STATUS OF THE ISO STANDARDS ON SPACE DEBRIS MITIGATION

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ABSTRACT

The past decade has seen the publication of a number of internationally-agreed guidelines and recommendations aimed at mitigating the growth in orbital space debris. In particular, the guidelines of the Inter-Agency Space Debris Co-ordination Committee (IADC) recommend a number of important debris mitigation measures. ISO – the International Organisation for Standardisation – is now transforming these guidelines into a set of measurable and verifiable requirements to minimise the creation of debris during the launch, operation, and disposal of space systems. The requirements are contained in a series of standards that also capture industry best practice and specify definite actions to be taken by satellite manufacturers and operators to achieve compliance. In this paper, the scope and status of each standard is discussed. Particular emphasis is given to the top-level standard, which contains all of the high-level debris mitigation requirements, and four high priority supporting standards that provide procedures and practices to enable compliance with the high-level requirements.

1. INTRODUCTION

Over the past 50 years the population of man-made debris orbiting the Earth has grown to such an extent that users of space can no longer ignore the hazard that it presents. There is now international acceptance that space activities need to be carefully managed to minimise the generation of space debris and its associated risks. Widespread awareness of the problem has been achieved largely thanks to the efforts of organisations such as the Inter-Agency Space Debris Coordination Committee (IADC), the International Telecommunication Union (ITU), and the United Nations (UN), all of whom have published internationally-agreed guidelines or recommendations aimed at mitigating the growth in space debris [1][2][3][4].

In recognition of the importance of these publications the International Organization for Standardization (ISO), approximately five years ago, initiated the development of a series of spacecraft engineering standards for space debris mitigation. The purpose of these standards is to transform the internationally-agreed debris mitigation guidelines into (a) a set of measurable and verifiable high-level requirements, and (b) detailed methods and processes to enable compliance with the high-level requirements. Ultimately, it is intended that the standards will help to reduce the growth in space debris by ensuring that space systems are designed, operated and disposed of in a manner that prevents them from generating debris throughout their orbital lifetime.

The top-level standard in the series is designated ISO 24113 "Space Systems – Space Debris Mitigation". It contains all of the high-level debris mitigation requirements, and is scheduled to be published in 2009. Detailed procedures and practices to achieve compliance with the high-level requirements in ISO 24113 are contained in a series of lower level implementation standards, of which the four highest priority are:

- Space Systems – Disposal of Satellites Operating at Geosynchronous Altitude (ISO 26872).
- Space Systems – Disposal of Satellites Operating in Low Earth Orbit.
- Space Systems – End of Life Passivation of Unmanned Spacecraft.
- Space Systems – Re-entry Risk Management for Unmanned Spacecraft and Launch Vehicle Orbital Stages (ISO 27875).

Publication of these implementation standards is due to begin in 2009. This paper describes their scope and status, with particular reference to the requirements in ISO 24113.

2. ISO 'SPACE' STANDARDS

The ISO Technical Committee "Aircraft And Space Vehicles" Sub-Committee "Space Systems And Operations" (known as ISO TC20/SC14) has been developing standards on space system manufacture and operation since 1993. TC20/SC14 comprises national delegations, which are usually represented by the standards bodies of those countries. In TC20/SC14 the

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following countries participate as Permanent (P-) Members: Brazil, Canada, China, France, Germany, Israel, Italy, Japan, Russia, Ukraine, UK, and USA. P-Members have the right to vote on standards.

The development of standards is carried out by six working groups within TC20/SC14. These comprise technical experts from each of the national delegations. In addition to this expertise, TC20/SC14 also maintains liaisons with experts in other organisations, including COSPAR, ECSS, ESA, and IADC.

ISO standards are generally developed according to a three-year timescale, although an accelerated two-year schedule or an enlarged four-year schedule is also permissible. During this period, a draft document generally passes through the following review stages before it can be published:

- Working Draft (WD)
- Committee Draft (CD)
- Draft International Standard (DIS)
- Final Draft International Standard (FDIS)
- International Standard (IS)

After publication, a standard must also undergo periodic systematic reviews to ensure that it remains current and in use.

