STATUS OF THE ISO SPACE DEBRIS MITIGATION STANDARDS (2017)

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ABSTRACT

Since 2010, the International Organization for Standardization (ISO) has published a comprehensive set of space system engineering standards aimed at mitigating space debris. The standards are arranged in a hierarchical structure. Primary requirements are defined in the top-level standard, ISO 24113. Below ISO 24113 in the hierarchy is a collection of lower-level standards and technical reports. These contain detailed requirements, implementation measures and engineering practices for complying with the high-level requirements in ISO 24113. This paper describes the current scope of each of the standards before discussing how they will evolve in the near future. Particular attention is given to ISO 24113, which is currently undergoing a major review. It is likely that a number of fundamental changes will be incorporated.

1 INTRODUCTION

The growing population of space debris poses an increasing hazard to space missions. In response to this problem, there is international consensus that space activities need to be carefully managed to minimize debris generation and risk. This consensus is embodied in space debris mitigation guidelines published by organizations such as the International Telecommunication Union (ITU) [1], the Inter-Agency Space Debris Coordination Committee (IADC) [2][3] and the United Nations (UN) [4]. The transformation of these guidelines into engineering practice is a key aim of the space debris mitigation standards published by the International Organization for Standardization (ISO). This paper provides an update on the status of ISO's space debris mitigation standards, and explains how the standards will evolve over the next few years.

2 CURRENT FRAMEWORK

Since 2010, ISO has been publishing a set of International Standards and Technical Reports with the aim of ensuring that spacecraft and launch vehicle orbital stages are designed, operated and disposed of in a manner that prevents them from generating space debris throughout their orbital lifetime [5] – [19]. This framework of documents has a hierarchical structure, as shown in Fig. 1. The top-level International Standard, ISO 24113, is perhaps the most important document. It defines the primary space debris mitigation requirements applicable to all elements of unmanned systems launched into or passing through near-Earth space, including launch vehicle orbital stages, operating spacecraft and any objects released as part of normal operations or disposal actions.

Below ISO 24113 in the framework's hierarchy there are several lower-level International Standards and Technical Reports which describe detailed requirements and implementation measures designed to enable compliance with the high-level requirements in ISO 24113. These documents address all of the important aspects of debris mitigation for spacecraft and orbital stages, including post-mission disposal, preventing on-orbit break-ups, estimating orbit lifetime, limiting re-entry risk, avoiding collisions and assessing survivability against debris impacts.

At the lowest level in the framework's hierarchy there are two supporting Technical Reports which contain non-normative information to guide space system engineers in the application of the aforementioned standards.

Most of the ISO space debris mitigation standards have now been published and can be employed in a variety of ways. For example, they can be adopted voluntarily by a spacecraft manufacturer or operator, or brought into effect through a commercial contract between a customer and supplier, or used as the basis for establishing a set of national regulations on space debris mitigation.

