NASA TECHNICAL STANDARD

**National Aeronautics and Space Administration**
**Washington, DC 20546**

NASA-STD-8719.14
(with Change 4)

**Approved: 2007-08-28**
**With Change 4 of: 2009-9-14**

# Process for Limiting Orbital Debris

Measurement System Identification:
Metric

APPROVED FOR PUBLIC RELEASE – DISTRIBUTION IS UNLIMITED

This page intentionally left blank.

# DOCUMENT HISTORY LOG

| Status | Document Revision | Approval Date | Description |
|---|---|---|---|
| Baseline | | 2007-08-28 | Initial Release |
| Change | Change 1 | 2007-09-06 | Administrative correction to remove supersession |
| | Change 2 | 2009-06-10 | Update to clarify requirements with respect to update of NPR 8715.6A (with Change 1) and NASA-HDBK 8719.14. Clarification of battery passivation and required ODAR/EOMP signatures. *JWL4* |
| | Change 3 | 2009-07-23 | Update to clarify requirement for battery passivation in paragraph 4.4.4.1.2.g. *JWL4* |
| | Change 4 | 2009-09-14 | Administrative update to add hyperlinks to SMARTS data system for Chapters 1 & 4. *JWL4* |

*This document is subject to reviews per Office of Management and Budget Circular A-119, Federal Participation in the Development and Use of Voluntary Standards (02/10/1998) and NPD 8070.6, Technical Standards (Paragraph 1.k).*

This page intentionally left blank.

# FOREWORD

This NASA-STD is published by the National Aeronautics and Space Administration (NASA) to provide uniform engineering and technical requirements for processes, procedures, practices, and methods that have been endorsed as standard for NASA programs and projects, including requirements for selection, application, and design criteria of an item. Use of this NASA-STD is the responsibility of the user.

This NASA-STD is approved for use by NASA Headquarters and NASA Centers, including Component Facilities. This NASA-STD may be applied on contracts for spacecraft, instrument, or launch vehicle contractors per contractual documentation.

Collision with orbital debris is a risk of growing concern as historically-accepted practices and procedures have allowed artificial objects to accumulate in Earth orbit. To limit future debris generation, NASA Procedural Requirements (NPR) 8715.6, "NASA Procedural Requirements for Limiting Orbital Debris," requires each program and project to conduct a formal assessment of the potential to generate orbital debris during deployment, mission operations, and after the mission has been terminated. This NASA-STD serves as a companion to NPR 8715.6 and provides each NASA program and project with specific requirements and assessment methods to assure compliance with the NPR. This document shall be used for orbital debris assessments for all payloads, launch vehicle orbital stages, and released objects as required by NPR 8715.6. NASA-Handbook (NASA-HDBK) 8719.14 serves as a reference document to assist orbital debris practioners and program/project management in understanding the technical, physical, and political aspects of orbital debris.

This NASA-STD is consistent with the objectives of the U.S. National Space Policy (August 2006), the U.S. Government Orbital Debris Mitigation Standard Practices (February 2001), the Inter-Agency Space Debris Coordination Committee (IADC) Space Debris Mitigation Guidelines (October 2002), the Space and Missile Center Orbital Debris Handbook, Technical Report on Space Debris (July 2002), the space debris mitigation guidelines of the Scientific and Technical Subcommittee of the United Nations Committee on the Peaceful Uses of Outer Space, (A/AC.105/720, 1999 and A/AC.105/890, Feb 2007). The requirements contained within this NASA-STD (and NPR 8715.6) encompass the requirements within the U.S. Government Mitigation Standard Practices, the IADC Space Debris Mitigation Guidelines, and the United Nations documents cited above and therefore imply compliance with the requirements in those documents.

Requests for information, corrections, or additions to this NASA-STD shall be submitted via "Feedback" in the NASA Technical Standards System at **http://standards.nasa.gov**. This NASA-STD was developed by the NASA Headquarters Office of Safety and Mission Assurance with the Orbital Debris Program Office at Johnson Space Center.

| | |
|---|---|
| /s/ | August 28, 2007 |
| Bryan O'Connor<br>Chief, Safety and Mission Assurance | Approval Date |

This page intentionally left blank.

# TABLE OF CONTENTS

# LIST OF FIGURES



# LIST OF TABLES

# Process for Limiting Orbital Debris

## 1. SCOPE

### 1.1 Purpose

1.1.1 This document serves as a companion to NASA Procedural Requirements (NPR) 8715.6 and provides specific requirements and methods to comply with the NASA requirements for limiting orbital debris generation. NASA-Standard (NASA-STD) 8719.14 updates NASA Safety Standard (NSS) 1740.14, which went into effect in August 1995. This NASA-STD helps ensure that spacecraft and launch vehicles meet acceptable standards for limiting orbital debris generation.

> *Note: Limited use of NSS 1740.14 for programs in effect as of approval of this NASA-STD is per the requirements in NPR 8715.6 paragraph P.2.*

1.1.2 This NASA-STD is primarily designed to limit the creation of new orbital debris and, therefore, to limit the risk to other current and future space missions. The methodologies described herein can be used by programs and projects to evaluate and to improve their own mission reliability and success with respect to the orbital debris and meteoroid environment. The assessments described in this NASA-STD are required per NPR 8715.6 and are reviewed for completeness as a part of the flight approval processes.

1.1.3 This document, along with the associated Debris Assessment Software (DAS) [version 2.0 or higher] provided by the NASA Orbital Debris Program Office (NASA ODPO) located at Johnson Space Center (JSC), shall be used by the program or project manager as the primary reference in conducting orbital debris assessments (Requirement 56244).