3. ISO 'DEBRIS MITIGATION' STANDARDS IN DEVELOPMENT

ISO TC20/SC14 initiated discussions on the development of space debris mitigation standards in 2001. At the annual plenary meeting in May 2003, TC20/SC14 agreed to the formation of the Orbital Debris Co-ordination Working Group (ODCWG). This group was tasked to: develop a plan for the preparation of ISO debris mitigation standards; coordinate the development of debris mitigation standards within TC20/SC14; and establish and maintain external liaisons with organisations involved in debris mitigation.

At the outset, ODCWG decided that the scope of the standards should be entirely consistent with existing internationally-agreed debris mitigation guidelines, particularly those published by the IADC. By transforming the guidelines into a set of measurable and verifiable requirements, this would provide a sound technical basis for the standards.

As of March 2009, seven debris-related ISO standards are in development and six more have been proposed for development (known as New Work Item Proposals or NWIPs). Fig. 1 provides a simplified representation of their interrelationship, and Fig. 2 shows the schedule of the seven that are in development.

The top-level debris mitigation standard, which is designated ISO 24113 "Space Systems – Space Debris Mitigation", contains all of the primary debris mitigation requirements over the life cycle of a space system, and is considered to be the highest priority of all the standards. It is also the main interface with the other standards, which are lower level documents containing procedures and practices to enable compliance with the primary requirements in ISO 24113. Four of these low-level 'implementation' standards are considered to be high priority developments, and are discussed more fully below.

3.1. ISO 24113: Space Systems – Space Debris Mitigation

ISO 24113 is due to be published in 2009. It provides high-level debris mitigation requirements for all elements of unmanned space 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.

Many of the requirements in ISO 24113 concern the removal of spacecraft or launch vehicle orbital stages from the geostationary orbit (GEO) and low Earth orbit (LEO) regions after end of mission. This is necessary to ensure the long-term, safe and sustainable use of both of these high-value regions, which the standard defines as 'protected' with regard to the generation of space debris. The boundaries of the protected regions are illustrated in Fig. 3.

Other requirements aim to avoid the intentional release of space debris into Earth orbit during normal operations. In this regard, the release of solid rocket motor products is of particular concern. Requirements have also been specified to avoid intentional or accidental break-ups in Earth orbit. The need for spacecraft and orbital stages to permanently deplete or make safe all on-board sources of stored energy after end of mission is especially important.

Finally, ISO 24113 requires the preparation of a Space Debris Mitigation Plan (SDMP) to define the approach, methods, procedures, resources and organisation to co-ordinate and manage all technical activities necessary to specify, design, verify, operate and maintain a space system or product in conformance with the applicable space debris mitigation requirements and regulations.

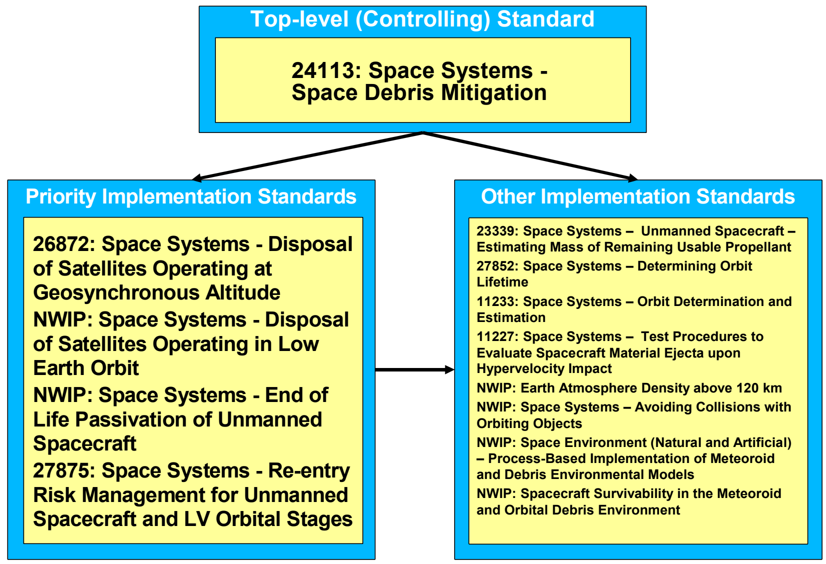

Figure 1. Relationship of ISO debris mitigation standards and proposals in development

