stages. These may be utilised for interplanetary missions; however, these missions are not in the scope of this document.

- **Practice (Direct Injection into GEO)**

  For direct injection of payloads into orbits near GEO (e.g., US Centaur upper stage), the best solution might be to insert the upper stage and payload directly into a disposal orbit above or below the GEO protected region and to have the payload then perform a minor manoeuvre to place itself into GEO.

- **References**

  References [13] to [19] are providing useful information in support of re-orbiting GEO spacecraft.

- **Practice (GTO Objects)**

  To avoid the long-term presence of launch vehicle orbital stages in the geo-synchronous region, the NASA Standard 8719.14 [2] recommends that apogee should decrease to 500 km lower than GEO within 25 years.

5.3.2 Objects Passing Through the LEO Region

Spacecraft or orbital stages that are terminating their operational phases in orbits that pass through the LEO region, or have the potential to interfere with the LEO region, should be de-orbited (direct re-entry is preferred) or where appropriate manoeuvred into an orbit with an expected residual orbital lifetime of 25 years or shorter. The probability of success of the disposal should be at least 90%. For specific operations such as large constellations, a shorter residual orbital lifetime and/or a higher probability of success may be necessary. Retrieval is also a disposal option.

If a spacecraft or orbital stage is to be disposed of by re-entry into the atmosphere, debris that survives to reach the surface of the Earth should not pose an undue risk to people or property. This may be accomplished by limiting the amount of surviving debris or confining the debris to uninhabited regions, such as broad ocean areas. Also, ground environmental pollution, caused by radioactive substances, toxic substances or any other environmental pollutants resulting from on-board articles, should be prevented or minimised in order to be accepted as permissible.

In the case of a controlled re-entry of a spacecraft or orbital stage, the operator of the system should inform the relevant air traffic and maritime traffic authorities of the re-entry time and trajectory and the associated ground area.

- **Purpose**

The LEO region is a useful orbital regime that many countries use for Earth observation, micro-gravity experiments, communications, space scientific observation and experiments, and so on. It also includes manned missions conducted since 12 April 1961. Preserving the orbital environment of this region is very important both for the use of this region and also for passing through this region to GEO and beyond. Consequently, the removal of objects from LEO as soon as possible after the end of a mission is beneficial. Fortunately, natural forces, especially drag, work to clean debris from this region, although this is effective primarily for satellites below 700 km. It is recommended that orbital lifetime be reduced to less than 25 years at the end of mission (approximately 750 km circular orbit for A/m = 0.05 m^2/kg, and approximately 600 km circular orbit for A/m = 0.005 m^2/kg, depending on solar activity). For a given amount of propellant, lowering perigee only will minimise the remaining orbital lifetime, compared with lowering both apogee and perigee to a new, lower circular orbit.

This guideline is appropriate for all spacecraft and orbital stages, regardless of size: satellites without de-orbiting capability should not be launched to the orbits within the LEO protected region if their post-mission lifetime is greater than 25 years.

- **Practice (Reduction of Orbital Lifetime)**

  Computations related to orbital lifetime as a function of initial orbit, air drag and area-to-mass ratios may be found in many documents. Similarly, the fuel required for decreasing a low orbit perigee down to a given value is easy to compute. The IADC recommendation is to ensure that the lifetime after disposal will not exceed 25 years.

  IADC Working Group 2 studied the effect of limited (25 years) post-mission orbital lifetimes (Figure 5) [Ref: Update to Support Document – DAMAGE Figure 5.3.2-1, H.G. Lewis, University of Southampton (UK Space Agency), 30 June 2013] [9].