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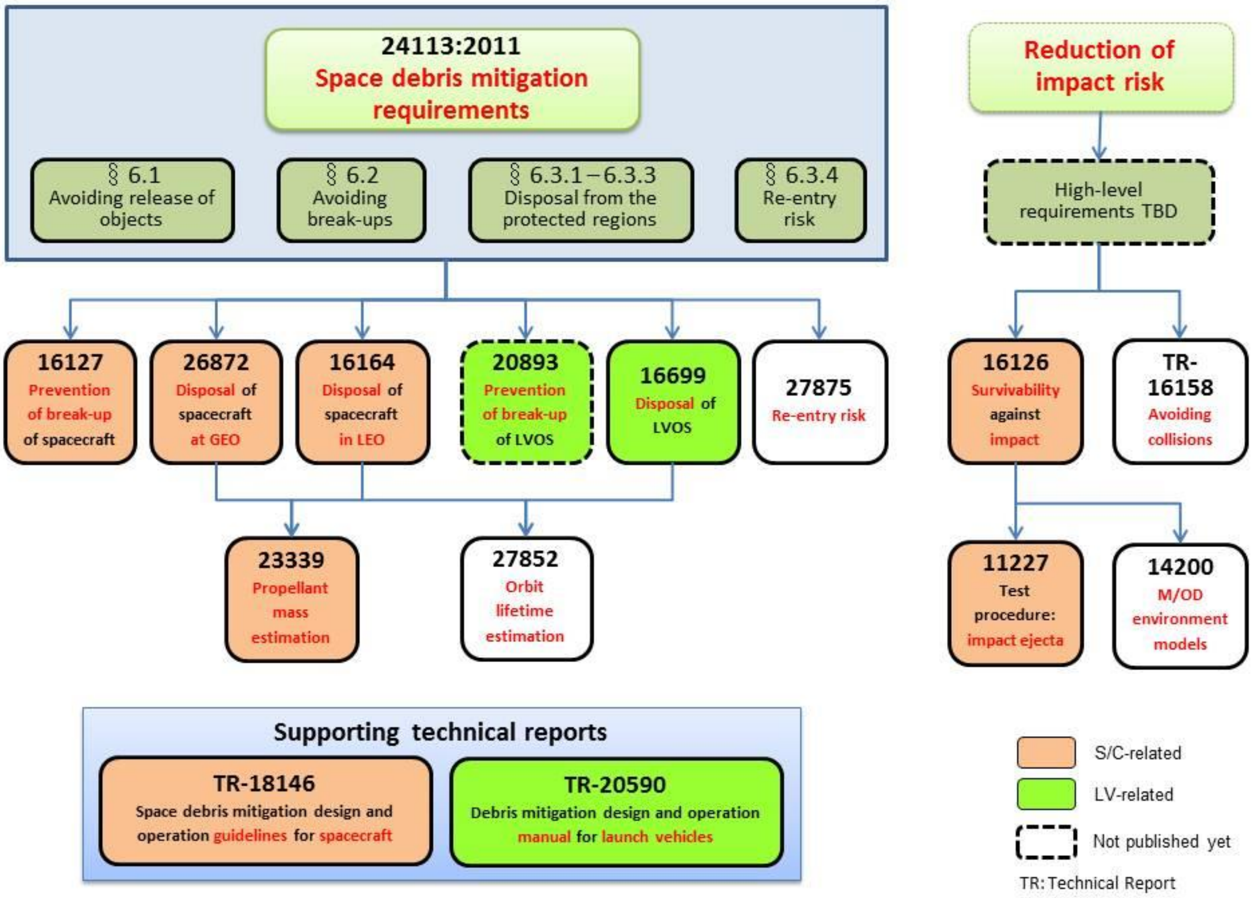


Figure 1. Current framework of the ISO space debris mitigation standards

3 SCOPE OF EACH STANDARD

3.1 ISO 24113:2011 (Space systems — Space debris mitigation requirements)

ISO 24113 is the top-level standard in a family of standards addressing debris mitigation. It is the main interface for the user, bridging between the primary debris mitigation requirements and the lower-level implementation standards that will ensure compliance.

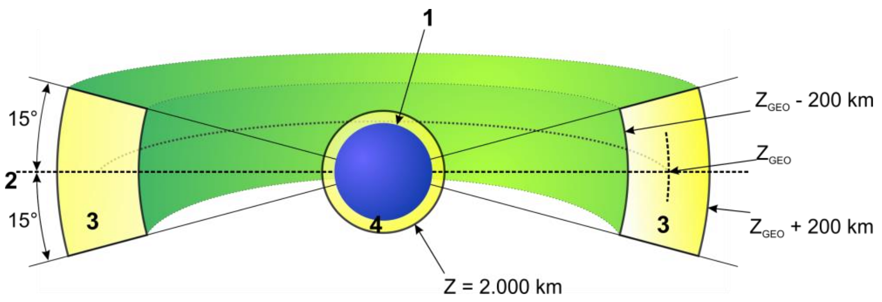
The high-level requirements in ISO 24113 are intended to reduce the growth of space debris by ensuring that spacecraft and launch vehicle orbital stages are designed, operated and disposed of in a manner that prevents them from generating debris throughout their orbital lifetime. This is accomplished by implementing the following measures:

1. avoiding the intentional release of space debris into Earth orbit during normal operations,
2. avoiding break-ups in Earth orbit,
3. removing spacecraft and launch vehicle orbital stages from the protected orbital regions (see Fig. 2) after end of mission,
4. performing the necessary actions to minimize the risk of collision with other space objects, and
5. controlling the risk to the human population from space objects re-entering the Earth's atmosphere.