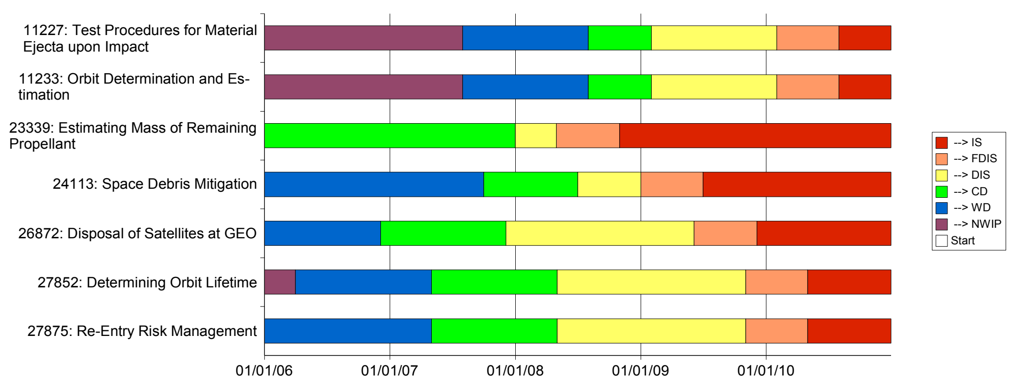

Figure 2. Schedule for ISO debris mitigation standards in development

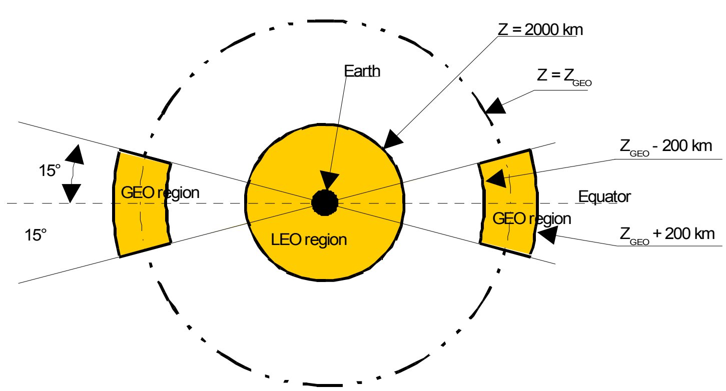

Figure 3. View in the equatorial plane of Earth and the protected regions (not to scale). Z is the altitude above the surface of a spherical Earth with a radius of 6,378 km; geostationary altitude (Z_{GEO}) is approximately 35,786 km

3.2. ISO 26872: Space Systems – Disposal of Satellites Operating at Geosynchronous Altitude

One of the most important requirements in ISO 24113 is that "a spacecraft or launch vehicle orbital stage operating in the GEO protected region, with either a permanent or periodic presence, shall be manoeuvred in a controlled manner during the disposal phase to an orbit that lies entirely outside the GEO protected region". Furthermore, the post-mission removal of spacecraft from the GEO protected region must satisfy at least one of the following two conditions:

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

$$\Delta H = 235 + 1000 \times C_R \times A/m \quad (1)$$

  where C_R is the solar radiation pressure coefficient ($0 < C_R < 2$) of the spacecraft, and A/m is its aspect area to dry mass ratio ($m^2\ kg^{-1}$).
- The disposal orbit has a perigee altitude sufficiently above the geostationary altitude that long-term perturbation forces do not cause the spacecraft to enter the GEO protected region within 100 years.

ISO 26872, which is due for publication this year, sets out how to accomplish this for spacecraft. Particular consideration is given to: when to initiate the disposal actions; selecting the final disposal orbit; executing the disposal actions successfully; and depleting all energy sources to prevent explosions after disposal. The standard also requires that an end-of-mission disposal plan (EOMDP) be developed, maintained, and updated throughout the design and operation of a spacecraft. Amongst the information to be included in the EOMDP are details of the targeted disposal orbit, criteria and time lines for initiating and executing the disposal actions, estimates of remaining propellant, and the identification of entities requiring notification of the end of mission and disposal.

With regard to initiating the disposal actions, ISO 26872 requires that specific criteria be developed and monitored throughout the mission life. Examples are propellant amount remaining, redundancy remaining, status of electrical power, status of systems critical to a successful disposal action, and time required to execute the disposal action. Projections of mission life based on these criteria must be made as a regular part of mission status reviews.

