Proceedings of the First European Conference on Space Debris, Darmstadt, Germany, 5-7 April 1993 (ESA SD-01)

DEVELOPMENT OF REQUIREMENTS AND GUIDELINES FOR DEBRIS PREVENTION

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ABSTRACT

The paper discusses the policy and the requirements that have been adopted by ESA to minimise the creation of space debris and provides examples of design and operational measures that have been used in ongoing ESA programmes to implement the above quoted requirements. The results of an activity aimed at assessing the adequacy of the debris prevention requirements currently contained in the ESA System Safety standard PSS-01-40 are also presented.

1. INTRODUCTION

According to the results of surveys (Ref. 1-2) carried out in the last few years , man-made space debris constitute one of the major threats for manned stations and spacecraft in Low Earth Orbits (LEO). This has already led to the need of implementing protective measures in space systems (e.g. shielding of manned systems in LEO) against the risk of collision with a piece of debris. Additionally, there are concerns that, with the current launch rate of space systems, the space debris population can significantly increase in the next decade, if the design and operational practices used in the first 30 years of space activities are not modified. It is also estimated that the sole use of 'a posteriori' protective measures to try and reduce the debris risk to an acceptable level, would be in the long run extremely costly and can even jeopardise the feasibility of space activities in certain orbits (e.g. LEO). For preventing the occurrence of this scenario it is therefore essential that adequate policies aimed at minimising the creation of new space debris are adopted by the space faring countries and organisations.

The aim of this paper is to: outline the European Space Agency (ESA) preventative policy (section 2), describe the debris creation preventative requirements that have been introduced in the ESA Safety standard and provide examples of their implementation in a number of ESA programmes (section 3), and present the outcome of an activity aimed at assessing the adequacy of the above quoted requirements (section 4). Finally, guidelines on how to account for the space debris prevention issues during the performance of the various tasks of a space programme (e.g. requirements synthesis, safety analysis) are discussed in section 5.

2. THE ESA SAFETY POLICY AND ENVIRONMENT PROTECTION

The creation of space debris results in the immediate pollution of the near-Earth space, and could have delayed effects on the safety of space systems, civil population and ground assets. Safety threats can also be caused by other forms of environmental pollution associated to space activities. This is recognised in the formulation of the ESA safety policy, which is to protect:
- human life;
- public and private property;
- investment;
- the environment.

The implementation of this policy is of pro-active nature, which for space debris implies that measures aimed at minimising the creation of debris creation shall be given priority with respect to those aimed at removing them from space.

In order to implement its safety policy, ESA has established, in its standard PSS-01-40 'System Safety requirements for ESA Space Systems and associated equipment' (Ref. 3), a set of safety programme and technical requirements. A number of these are addressed to the protection of the environment and in particular to the minimisation of space debris creation (see section 3).

The ESA safety policy requires the performance during each ESA project, of a safety programme that is based on the:
* identification and evaluation of the hazards;
* application of the hazard reduction process;
* formal verification process aimed at providing evidence that the hazard control measures have been implemented.

The Safety Programme is applied from project conception to end-of-life. Implementation is formally monitored at defined Project Milestones by Safety Reviews which are held in parallel with the Milestone Reviews. Safety Reviews are chaired by a representative of the Product Assurance and Safety Department.

3. ESA REQUIREMENTS FOR DEBRIS CREATION PREVENTION

Apart from the requirements concerning the safety activities (e.g. analyses, reviews) to be performed during a space programme, PSS-01-40 contains a set of basic 'technical' requirements (e.g. failure tolerance, escape and rescue capabilities). These requirements are applicable to all the various types of space systems that are developed within ESA programmes and are normally reflected in the System Requirements Document (SRD) issued by ESA for its programmes. Any modification of the above quoted requirements to take into account the peculiarities of a given project (e.g. manned vs. unmanned systems), has to be approved by the Head of the ESA PA & Safety Department.

The space debris preventative requirements are part of these 'technical' requirements. Before discussing them it is useful to introduce the consequence severity categorisation used by ESA. According to PSS-01-40, the hazardous events (e.g. 'explosion of a pressure vessel', 'spacecraft collision with space debris') associated to the system design and operation are to be classified according to their consequence severity in:

I CATASTROPHIC:
- loss of life, life-threatening or permanently disabling injury or occupational illness.