Such measures are especially important for a space system that has one or more of the following characteristics:

- A large total collision cross-section
- Remains in orbit for many years
- Operates near manned mission orbital regions
- Operates in highly utilized regions (e.g. protected regions)
- Operates in regions of high debris population

Of particular importance in ISO 24113 is the requirement for post-mission disposal from the Low Earth Orbit (LEO) protected region. This states that "A spacecraft or launch vehicle orbital stage operating in



Key

1	Earth
2	equator
3	GEO protected region
4	LEO protected region
Z	altitude measured with respect to a spherical Earth whose radius is 6,378 km
Z_{GEO}	altitude of the geostationary orbit with respect to a spherical Earth whose radius is 6,378 km

Figure 2. Three-dimensional view of Earth and the protected regions

the LEO protected region, with either a permanent or periodic presence, shall limit its post-mission presence in the LEO protected region to a maximum of 25 years from the end of mission.” This so-called 25-year rule is derived from one of the guidelines in [2]. It represents an *upper limit* for the amount of time that a space system shall remain in orbit after its mission is completed. Ideally, the time to deorbit should be as short as possible (i.e. much shorter than 25 years).

3.2 ISO 16127:2014 (Space systems — Prevention of breakup of unmanned spacecraft)

One potential source of space debris is the break-up of an unmanned spacecraft either during or after the end of its operational life. This can be caused by the sudden release of a large amount of energy stored on-board the spacecraft as a result of an unplanned, internally-driven event. The cloud of debris ejected from the break-up of the spacecraft would then pose a significantly greater collision hazard in Earth orbit than a single intact spacecraft.

ISO 16127 defines design and operational requirements to reduce the risk of a spacecraft breaking up, both during and after its operational life. Particular attention is paid to those systems which are the most likely to cause the break-up of a spacecraft, including:

- Electrical systems, especially batteries
- Propulsion systems and associated components
- Pressurized systems
- Rotating mechanisms

ISO 16127 also specifies actions to be taken to passivate a spacecraft, which is the process for removing sources of stored energy, or depleting them to a safe level, in a controlled manner when they are no longer needed.

3.3 ISO 20893:— (Space systems — Prevention of breakup of orbital launch stages)

ISO 20893 is currently in development. When published, it will specify design and operational requirements to limit the risk of on-orbit break-up of a launch vehicle orbital stage caused by an unplanned, internally-driven event. Therefore, it can be considered as a sister document to ISO 16127.

The requirements in ISO 20893 will cover a range of break-up preventive measures, such as venting of propellant, the release of high-pressure gas, the prevention of the rupture of batteries and avoiding the explosion of range safety systems.

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

ISO 26872 prescribes requirements for planning and executing manoeuvres and operations to remove an operating spacecraft from geosynchronous orbit at the end of its mission, and place it in an orbit for final disposal where it will not pose a future hazard to other space systems operating in the geosynchronous ring.

In particular, ISO 26872 specifies requirements related to the following:

- When to initiate the disposal action. This includes planning for the disposal of a spacecraft operating at geosynchronous altitude to ensure that final disposal is sufficiently characterized and that adequate propellant will be reserved for the manoeuvre
- Selecting a final disposal orbit where the spacecraft will not re-enter the Geostationary Earth Orbit (GEO) protected region within 100 years
- Executing the disposal manoeuvre successfully

For a spacecraft operating in the geosynchronous ring, the most effective means of disposal is first to raise it to a super-synchronous orbit (well above the region of other operating spacecraft and the manoeuvre corridor used for relocating operating spacecraft to new longitudinal slots), and then to take actions to preclude a debris-producing event, i.e. passivating the spacecraft.

3.5 ISO 16164:2015 (Space systems — Disposal of satellites operating in or crossing Low Earth Orbit)

ISO 16164 prescribes requirements for planning, executing manoeuvres, and operations for the post-mission disposal of a spacecraft operating in or crossing LEO. Therefore, it can be considered as a sister document to ISO 26872. Included in ISO 16164 are requirements relating to the initiation and successful execution of the LEO disposal actions.

Specific requirements are defined for:

- Planning the disposal of spacecraft operating in LEO to ensure that final disposal is sufficiently characterized and that adequate propellant will be reserved for any propulsive manoeuvre required.
- Selecting a disposal orbit where the spacecraft will re-enter the Earth's atmosphere within 25 years of the end of mission. Alternatively, a disposal orbit may be selected where the spacecraft will not re-enter the LEO protected region within 100 years, but this is a less desirable option.
- Estimating, prior to launch, a 90% or better probability of successfully executing the disposal manoeuvre (under the condition of successfully completing the mission).