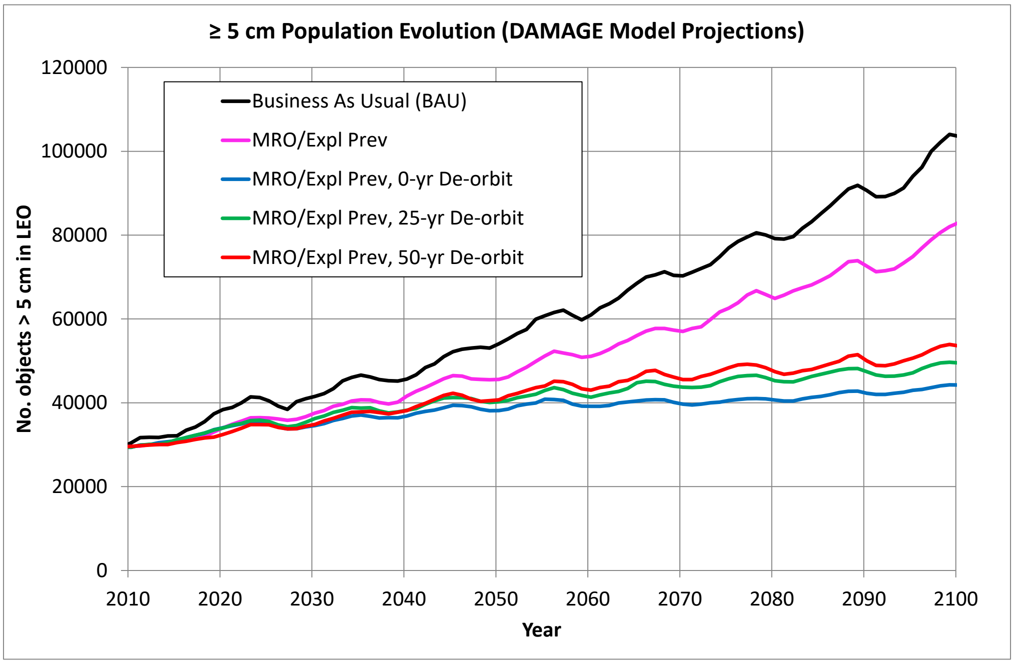


Figure 5. Debris (≥ 5 cm) average population evolution from DAMAGE

- **Practice (Probability of Success of the Disposal)**

  The probability of success associated with spacecraft and launch vehicle orbital stages performing an action during the disposal phase to ensure the expected residual orbital lifetime does not exceed 25 years is crucial to maintain the LEO protected region's useful orbits. This probability of success is the overall probability of an object which is not already meeting the guideline at the end of its mission phase to do so by the end of its disposal phase, or in other words the complement probability of an object being stranded in an orbit that does not conform with the guideline. When considering launch traffic models representative for the 1990s and 2000s, various IADC and other studies that performed long-term simulations of the space environment have indicated that a probability of success of at least 90% is required to limit the impact on the orbital environment. Even under those conditions the space debris environment is projected to grow in terms of number of objects in the vast majority of cases analysed [23]. Unsuccessfully disposed spacecraft and launch vehicle upper stages provide the mass and area in orbit to trigger and sustain a collisional cascade in the environment. Hence the value of the probability of success of the disposal should be significantly increased, with respect to currently achieved levels, when the density of objects in the environment increases due to fragmentation events and/or increased launch traffic [22].

IADC Working Group 2 studied the effect of limited (25 years) post-mission disposal scenarios with various probabilities of success (PMD 30%, 60%, and 90%) (Figure 7) [24].