To establish a stable disposal orbit, either one of the following two options must be adopted:

- Determine the initial disposal orbit conditions using Eq. 1 and the eccentricity constraint. ISO 26872 provides a set of tables to obtain the optimal eccentricity vector.
- Perform long-term (100-year) numerical integrations of the selected disposal orbit to ensure that the predicted minimum perigee altitude is above the GEO protected region. The simulations must be performed using a reliable orbit propagator.

Whichever option is chosen, it is noted that altitude stability will be improved: if the initial disposal perigee points toward the sun; and if the disposal manoeuvres are performed in the most favourable season of the year, such that the same amount of perigee altitude increase will give the largest clearance over 100 years.

Another important requirement in ISO 26872 is to determine a manoeuvre sequence that will: place the spacecraft in the required disposal orbit; have the optimal near-sun-pointing perigee; and exhaust all the propellant on-board. The disposal orbit is obtained after passivation, especially tank depletion, which can have unpredictable effects on orbital parameters and altitude.

Should the intention be to operate the vehicle after placing it in a disposal orbit, the effects of such operation on the orbit must be estimated to confirm that the long-term stability of the orbit will not be compromised (i.e. its perigee altitude will remain above the GEO protected region for at least 100 years).

If a malfunction or other circumstance makes it necessary to proceed to the disposal phase earlier than planned, then a contingency plan must be developed that includes provisions for: selecting an alternative orbit that is the least likely to interfere with the GEO protected area; manoeuvring the satellite to the alternative orbit; safing the satellite after the move; and safing the vehicle in the event specified criteria are met at any time in the mission.

An example of such a scenario is when the quantity of remaining propellant to perform a disposal manoeuvre is uncertain. This situation, however, need not arise if the amount of fuel is estimated from the design phase (according to the needed accuracy level) and reserved for the disposal phase. In fact, ISO 26872 requires this to be so. A ΔV capability ($3\text{-}\sigma$) sufficient for end-of-life orbit disposal must be maintained, and it is suggested that a ΔV reserve of 12 $m\ s^{-1}$ may be used to estimate the propellant required. Furthermore, it is a requirement of ISO 24113 that a spacecraft be designed such that "the probability of successful disposal (i.e. both manoeuvre and passivation) shall be at least 0.9 at the time disposal is executed", and that "this probability shall be evaluated as conditional probability (weighted on the mission success)."

3.3. ISO NWIP: Space Systems – Disposal of Satellites Operating in Low Earth Orbit

In a similar vein to ISO 26872, a New Work Item Proposal has been developed to address the disposal of spacecraft in low Earth orbit. If the proposal is accepted by ISO TC20/SC14, work on the standard should commence by mid-2009. A three-year schedule is anticipated.

The proposed standard will specify the necessary means for spacecraft to comply with the following requirement in ISO 24113: "A spacecraft or launch vehicle orbital stage operating in 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 must be accomplished by one of the following methods (in order of preference):

- Retrieval followed by controlled re-entry and safe recovery on the Earth.
- Controlled manoeuvre into a targeted re-entry with a well-defined impact footprint on the surface of the Earth to limit the possibility of human casualty.
- Controlled manoeuvre to an orbit with a shorter orbital lifetime.
- Augmentation of orbital decay using a deployable device.
- Natural orbital decay.
- Controlled manoeuvre to an orbit with a perigee altitude sufficiently above the LEO protected region that long-term perturbation forces do not cause it to re-enter this region within 100 years.

In particular the standard will specify how to: plan for disposal of satellites operating in LEO to ensure that final disposal is sufficiently characterised and that adequate propellant is reserved for any propulsive manoeuvre required; select decay orbits where the satellite will re-enter the Earth's atmosphere within the next 25 years; select disposal orbits where the satellite will not re-enter the protected region within the next 100 years; and execute the re-orbit manoeuvre successfully.

Some aspects of the proposed standard will have content in common with ISO 26872, such as the need to develop and maintain an EOMDP and a contingency plan. However, the focus of the standard will be the provision of means to comply with the required decay/disposal orbit lifetimes. In this regard, it is expected that another of the debris-related standards, namely ISO 27852 "Space Systems – Determining Orbit Lifetime", will be called up. ISO 27852, whose development is nearing completion, describes a process for the estimation of orbit lifetime for space objects and associated debris in LEO-crossing orbits.