The requirements in ISO 16164 provide means for a LEO spacecraft to comply with the following six disposal options specified in ISO 24113:

1. Retrieving it and performing a controlled re-entry to recover it safely on the Earth
2. Manoeuvring it in a controlled manner into a targeted re-entry with a well-defined impact footprint on the surface of the Earth to limit the possibility of human casualty
3. Manoeuvring it in a controlled manner to an orbit that has a decay lifetime short enough to meet all orbital debris mitigation requirements
4. Augmenting its orbital decay by deploying a device so that the remaining orbital lifetime is short enough to meet all orbital debris mitigation requirements
5. Allowing its orbit to decay naturally, given that all orbital debris mitigation requirements will be met without the need for a disposal manoeuvre or other action
6. Manoeuvring it in a controlled manner to an orbit with a perigee altitude sufficiently above the LEO protected region (i.e. a graveyard orbit) that long-term perturbation forces do not cause it to re-enter the LEO protected region within 100 years.

3.6 ISO 16699:2015 (Space systems — Disposal of orbital launch stages)

A launch vehicle orbital stage plays a critical role in moving a spacecraft towards its final mission orbit. Once the spacecraft has been delivered to the desired orbit, the stage can then be separated from the spacecraft. If the stage itself is in orbit and is deactivated at this point, it becomes another object in the growing population of space debris – an uncontrolled object that could be a hazard to operational satellites for the remainder of its orbit lifetime.

ISO 16699 specifies how a spacecraft owner and a launch service provider shall work together to develop spacecraft deployment options which will lead to the disposal of an orbital launch stage in compliance with ISO 24113. That is, the orbital stage must either re-enter the Earth's atmosphere within 25 years, or it must be placed into an orbit that does not intersect the protected regions for a very long time. Furthermore, all sources of stored energy remaining in the stage must be eliminated prior to the stage's final disposal (except in cases where the stage will execute a controlled re-entry into the atmosphere).

3.7 ISO 23339:2010 (Space systems — Unmanned spacecraft — Estimating the mass of remaining usable propellant)

For spacecraft disposal manoeuvres to be performed as planned, the estimation of available propellant mass is essential. ISO 23339 gives requirements for estimating the mass of the remaining usable propellant of an unmanned spacecraft in LEO or GEO, and for designing propellant measurement systems. It is applicable to spacecraft with either mono- or bi-propellant propulsion systems using liquid or gaseous chemical propellants, as these are the most common for spacecraft in LEO and GEO. ISO 23339 can be considered as a supporting document to the two spacecraft disposal standards – ISO 26872 and ISO 16164.

3.8 ISO 27852:2016 (Space systems — Estimation of orbit lifetime)

ISO 27852 is a supporting document to ISO 24113 and all of the GEO and LEO disposal standards (ISO 26872, ISO 16164 and ISO 16699). The purpose of this standard is to provide a common consensus approach to determining orbit lifetime within the context of the post-mission 25-year orbit lifetime requirement, one that is sufficiently precise and easily implemented that compliance with ISO 24113 can be readily demonstrated.

In particular, ISO 27852 describes a process and analysis methods to estimate the orbit lifetimes of spacecraft, launch vehicle orbital stages and associated debris in LEO-crossing orbits (see Fig. 3). The standard

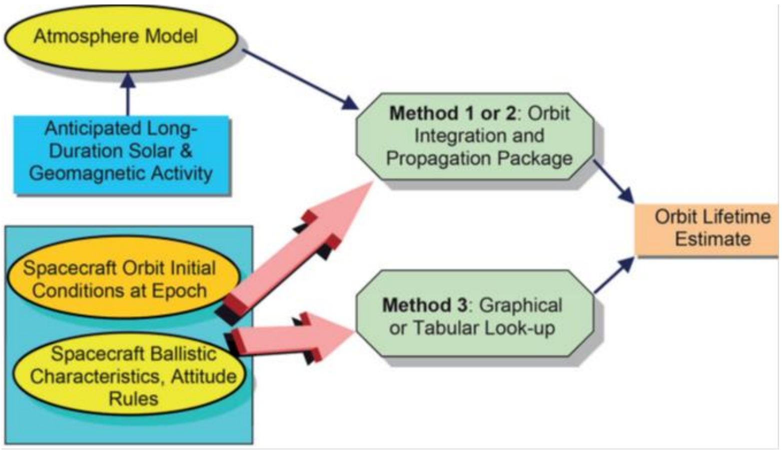


Figure 3. Orbit lifetime estimation process

also describes:

- Modelling approaches and resources for solar and geomagnetic activity modelling
- Resources for atmosphere model selection
- Approaches for spacecraft ballistic coefficient estimation

3.9 ISO 27875:2010 + Amendment 1:2016 (Space systems — Re-entry risk management for unmanned spacecraft and launch vehicle orbital stages)

According to international treaties, the Launching State is liable for damage or injuries caused by unmanned spacecraft and launch vehicle orbital stages that re-enter the Earth's atmosphere. Furthermore, commercial operators who plan to re-enter a spacecraft or orbital stage must abide by the relevant national regulations of the Launching State. In order to minimize damage and injury from the re-entry of a spacecraft or orbital stage, it is the responsibility of all parties (developers, manufacturers, space service providers, satellite operators and launch service providers) to implement preventive measures during the design and operation of a space vehicle.

ISO 27875 provides a framework with which to assess, reduce and control the potential risks that spacecraft and launch vehicle orbital stages pose to people and the environment when these space vehicles re-enter the Earth's atmosphere and impact the Earth's surface. It is intended to be applied to the planning, design and review of space vehicle missions for which controlled or uncontrolled re-entry is possible. This standard is currently being revised to include more detailed requirements for controlled re-entry.

3.10 ISO/TR 16158:2013 (Space systems — Avoiding collisions with orbiting objects)

ISO/TR 16158 describes the work flow for perceiving and avoiding collisions among orbiting objects, data requirements for these tasks, techniques that can be used to estimate the probability of collision and guidance for executing avoidance manoeuvres.

The process begins with obtaining the best possible trajectory and uncertainty data from satellite operators and/or sensor systems developed for this purpose. The orbits of the conjuncting space objects must be compared with each other to identify close approaches that could feasibly result in a collision. The trajectories so revealed must then be examined more closely to estimate the probability of collision. Should a collision be likely within the criteria established by each satellite operator, the spectrum of feasible manoeuvres must be examined.

It should be noted that ISO/TR 16158 is a Technical Report, not an International Standard. At the time this technical report was published (2013), there was insufficient consensus to derive a meaningful set of detailed requirements relating to conjunction assessment and collision avoidance. Therefore, the content of ISO/TR 16158 is informative rather than normative.

3.11 ISO 16126:2014 (Space systems — Assessment of survivability of unmanned spacecraft against space debris and meteoroid impacts to ensure successful post-mission disposal)

Any space system in Earth orbit will be exposed to impact fluxes from space debris and meteoroids. These fluxes can be large enough to represent a significant risk to some spacecraft. ISO 16126 prescribes high-level requirements for assessing the impact survivability of an unmanned spacecraft operating within this environment. Compliance with these requirements should ensure the survival of spacecraft components used to perform post-mission disposal.

To this end, ISO 16126 also defines two alternative impact risk analysis procedures. The first procedure is relatively simple, whereas the second is more detailed and rigorous. With careful application, either of these procedures can be used to demonstrate that a spacecraft design will be robust enough to exceed a certain 'probability of no failure' threshold.

Finally, ISO 16126 contains several annexes providing background information on a variety of relevant survivability assessment topics, such as ballistic limit equations, hypervelocity impact testing and modelling, and options for improving impact protection on spacecraft.

3.12 ISO 14200:2012 (Space environment (natural and artificial) — Guide to process-based implementation of meteoroid and debris environmental models (orbital altitudes below GEO+2000km))

A wide variety of software models have been developed over the past 20 years to describe the populations of meteoroids and space debris. The models differ in terms of their input data sources and the mathematical techniques and physical processes employed. Not surprisingly, results from the models can diverge significantly, particularly when characterising the populations of small size debris and meteoroids. An example of this is shown in Fig. 4. Consequently, at the present time it is not possible to define a single, standard model of the debris and meteoroid environments.