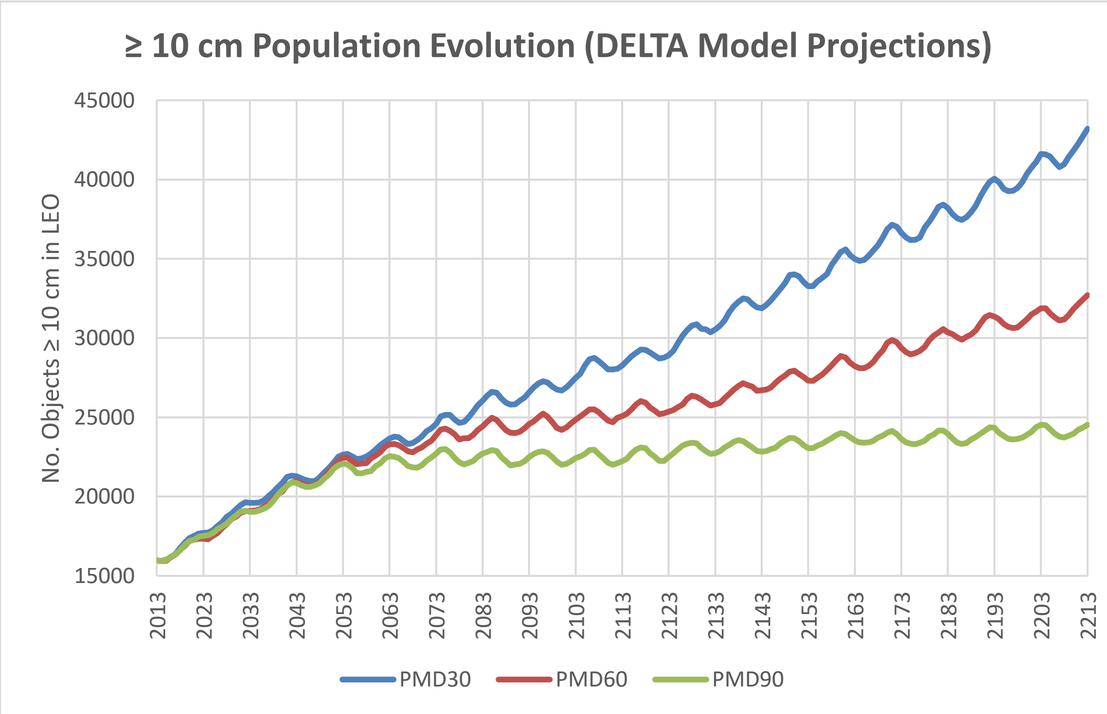


Figure 7. Debris (⩾ 10 cm) average population evolution in LEO as a function of the success probability of post-mission disposal in orbits with a residual lifetime of 25 years [ESA figure for IADC AI 31.5]

- **General**

  A combination of mission-related object elimination, passivation and post-mission de-orbiting to a limited lifetime orbit was found to be successful at controlling the future LEO debris environment in the long-term.

- **Post-mission de-orbiting to a limited lifetime orbit**

  It is desirable to shorten post-mission lifetime as far as possible in order to reduce population levels and collision risks in the long-term. However, shorter post-mission lifetimes are costlier for space systems to achieve using on-board propulsion systems.

  Only a modest near-linear increase in de-orbit manoeuvre propellant consumption would be needed to reduce post-mission lifetime over much of the range considered in this study. However, it has been found that decreasing post-mission lifetime to very short times would involve a substantial increase in the de-orbit propellant requirement.

Hence, based on the analysed post-mission lifetimes, a 25-year post-mission lifetime was found to be practicable without significant and disproportionate increases in de-orbit propellant consumption.

Therefore, a 25-year post-mission lifetime appears to be a good compromise between an immediate (or very short lifetime) de-orbit policy which is very effective but much more expensive to implement, and a 50 or 100-year lifetime de-orbit policy which is less costly to implement but can lead to higher collision risks in the long term.

Any concern for low-altitude manned mission safety in connection with post-mission de-orbiting is not warranted. Though the population of >10 cm objects will slightly increase in this region mainly due to perigee lowering, these large disposed objects can be, and are, tracked and avoided. The benefit to low-LEO altitudes attained by post-mission de-orbiting is a low and stabilised overall LEO collision rate. This directly prevents significant growth in the untrackable (but hazardous) centimetre-sized object population at all LEO altitudes, including low-LEO altitudes where manned missions are operating.

- **Estimation of penalty**

The propellant requirement to achieve a specified orbital lifetime will be higher if the operating orbit is high. For example, if orbital lifetime is limited to 25 years after mission completion, an amount of propellant equal to 4.59% of the mass of the vehicle will be required for the disposal operations from an altitude of 1000 km (see Table 3).