3.4. ISO NWIP: Space Systems – End of Life Passivation of Unmanned Spacecraft

Passivation is the removal of all sources of stored energy on a spacecraft or launch vehicle orbital stage for the purpose of reducing the risk of break-up. In the top-level debris mitigation standard, ISO 24113, it is stated that "during the disposal phase, a spacecraft or launch vehicle orbital stage shall permanently deplete or make safe all remaining on-board sources of stored energy in a controlled sequence." Both of the above 'disposal' documents also contain clauses relating to the need for passivation of spacecraft as part of the disposal process. However, detailed actions and measures to achieve passivation are not provided. A separate standard has been proposed for this purpose, with a likely publication date of 2012. The document is currently at the New Work Item Proposal stage awaiting approval by ISO TC20/SC14.

The proposed standard is intended for use in the planning, verification and implementation of passivation in a spacecraft, and is therefore applicable to those performing spacecraft design, verification and operation. It will require the identification of all energy sources remaining at end of mission, quantification of the associated risks, and the remedial actions to be taken. All of these must be documented in a passivation plan during the spacecraft design process, and the implementation of the plan must be verified by test, analysis or simulation (in that order of preference).

The standard will provide a breakdown of the energy systems commonly used on spacecraft. A provisional breakdown is shown in Fig. 4. For each system, a set of energy removal actions and design measures will also be specified. An example is "the propellant in a liquid propulsion system shall be consumed until nominal thruster firings can no longer continue (i.e. depletion of a tank in a bipropellant system, or bottoming of a monopropellant diaphragm)".

The quantification of the risks associated with each stored energy system will have to consider not just the amount of stored energy contained in a subsystem, but how it is contained, and what damage it could do in terms of debris release. A risk assessment is also necessary to enable compliance with the following primary requirements in ISO 24113:

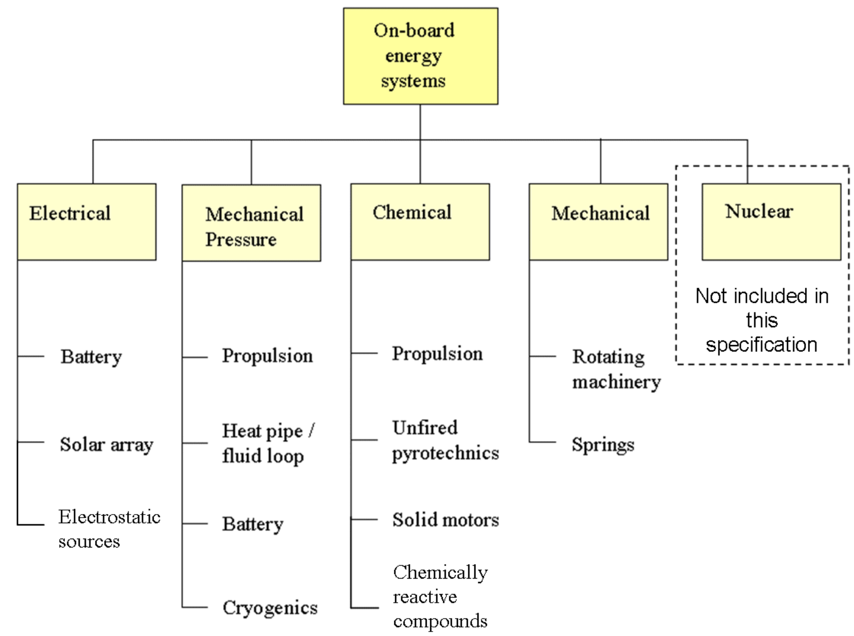

Figure 4. Energy systems commonly used on spacecraft

- "The probability of accidental break-up of a spacecraft or launch vehicle orbital stage shall be no greater than 10^{-3} during its operation."
- "The determination of accidental break-up probability shall quantitatively consider all known failure modes for the release of stored energy, excluding those from external sources such as impacts with space debris and meteoroids."

It is expected, therefore, that the passivation standard will outline the use of a system level risk assessment approach.

In terms of operations, the standard will require the production of a detailed set of passivation procedures prior to the end of mission. These must take account of the operational condition of the spacecraft, especially any failures that may have occurred during the mission. Of particular importance is the need to ensure that passivation operations are performed in the correct sequence, and in a manner that does not cause uncontrolled disturbances on the spacecraft or an undesirable change in its orbit.