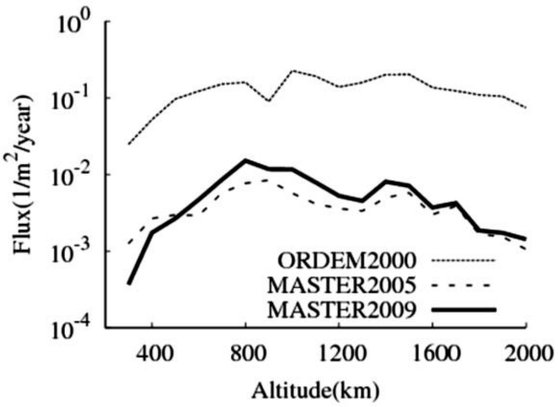


Figure 4. Comparison of results from different debris models (cumulative flux of debris >1 mm in diameter on an object in a circular, 100° inclination orbit at different altitudes during the year 2000)

In recognition of this situation, ISO has published an International Standard, ISO 14200, which specifies a common process for the selection and use of a model from the many available models. This is especially important if the output flux data from the model is to be used as an input to impact risk analysis codes for the purpose of assessing the impact survivability of a spacecraft. Therefore, ISO 14200 can also be considered as a supporting document to ISO 16126.

3.13 ISO 11227:2012 (Space systems — Test procedures to evaluate spacecraft material ejecta upon hypervelocity impact)

ISO 11227 describes an experimental procedure for assessing the behaviour, under orbital debris or meteoroid impacts, of materials that are intended to be used on the external surfaces of spacecraft and launch vehicle orbital stages. ISO 11227 provides a unified method by which to rank such materials. The ejecta production characteristics of different materials are compared under standardized conditions in which a limited set of test parameters is defined. Optional tests with different parameters are also suggested for the proper selection of materials in other conditions.

ISO 11227 establishes testing method requirements for characterizing the amount of ejecta produced when a surface material is impacted by a hypervelocity projectile. Its purpose is to evaluate the ratio of ejecta total mass to projectile mass, and the size distribution of the resulting fragments. These are the necessary inputs for modelling the amount of impact ejecta that a surface material might release during its orbital lifetime. From this, it is possible to assess the suitability of the material for use in space, particularly in terms of mitigating the production of small-size debris.

3.14 ISO/TR 18146:2015 (Space systems — Space debris mitigation design and operation guidelines for spacecraft)

ISO/TR 18146 contains non-normative information on spacecraft design and operational practices for mitigating space debris. It is a supporting document to the family of international standards addressing space debris mitigation, as summarised in the preceding sub-sections.

This Technical Report can be used to guide spacecraft engineers in the application of the space debris mitigation standards. It begins by listing the main debris mitigation requirements defined in the standards and compares them to equivalent recommendations published by the United Nations and the Inter Agency Space Debris Coordination Committee. The document then discusses the following in some detail:

- The main space debris mitigation requirements

- Guidance for implementing debris mitigation in a spacecraft at each phase of its lifecycle
- Consideration of system level aspects to ensure compliance with debris mitigation requirements
- The impact of debris mitigation measures on the design and operation of spacecraft at subsystem and component levels

It is expected that ISO/TR18146 will be particularly beneficial for spacecraft manufacturers and operators who are relatively new to the space industry and have little experience with addressing space debris issues. The document should also be useful to those who are engaged in the development of low cost / low reliability spacecraft. While the failure of these types of spacecraft may not pose a significant problem for their owners, such failures may adversely affect the orbital environment and undermine the sustainability of space activities. This Technical Report suggests activities that can improve spacecraft reliability and quality sufficiently to avoid this problem.

3.15 ISO/TR 20590:2017 (Space systems — Debris mitigation design and operation manual for launch vehicle orbital stages)

ISO/TR 20590 is a sister document to ISO/TR 18146 and follows exactly the same structure. However, this document's focus is to provide non-normative information on launch vehicle orbital stage design and operational practices for mitigating space debris.

4 FUTURE FRAMEWORK

Following the publication of the debris mitigation standards, the ISO working group responsible for their development – ISO/TC20/SC14/WG7 – has been considering a number of options for improving these documents. Feedback from industry has been particularly important in this respect. As a consequence, WG7 has constructed a new framework with the aim of consolidating the lower-level standards into a more concise and coherent set of documents whilst retaining all of the key debris mitigation requirements that have been published to date. It is expected that this new set of documents will be available within the next two years.

The new framework is illustrated in Fig. 5. The main differences between this framework and that shown in Fig.1 concern the mid-level documents. Firstly, the four spacecraft-related debris mitigation standards will be combined, i.e. the content of ISO 16127, ISO 16164, ISO 23339 and ISO 26872 will be merged into one document. The five-digit ISO number for this new document has not yet been assigned. However, it is expected that the title will be "Space systems — Detailed space debris mitigation requirements for spacecraft". Once this document is published, the four spacecraft-related standards – ISO 16127, ISO 16164, ISO 23339 and ISO 26872 – will be cancelled.