Table 3. Required propellant examples for lifetime reduction within 25 years

(I_{sp} = 200 sec, A/m = 0.05 m^2/kg)

Initial Circular Orbit Altitude	Final Perigee Altitude	Delta Velocity (ΔV)	Mass Fraction (Propellant / Dry Mass)
800 km	730 km	18 m/s	0.8%
1,000 km	630 km	88 m/s	4.3%
1,500 km	535 km	236 m/s	11%
2,000 km	495 km	349 m/s	17%

[Ref: Space Debris Handbook NASDA-CRT-98006, 1998] [8]

The IADC WG2 report [End-of-life Disposal of Space Systems in the Low Earth Orbit Region, IADC/WG2-2002-02, Version 2, March 2002] [10] also gives the propellant mass for re-orbit as shown in Figure (in the case of I_{sp} = 260 sec).

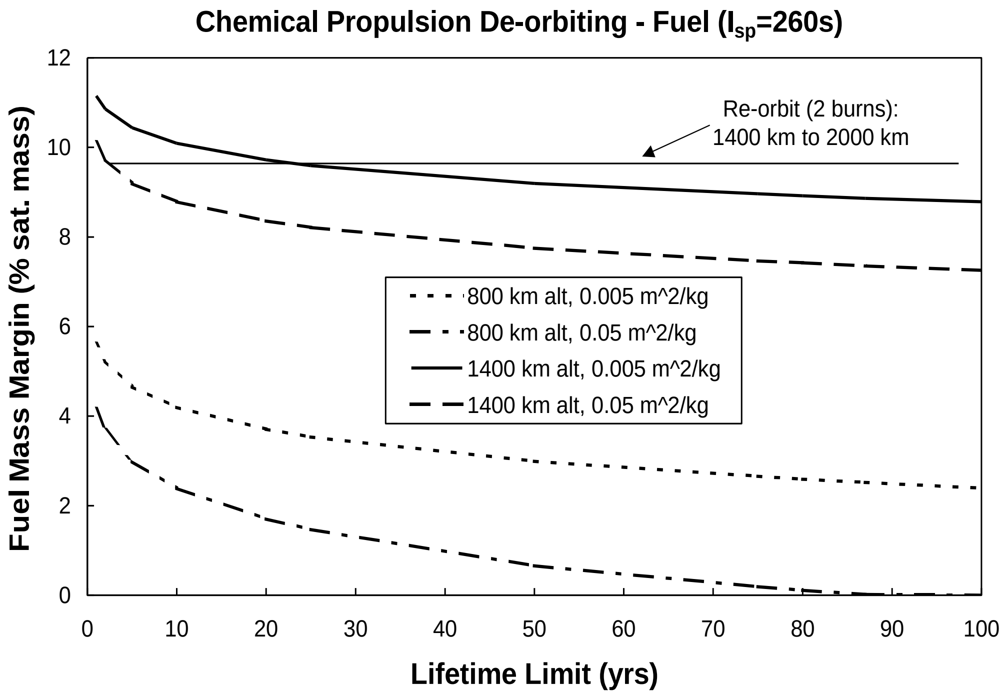


Figure 8. Cost of N-year post-mission lifetimes in terms of added fuel mass assuming use of conventional chemical propulsion systems

- **Practice (On-orbit retrieval)**

  With current technology, this option is not feasible for most spacecraft owners/operators. So, until such time that direct retrieval is a more commonly available option (perhaps by robotic means), this is not a practical solution.

- **Tailoring guide (Reduction of Orbital Lifetime)**

  One can take advantage of anticipated residual propellants set aside for other purposes, e.g., initial orbital injection, in determining propellant reserves for disposal manoeuvres.

- **Purpose (Ground Safety for Objects Surviving Re-entry)**

  One effective space debris mitigation measure is the removal of mission-terminated space objects from useful orbit regions and the disposal of them by aerodynamic heating during re-entry, if possible. However, the ground casualties that might be caused by fragments surviving atmospheric re-entry should be carefully considered in planning uncontrolled re-entry, particularly for large spacecraft.