II SERIOUS:
- temporarily disabling but not life threatening injury, or temporary occupational illness;
- loss of, or major damage to flight systems, major flight-system elements, or ground facilities;
- loss of, or major damage to public or private property; or
- long term detrimental environmental effects.

III MARGINAL:
- minor non-disabling injury or occupational illness;
- minor damage to other hardware;
- minor damage to public or private property;
- temporary detrimental environmental effects.

The following general debris creation preventative requirement is contained in PSS-01-40:

"The creation of space debris that repeatedly intersect orbital paths used by space systems shall be avoided" [paragraph II-1.6.4]

Due to the fact that the creation of space debris is classified as 'serious' being it a 'long term environmental effect', the following requirement also applies:

"The failure tolerance requirements (i.e. no single failure shall lead to serious consequences) shall be applied to the prevention of debris creation" [(Ref. 3) paragraph II-1.6.1]

Additional specific requirements are provided for launchers:

"Orbiting spent stages shall have the capability of being safely deorbited" [(Ref. 3) paragraph II-3.1.1.3]

"Residual propellants contained in spent or aborted stages shall be safely dispersed" [(Ref. 3) paragraph II-3.1.2.5]

It is to be noted that, apart from the requirements aimed at preventing the creation of space debris, PSS-01-40 also contains requirements that are aimed at avoiding the uncontrolled re-entry of space systems (or parts of them) in the Earth's atmosphere. This last set of requirements is not discussed in this paper.

The preventative requirements have been implemented into the ESA programmes (e.g. POEM 1/Envisat) that started after the date of issue of PSS-01-40 (September 1988). Implementation on programmes that were ongoing (e.g. Ariane 4 and 5, Columbus, Meteosat) at that date has been decided on a case-by-case base taking into account factors like: the level of risk associated to future space missions if measures were not applied, the impact on system reliability, cost and schedule if the measures were to be implemented. Amongst the steps taken in ongoing ESA programmes to comply with the above quoted requirements the following can be quoted:

* The 'passivation' (i.e. the safe dispersion of the remaining fuel) of the Ariane 4 upper stage H10 after LEO & SSO missions since flight V35 (1990). A similar measure is going to be adopted on all missions as per flight V60 (1993).
* Re-orbiting of geo-stationary satellites after end-of-mission (e.g. Meteosat, Olympus).

Amongst the preventative measures that have been included in the design of ongoing programmes the following can be mentioned:

* The controlled natural re-entry of the ARIANE 5 cryogenic H150 stage, and the passivation of its upper stage L7 for all missions;
* The retrieval by means of the U.S. Shuttle of the Attached Pressurised Module (European contribution to the International Space Station) at the end of its mission;
* The minimisation of the intended release of items (instrument covers, ABMs,.) during the mission.

4. ASSESSMENT OF THE CURRENT DEBRIS PREVENTATIVE REQUIREMENTS

In order to assess the adequacy of the debris preventative requirements currently contained in PSS-01-40 and identify the need for possible additional ones a review activity was performed, covering:
a) identification of debris creation scenarios;
b) recommendations for additional requirements.
A summary of the outcome of this review is described below.

4.1 Identification of debris creation scenarios

It has to be noted that for a given system, space debris can be created through scenarios that are composed of:
- intended events (e.g. release of payload adapters or optical instrument covers); and/or
- unintended events (e.g. due to failures of the space system or errors of its operators).

The identification of the scenarios for the following classes of space systems was performed:
* launchers;
* satellites in polar orbits;
* satellites in geostationary orbits;
* satellites in Highly Elliptical Orbits (HEO);
* manned stations in Low Earth Orbits;
* re-usable space planes;

The above classes cover broadly the range of ESA projects that are either ongoing or under consideration. For the sake of focusing the subsequent analyses, one ESA space system was selected as representative for each class of space systems. Due to the fact that the aim of the activity was the identification of requirements (and not the design review of the various systems), the scenarios were generally identified at system and subsystem level. The scenario identification was carried out through the following steps:

Data Gathering For each representative space system the following documents were retrieved:
* system specification;
* operations description;
* sub-system specification.
* system level safety analyses;

and information relevant for further analysis was screened.