Secondly, the content of the two launch vehicle-related standards, ISO 16699 and ISO 20893, will also be combined into one standard. Since ISO 20893 is not yet published, this newly-merged document will be developed under the ISO five-digit number, 20893, and the title modified accordingly. When ISO 20893 is ready for publication, ISO 16699 will then be cancelled.

5 NEW VERSION OF ISO 24113

In addition to the consolidation activity, the first five-year systematic review of ISO 24113 has recently been initiated. All ISO standards undergo such a process to ensure that they remain relevant and up-to-date, and WG7 is responsible for overseeing the review of ISO 24113. It is likely that a substantially-revised version of the document will be published in 2018. The main changes currently being considered are as follows:

- Several of the definitions for terms such as 'spacecraft' and 'launch vehicle' may be modified to increase consistency in the use of these terms across all of ISO's space-related standards.
- A limit may be placed on the number of space debris objects released into Earth orbit by a launch vehicle during normal operations. For the launch of a single spacecraft, it is expected that no objects shall be released, whereas for the launch of multiple spacecraft, a maximum of one object (typically an adapter) will be allowed.
- A size limit of 1 mm may be placed on the diameter of slag particles ejected from solid rocket motors. The use of solid rocket motors on GTO / GEO missions is not recommended.
- The requirement for a spacecraft or orbital stage to have a 'conditional' probability of successful post-mission disposal of at least 0.90 may be modified. It is likely that the probability will no longer be conditional (i.e. based on mission success). As a consequence of this redefinition of the disposal probability, it may be necessary to require a non-conditional probability of successful disposal with a value in the region of 0.85. This is still being debated within WG7.
- A possible change to the requirement for a LEO spacecraft or orbital stage to be deorbited within 25 years of the 'end of mission' is under consideration. Specifically, if a spacecraft or orbital stage has no capability to perform collision avoidance manoeuvres, then the 25-year deorbit timescale may be modified to begin at the original orbit injection epoch rather than at the end of mission.