  To assess the human casualty risk of impact by objects that survive re-entry, assessment parameters and their allowable levels, reliable analysis tools for survivability, and acceptable analysis conditions should be used.

- **Practice (Assessment of Re-entry Safety)**

  By January 2014 nearly 5,000 missions to Earth orbit had been accomplished since 1957. More than 50 large objects with an aggregate mass of approximately 100 metric tons typically re-enter in an uncontrolled manner every year.

  The re-entries of Cosmos 954 on Canadian territory in January 1978 and Skylab in the oceans and on Australia in July 1979 are well-known. Some additional major re-entries are listed in the following table.

Table 4. Examples of major unmanned re-entry events since 1980

Name	Nationality	Mass [kg]	Date of Decay	Mode
Salyut 6/Cosmos 1267	Russia	35,000	29-Jul-82	Controlled Re-entry
Cosmos 1443	Russia	15,000	19-Sep-83	Controlled Re-entry
Cosmos 1870	Russia	20,000	29-Jul-89	Controlled Re-entry
Salyut 7/Cosmos 1686	Russia	40,000	7-Feb-91	Uncontrolled Re-entry
Almaz 1	Russia	18,550	17-Oct-92	Controlled Re-entry
Compton GRO	USA	14,910	4-Jun-00	Controlled Re-entry
Mir	Russia	120,000	23-Mar-01	Controlled Re-entry

Typical parameters to assess re-entry safety are casualty area and the casualty expectation (Ec). An allowable Ec is not currently recommended in the IADC Guidelines, while the NASA Standard 8719.14 [2], the U.S. Government Orbital Debris Mitigation Standard Practices [4], the European Code of Conduct for Space Debris Mitigation [5] and the JAXA Space Debris Mitigation Standard) [3] limit the value of casualty expectancy (Ec) per re-entry event to less than or equal to 10^{-4}.

5.3.3 Other Orbits

Spacecraft or orbital stages that are terminating their operational phases in other orbital regions should be manoeuvred to reduce their orbital lifetime, commensurate with LEO lifetime limitations, or relocated if they cause interference with highly utilised orbit regions.

- **Purpose**

  General guidance is provided for end-of-life disposal of spacecraft and orbital stages in MEO, GTO and Molniya orbits. Technical studies have shown that disposal actions should consider the long-term stability of planned disposal orbits [12]. The required level of analysis and need to consider the relevant characteristics of the spacecraft or orbital stage to be disposed preclude the identification of specific guidelines.

A summary of end-of-life disposal actions for spacecraft or orbital stages in various orbital regions (GTO, MEO, Molniya) is given in the report of the Action Item 18.2 (GTO-MEO-Molnya Upper Stage Disposal) performed by IADC Working Group 4 [19]. The following Table 5 provides an overview of end-of-life disposal actions studied in detail.

Table 5. End-of-life disposal actions overview

Disposal Action	Subsynchronous GTO	Supersynchronous GTO	MEO Navigation Satellite Orbits	Molniya
25-Year Decay	Lower perigee to ~ 200 km.	Initial perigee ~ 200 km	Not recommended due to large ΔV required.	Not studied, but lowering perigee would require least ΔV.
Disposal Orbit	Between 2500 km and GEO-500 km. Launch Vehicle Upper Stages should reach GEO−500 km in less than 25 years	Not recommended	TBC: 1. Minimum long-term perigee of 2000 km, apogee below MEO. 2. Perigee 500 km above MEO or nearby operational region and e $\leq$ 0.003; RAAN and argument of perigee selected for stability	Set initial perigee of disposal orbit at 3000 km.
Direct Re-entry	Broad ocean area impact or other safe zone.	Not studied, but similar to *Subsynchronous GTO* case	Not recommended due to large ΔV required.	Broad ocean area impact or other safe zone.

5.4 Prevention of On-Orbit Collisions

In developing the design and mission profile of a spacecraft or orbital stage, a program or project should estimate and limit the probability of accidental collision with known objects during the spacecraft or orbital stage's orbital lifetime. If reliable orbital data is available, avoidance manoeuvres for spacecraft and co-ordination of launch windows may be considered if the collision risk is not considered negligible. Spacecraft design should limit the probability of collision with small debris which could cause a loss of control, thus preventing post-mission disposal.