3.5. ISO 27875: Space Systems – Re-entry Risk Management for Unmanned Spacecraft and Launch Vehicle Orbital Stages

Several of the options for disposal in LEO will result in spacecraft and launch vehicle orbital stages re-entering the Earth's atmosphere, possibly resulting in some fragments impacting the Earth's surface. The risks to people and the environment must therefore be assessed and controlled. ISO 27875 provides the framework to do that. It is intended to be applied to the planning, design and review of unmanned space missions for which controlled or uncontrolled re-entry is possible.

The standard requires that a re-entry safety programme be established to ensure that damage and injury caused by re-entering vehicles is minimised, and that corrective action is taken if re-entry risks are assessed to exceed predefined thresholds. The safety programme is one of the key components of re-entry risk management, along with the preparation of a Re-entry Risk Assessment and Mitigation Plan (RRAMP) and implementation of suitable oversight.

ISO 27875 also requires that re-entry risk assessment actions (i.e. analyses, reports, etc.) be defined. Analyses must be conducted using approved processes, methods, tools, models and data. These include atmospheric models, human population distribution models, details of the design and orbit of the spacecraft or launch vehicle orbital stage, and mission-dependent assumptions such as its attitude during re-entry. The estimation of re-entry risks must consider: the characteristics of fragments that are likely to survive re-entry (i.e. sizes, trajectories, etc.); the probability that the fragments will cause injury or damage; the ground area that might be affected by the falling objects (in the case of a controlled re-entry); and the effects of any toxic or radioactive substances that could be released into the environment.

Fig. 5, which is derived from ISO 27875, shows a flow diagram for re-entry risk assessment and disposal planning, including the risk decisions and actions that need to be taken. With regard to assessing the 'risk to humans', the 'predefined threshold' can be expressed in terms of a 'maximum acceptable casualty risk'. This is consistent with one of the requirements in the top-level debris mitigation standard, ISO 24113, namely that "the re-entry of a spacecraft or launch vehicle orbital stage (or any part thereof) shall comply with the maximum acceptable casualty risk, in accordance with the norms issued by approving agents".

Finally, ISO 27875 states that risk reduction must be achieved by at least one of the following three measures:

- Performing a controlled re-entry rather than an uncontrolled one.
- Using structural designs and materials that minimise the survivability of fragments.
- Notifying any nation or organisations that could potentially be affected by re-entering fragments, especially any hazardous materials.

3.6. Other ISO debris mitigation standards

The scope of the other ISO debris-related standards and NWIPs that are currently in development is as follows:

- ISO 23339 "Space Systems – Unmanned Spacecraft – Estimating the Mass of Remaining Usable Propellant" prescribes requirements for estimating the mass of remaining usable propellant in unmanned spacecraft, and for designing fuel measurement systems. It applies to spacecraft with either mono- or bi-propellant propulsion systems.
- ISO 27852 "Space Systems – Determining Orbit Lifetime" provides a sufficiently precise and easily implemented approach for demonstrating the compliance of LEO spacecraft with the 25-year post-mission lifetime limit as defined in ISO 24113.
- ISO 11233 "Space Systems – Orbit Determination and Estimation" prescribes the manner in which satellite owners/operators (a) describe techniques used to determine orbits from active and passive observations, and (b) estimate satellite orbit evolution. Safe and cooperative operations among those who operate satellites demands that each understand the differences among their approaches to orbit determination and propagation. This is particularly important when determining the need for collision avoidance manoeuvres.
- ISO 11227 "Space Systems – Test Procedures to Evaluate Spacecraft Material Ejecta upon Hypervelocity Impact" describes an experimental procedure for assessing the amount of ejecta produced when spacecraft external surfaces are impacted by debris or meteoroids. This helps to quantify the suitability of surface materials for use in space.
- ISO NWIP "Earth Atmosphere Density above 120 km" will provide reference and standard atmosphere models for use in space engineering design and scientific research. It is particularly relevant to orbit determination and estimation (ISO 11233) and determining orbit lifetime (ISO 27852).
- ISO NWIP "Space Systems – Avoiding Collisions with Orbiting Objects" will specify techniques for the prediction of close approaches between orbiting objects, the implementation of effective avoidance manoeuvres, and the selection of operational and disposal orbits where probability of collision is low. Guidance will also be provided on the development of cooperative approaches to minimise collision probability for repeating events.
- ISO NWIP "Space Environment (Natural and Artificial) – Process-Based Implementation of Meteoroid and Debris Environmental Models" will specify a common process for identifying, selecting and implementing meteoroid and debris environment models in the assessment of impact risk on spacecraft. There are several models available, so the choice and use of one can be an important consideration in the design of a spacecraft and its mission.
- ISO NWIP "Space Systems – Survivability of Unmanned Spacecraft against Space Debris and Meteoroid Impacts – Assessment Procedure" will provide an assessment procedure for determining and improving the survivability of a spacecraft against space debris and meteoroid impacts. The procedure is a necessary step in the design of a spacecraft when impact protection is considered important.