Identification of 'intended' events. The space system operational scenario was reviewed and intended operations leading to debris production were singled out (if any).

Identification of 'unintended' events. For each mission phase, the hardware or software failures, human errors, external events outside the design range that can lead to debris production were identified. This was done through design and operations review and the use of check-lists.

Synthesis of debris creation scenarios. Taking the results of the two steps above outlined, for each system a list of debris creation scenarios was compiled.

Outline of the results of debris creation scenario identification. Examples of scenarios resulting from <u>intended</u> events are the following ones:
* jettisoning of payload adapters and fairings from launchers;
* abandon of spent stages or satellites in orbit;
* ejection of fragments from pyrotechnic devices (used by various classes of space systems);
* release of experiment covers.

Amongst the debris creation scenarios caused by <u>unintended</u> events the following are quoted as examples:
* fragmentation of spent stages after end of mission;
* release of tools, removed items or Orbit Replaceable Units (ORU) during EVA operations;
* failure of the functions that are necessary for the end-of-life disposal of the space system;
* failure of prime function, which may require jettisoning.

Screening of scenarios for further investigations. Apart from the above quoted examples several other scenarios leading to space debris creation were identified. Most of them (e.g. explosion of pressurised vessels during the mission, collision of the launcher with the payload) were actually leading to severe impact on system safety and reliability as well. Requirements to prevent their occurrence are already implemented in the relevant system requirements' documents. Consequently it was decided to focus on those scenarios that were either the result of intended operations or although being caused by unintended events were not usually addressed by the safety and reliability activities. In this last class particular mention should be made of those scenarios that:
- occur during the space system mission but lead to no, or marginal, consequences on system safety and reliability (e.g. release of tools during EVA operations); or
- occur after the end of the mission.

For these two classes of scenarios it was decided to investigate their causes in more detail by performing fault-tree analysis to identify also the combinations of 'initiator events' (and possibly also combinations of them with 'intended' events or conditions) that could lead to debris production.

4.2 <u>Synthesis of additional requirements</u>

At first, it was assessed whether the causes of the identified scenarios would have been prevented by the application of the current set of PSS-01-40 requirements or not. With regard to this, it was immediately apparent that top-level requirements exist already in PSS-01-40 that are addressing all causes of debris creation (see section 3 requirements II-1.6.4 and II-1.6.1). On the other hand, it was also noted that PSS-01-40 was giving more detailed requirements for certain classes of space systems (e.g. launchers, see section 3: requirements II-3.1.1.3 and II-3.1.2.5), whilst no explicit mention was made of other classes. This creates some 'unbalance' in the level of detail of PSS-01-40. It was also deemed that, in order to provide more effective guidance to ESA and Industry project personnel on debris prevention, more detailed system level requirements than those quoted in section 3 were needed.
In synthesising recommendations for new requirements, precedence was given to those implementable at reasonable costs that could significantly reduce the rate of increase of the debris population and the risk of collision with other space systems. This reduction was estimated for each scenario controlled by the 'candidate' requirements by taking into consideration:
* the number and mass of the debris released;
* the expected 'lifetime' of the debris released;

and accounting for the 'crowding' of the orbit in which the debris would be released or that are crossed by the debris during their lifetime.
It turned out that the most 'severe' scenario were the ones associated with the fragmentation of space systems (e.g. spent upper stages, non-operational satellites) abandoned after the end of their mission in LEO. Also the intended release in LEO of sizeable spacecraft items could have serious impacts on the safety of future space activities.

After having taken into account the availability of the technology needed to practically implement the associated design solutions, the inclusion of the following lower level design and operational requirements was recommended (comments on each requirement are also listed, where appropriate):

(1) "Safe Disposal of space systems shall be performed at the end of their missions"

In this requirements 'safe disposal' can be implemented through:
- controlled destructive re-entry into the atmosphere for non-reusable systems (e.g. earth observation satellites in LEO below 800 km average altitude); or
- retrieval by another space system; or
- re-orbiting of objects in GEO to 'graveyard' orbits that are not used for operational purposes.

(2) Subsystems/equipment used to implement the safe disposal function shall be monitored during the space system mission.

Requirement (2) is to be used to ensure that the disposal manoeuvre can take place before major space system failures can bring it in an uncontrollable state.