- **Purpose**

  The above recommendation addresses:

  (1) Estimation of collision probability and taking measures, if necessary, in the planning phase;

  (2) Collisions with large objects during mission operations (collision avoidance);

  [This may be applied for large debris or orbiting vehicles (already tracked), and by an operational action (authorisation for launcher lift-off, collision avoidance manoeuvre). Such measures are already in place for some manned and unmanned spacecraft.]

  (3) Collision with small debris during mission operations.

  [This may be applied for small or very small debris (on the order of 1mm) with additional satellite shielding, a specific lay-out to protect the most sensitive components, or a separation of redundant components.]

- **Practice (Avoidance of On-orbit Collision)**

  The United States Space Surveillance Network (SSN), the Russian Space Surveillance System (SSS), France and some other sensor operators from various agencies monitor the Earth orbital environment and have the capability to predict close approaches between catalogued objects. This capability may be reduced when operational satellites are manoeuvred. The available public TLEs alone provided by the SSN are clearly an insufficient basis upon which to make manoeuvre decisions. The Combined Space Operations Center (CSpOC) notifies each spacecraft operator around the world whenever a close approach is predicted. Operators are also provided with covariance information sufficient to calculate a probability of collision.

  Information exchange between operators is encouraged especially in GEO when a controlled satellite approaches another operational satellite: exchange of orbital parameters allows the possibility to check distances, determine a possible collision risk and consider the necessity for an avoidance manoeuvre.

  Collision avoidance manoeuvres can affect satellite operations in several ways (e.g., propellant consumption, payload data and service interruptions, and temporary reduction in tracking and orbit determination accuracy), and manoeuvres should be minimized, consistent with spacecraft safety and mission objectives. Collision avoidance strategies are most effective when the uncertainty in the close approach distance is kept small, preferably less than 1 km. Ideally, collision avoidance would be based on the probabilistic approach. But this is not always practical. In such cases, a geometric criterion may be acceptable.

For GEO spacecraft and certain spacecraft constellations, coordinated stationkeeping is beneficial. Inclination and eccentricity vector separation strategies can be efficiently employed to maintain co-located GEO spacecraft at safe distances. Eccentricity vector control may also be employed to reduce the risk of collision between members of a given LEO satellite constellation.

- **Practice (Avoidance of Collision with New Launch)**

  Collision between an ascending launch vehicle and manned systems should be avoided. In some agencies, collision avoidance analysis for new launches is conducted and safe launch windows are established. In the event of a predicted conjunction, the launch is delayed.

- **Practice (Best Practices for Longitude Drift Phases in the GEO Region)**

  In the GEO region it is safer to avoid controlled longitude drifts (launch, relocation…), with an altitude too close to GEO altitude. The region between ± 40 km displays a high density of operational manoeuvring satellites together with abandoned satellites and rocket bodies. Standard collision avoidance process is difficult to conduct and can be less efficient in this case. Moreover, coordination between operators is not always possible because many longitude slots can be crossed during one relocation (or initial insertion) and operators might not have the knowledge of every other operator controlling a satellite on the way.

  For launch, targeting an altitude stand-off of 40 km below GEO is a good way to avoid this region. For a relocation, a combination of semi-major axis and eccentricity should be selected that ensures no penetration of this zone (GEO ± 40km) during the drift [21].

- **Practice (Protection)**

  All of these types of protection could add mass, volume, or layout complexity and could become cost drivers for satellites, where one usually tries to reduce mass and volume (hence, possibly decreasing launch cost). Furthermore, it can be difficult to demonstrate their efficiency (in reasonable extra costs) for the protection against collision effects, with relative velocities higher than 10 km/sec. Therefore, protection strategy (debris size, impact direction, protected devices, etc.) should be studied.

6. Update

These guidelines may be updated as new information becomes available regarding space activities and their influence on the space environment.