4. POSSIBILITIES FOR FUTURE ISO 'DEBRIS MITIGATION' STANDARDS

The ODCWG, in conjunction with other TC20/SC14 working groups, is currently considering a number of debris-related topics for development as New Work Item Proposals.

At present, the top-level standard (ISO 24113) specifies high-level requirements for the disposal and passivation of launch vehicle orbital stages in the GEO and LEO regions. However, there are no low-level supporting standards to enable compliance with these requirements. The need for such standards is currently being investigated. If developed, they will be based firmly on current industry procedures and best practice.

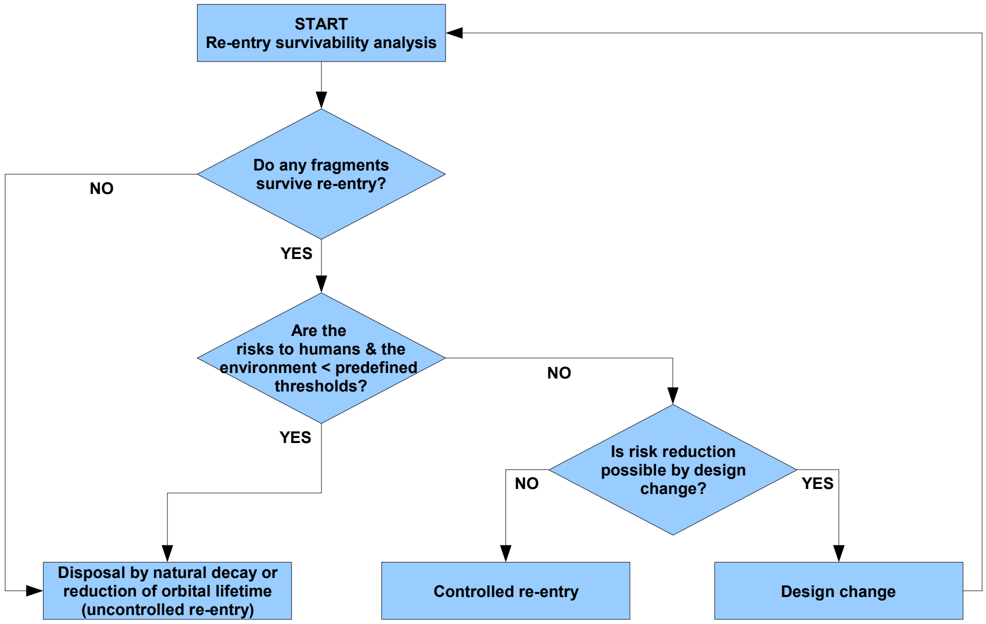

Figure 5. Flow diagram for re-entry risk assessment and disposal planning

To complement ISO 11227, additional test procedure standards are being considered to evaluate the suitability of spacecraft surface materials and coatings with respect to other debris-release mechanisms such as UV degradation, thermal cycling, and atomic oxygen erosion. A higher level standard that defines a process for selecting surface coatings and materials, and calls up the test procedure standards, is also a possibility.

5. SUMMARY

In 2003, ISO commenced development of a series of spacecraft engineering standards aimed specifically at space debris mitigation. The first of these is due to be published within the next few months. The standards prescribe debris mitigation requirements that have been derived in large part from internationally-agreed guidelines such as those published by the IADC. They also capture industry best practice and specify definite actions to be taken by satellite manufacturers and operators to achieve compliance. The highest level requirements are contained in a top-level standard designated ISO 24113 “Space Systems – Space Debris Mitigation”. Their purpose is to avoid 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 end of mission. Detailed procedures and practices for complying with the high-level requirements are contained in a set of lower level implementation standards. Once published, the standards will undergo periodic reviews to ensure they remain up-to-date and usable by industry.

6. ACKNOWLEDGEMENTS

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