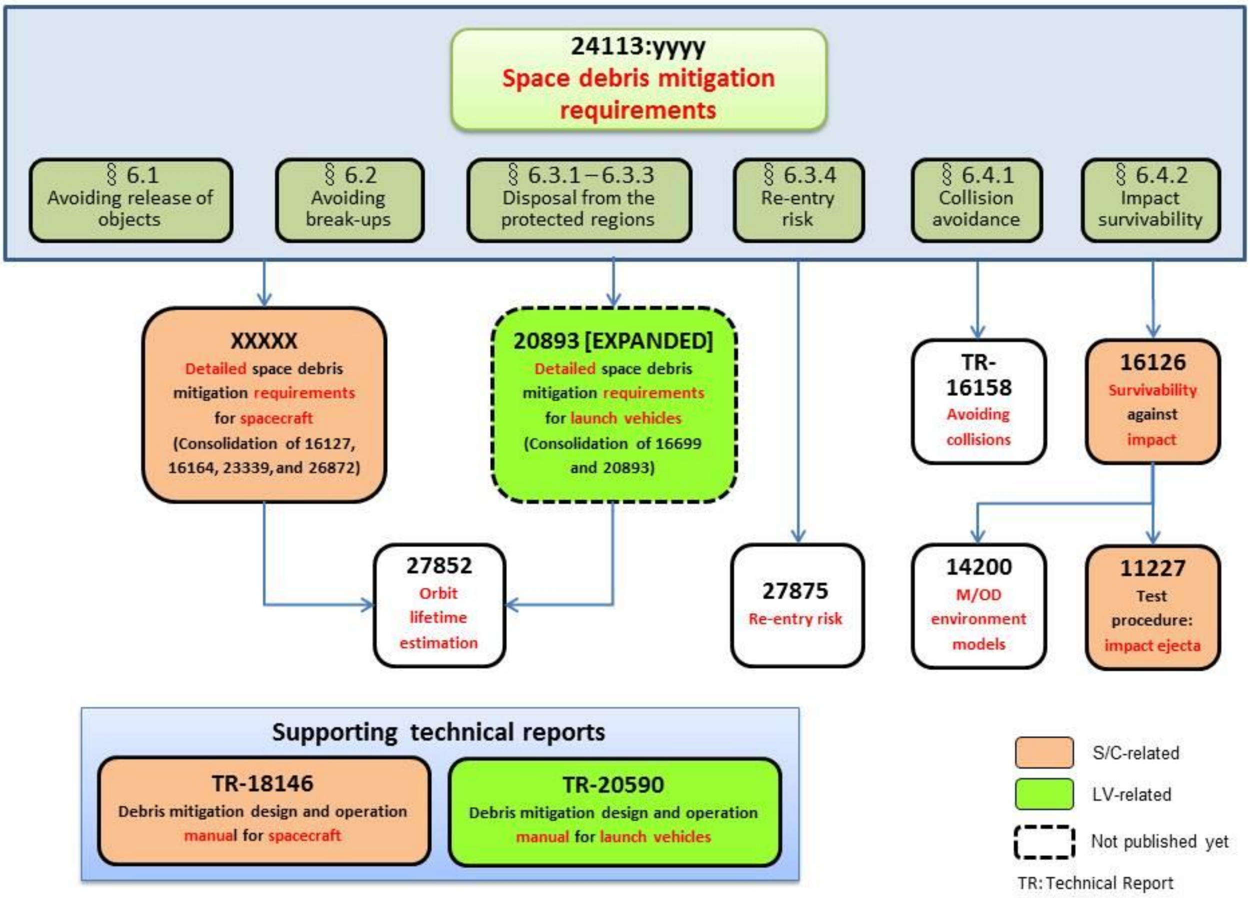


Figure 5. Future framework of the ISO space debris mitigation standards

When ISO 24113 was first published in 2011, it was not possible to include high-level requirements pertaining to collision avoidance or survivability against small debris and meteoroid impacts. This resulted in a disconnect between ISO 24113 and some of the mid-level debris documents, such as ISO 16126 and ISO 16158, as shown in Fig. 1. However, changes in the industry since 2011 have allowed such requirements to be considered again for ISO 24113. In particular, clauses are now being introduced which will require spacecraft collision risk to be actively managed and, where appropriate, avoidance manoeuvres performed. It is likely that there will also be a requirement for debris/meteoroid impact risk to be assessed during the design of a spacecraft. These additions and enhancements will enable ISO 24113 to be fully connected to all of the lower-level standards, as illustrated in Fig. 5.

Another significant difference in the space industry since 2011 has been the rapid increase in the volume of launch traffic. Large numbers of small spacecraft, especially CubeSats, are now being placed into low Earth orbit on a regular basis by a wide variety of organisations, many of whom are new to the industry. Furthermore, in the near future it is expected that large constellations comprising hundreds or even thousands of satellites will be launched into LEO. As a consequence of these ‘en masse deployments’, several new clauses have been proposed for ISO 24113 to minimise the inherent collision risks. These are currently being actively discussed within WG7.

The membership of WG7 comprises representatives from industry and major space agencies. The group is keenly aware of the delicate balance that ISO 24113 must strike between preserving the space environment and facilitating its commercial exploitation. Widespread adoption of ISO 24113, particularly by newcomers to the space industry, is seen as an important step in creating a sustainable space environment.

6 SUMMARY

Since 2010, the International Organization for Standardization, ISO, has been publishing a comprehensive set of spacecraft engineering standards specifically aimed at mitigating space debris. These documents consist of a top-level standard supported by a collection of lower-level implementation standards and informative technical reports. The top-level standard, ISO 24113 (Space systems – Space debris mitigation requirements) prescribes high-level debris mitigation measures which have been derived largely from internationally-agreed guidelines, such as those established by the IADC. The purpose of these documents is to prevent the intentional release of debris into Earth orbit during normal operations, avoid break-ups in Earth orbit, and remove spacecraft and launch vehicle orbital stages from high-value orbital regions after the end of mission. To help achieve compliance with these high-level measures, the lower-level implementation standards provide detailed methods and procedures that specify definite actions to be taken by satellite manufacturers and operators. In general, the implementation standards capture the best practices of industry, thus maximizing their potential for adoption.

7 ACKNOWLEDGEMENTS

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12. ISO 27852:2016, *Space systems — Estimation of orbit lifetime*
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19. ISO/TR 20590:2017, *Space systems — Debris mitigation design and operation manual for launch vehicle orbital stages*