(3) Intended release of space systems' elements (hats, covers, etc.) shall not be performed during the space system mission

(4) Energy sources in space systems shall be put in safe state after end of mission.

This implies, for example, that pressurant and propellant shall be safely dispersed and energy sources (e.g. batteries) shall be put in a safe state by means of appropriate inhibits after the end of the mission for all those space systems that are to remain in orbit (e.g. GEO satellites in graveyard orbit).

The above requirements are currently under consideration for inclusion in the next issue of PSS-01-40. In some cases (req. 1, 3) their inclusion in PSS-01-40 would constitute the formalisation of 'practices' already followed by ESA. Requirement (4), instead, enlarges the scope of requirement II-3.1.2.5 currently contained in PSS-01-40 (see section 3).

5. DEBRIS PREVENTION AND SAFETY ACTIVITIES

The implementation of the debris preventative requirements during a space programme can be basically performed, as for any other safety requirement, by incorporation in the technical requirements for specific ESA projects and, subsequently, in the System Specification implemented by the Contractor. Inclusion of more specific provisions in the sub-system (or lower level) specification for those items that are prone to debris production is also generally necessary. There are, anyway, specific issues that deserve some additional remarks.

The first one is that the 'production of space debris' shall be included amongst the list of undesired consequences that are considered during the safety analysis of a specific system. This will allow to properly assess (as for any other safety requirement) whether the debris preventative requirements have been taken into account into the system design and operational scenario. Identification of possible causes of debris production and recommendation for controlling them would also result from the above quoted analyses. The safety analysis will also provide support to the verification activities. It is noted that attention of the analysts should be focused, in the case of unmanned systems, to the phase that follows the end of the mission but precedes the safe disposal, because this part of the life of the space system has not been covered adequately by the reliability and safety analyses until now.

The second point that must be noted pertains to those instances in which complete elimination of debris creation cannot be achieved due to the existence of constraints on the mission objectives, reliability, crew safety and cost. In these cases debris prevention should strive at minimising the number and the mass of debris and/or to release them in orbits where the extra risk introduced for future space activities is considered acceptable. This can best be done at an early project stage by including in the technical requirements the 'achievable' debris prevention requirement (upon approval of the Head of the ESA Product Assurance and Safety Department). When required, waivers can be requested (following the normal procedures used in these cases) by the Contractor to ESA, if it turns out to be impossible to fully meet the debris preventative requirements. Proper and sound rationale is to be provided in this case by the Contractor, with an assessment of the level of risk for future space activities resulting from the debris that are going to be produced.

Finally, it is pointed out that the performance of an End-Of-Life review (EOLR) is necessary to provide assurance that the safe disposal operations are properly planned and implemented. An EOLR was performed by ESA in connection with the Meteosat F2 satellite re-orbiting.

6. CONCLUSION

ESA has recognised that prevention is the most effective way to counter the space debris problem. Accordingly, top level preventative requirements have been included in ESA PSS-01-40 and a number of measures to minimise debris creation have been implemented for ongoing ESA programmes. Additional detailed requirements have also been identified and implementation in ESA PSS-01-40 is currently under consideration.

Although technology for implementing the above quoted requirements is generally available, some R&D activities are needed to increase the dependability of the associated measures. The need for more accurate monitoring of the remaining propellant in order to reduce the uncertainties on the safe disposal manoeuvres or the replacement of ejectable payload adapters with deployable ones in launchers can be mentioned as examples.

The adoption of even more drastic measures to reduce the rate of creation of space debris would basically depend, apart that from availability of new technologies (e.g. reusable launchers), on international agreements between space-faring countries and organisations about the adoption of debris preventative requirements. In fact the implementation of these requirements has, in some cases, a significant impact on cost, performances or reliability of a given space systems. On the other hand, only marginal effects on the debris environment stem from the application of preventative measure by a single organisation like the European Space Agency. It is therefore essential that, in order to achieve a substantial reduction of the debris creation, as currently projected, similar steps are required to be implemented by other space faring nations prior to eventual control by international space law. Agreements at international level to commonly strive towards minimisation of debris will also allow for the fair competition between the various space powers in the area of commercial space activities.

7. REFERENCES

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