1.1.4 This NASA-STD establishes requirements for (1) limiting the generation of orbital debris, (2) assessing the risk of collision with existing space debris, (3) assessing the potential of space structures to impact the surface of the Earth, and (4) assessing and limiting the risk associated with the end of mission (EOM) of a space object. In addition to requirements in Section 4 and methods for assessment, this NASA-STD provides the format for the required debris assessment and reports which must be submitted to the Office of Safety and Mission Assurance as required in NPR 8715.6.

> *Note: NASA-HDBK 8719.14 serves as a reference document to assist orbital debris practioners and program/project management in understanding orbital debris. Topics in NASA-HDBK 8719.14 include the OD environment, measurements, modeling, shielding, mitigation, and reentry. It is strongly encouraged that the NASA-HDBK be used with the implementation of NPR 8715.6 and NASA-STD 8719.14.*

1.1.5 This document is primarily intended for use in assessing orbital debris that is in Earth orbit. For spacecraft and launch vehicles traveling beyond Earth orbit, the beginning of Sections 4.3-4.8 state how the requirements in this NASA-STD are applicable to missions traveling beyond Earth orbit.

## 1.2 Applicability

a. This NASA-STD is applicable to all objects launched into space in which NASA has lead involvement and control or has partial involvement with control over design or operations via U.S. internal or international partnership agreements, including the launch vehicle. This document has no automatic exclusions for any program or project due to limited funding, responsibility, or involvement of NASA in the program or project. NASA involvement includes design, manufacture, or funding of instruments, spacecraft bus, spacecraft systems, the launch vehicle, and launch processing. The use of this NASA-STD is only required for those portions of a space mission under NASA control. This NASA-STD defines being in ‘space’ as exceeding 100 km (~62 mi) in altitude and achieving or exceeding Earth orbital velocity.

b. This NASA-STD has been designed to be cited in contract, program, and other Agency documents as a technical requirement or as a reference for guidance.

c. Any decision to waive or vary from the requirements in this NASA-STD requires the concurrence of the Chief, Safety and Mission Assurance, Office of Safety and Mission Assurance (Chief/OSMA).

d. Within this NASA-STD, the word “shall” indicates a mandatory requirement, the word “should” indicates that a statement is strongly recommended for implementation but not required, and the word “may” indicates an optional implementation.

e. NASA spacecraft, launch vehicles, and instruments that passed Preliminary Design Review (PDR) prior to August 1995 (release of NSS 1740.14, Guidelines and Assessment Procedures for Limiting Orbital Debris) are not required to perform an orbital debris assessment (ODA) unless a large change in design or changes in space object capability or risk affect the ability to achieve compliance with the requirements. If one or more of these conditions occur, an ODA Report (ODAR) shall be performed (Requirement 56255).

f. Programs/projects that have passed spacecraft PDR at the time of approval of NPR 8715.6 may elect to follow the mission and hardware design and operation requirements of NPR 8715.6 and the procedures in NSS 1740.14 for ODARs.

> *Note: For future changes to NPR 8715.6 and this NASA-STD, programs may request a waiver to the new requirements per NPR 8715.3 Paragraph 1.13.*

g. Programs within four months of launch at the time of approval of NPR 8715.6 are not required to submit the prelaunch End-of-Mission (EOM) Plans (EOMP); however, the information should be included within the ODAR.

h. Programs less than three months from EOM at the time of approval of NPR 8715.6 are not required to submit an EOMP; however, it is desirable to develop an EOMP in conjunction with performing the requirements contained in NPD 8010.3, Notification of Intent to Decommission or Terminate Operating Space Systems and Terminate Missions.

i. For international programs/projects where NASA is the lead but a foreign agency is responsible for providing the launch vehicle, the NASA program/project manager should request from that agency a summary of orbital debris limitation activities for the launch vehicle, in particular regarding the disposition of the upper stage.

# 2. APPLICABLE AND REFERENCE DOCUMENTS

## 2.1 Applicable Documents

### 2.1.1 General

The documents listed in this section contain provisions that constitute requirements of this NASA-STD as cited in the text of Section 4. The latest issuance of cited documents is to be used unless otherwise approved by the assigned Technical Authority. The applicable documents are accessible via the NASA Online Directives Information System at http://nodis3.gsfc.nasa.gov/, or directly from the Standards Developing Organizations (SDOs) or other document distributors.

### 2.1.2 Government Documents

NPD 8010.3, Notification of Intent to Decommission or Terminate Operating Space Systems and Terminate Missions.

NPR 8715.3, NASA General Safety Program Requirements.

NPR 8715.6, NASA Procedural Requirements for Limiting Orbital Debris.

### 2.1.3 Non-Government Documents

Inter-Agency Space Debris Coordination Committee (IADC) Space Debris Mitigation Guidelines, October 2002 (http://www.iadc-online.org/index.cgi?item=docs_pub).

## 2.2 Reference Documents

The documents listed in this section contain supporting information to assist in the implementation of the provisions that constitute requirements of this NASA-STD as cited in the text of Section 4. The documents are accessible via the NASA Online Directives Information System at http://nodis3.gsfc.nasa.gov/, or directly from the SDO.

U.S. National Space Policy (August 2006).

U.S. Government Orbital Debris Mitigation Standard Practices, February 2001.

NPD 8020.7, Biological Contamination Control for Outbound and Inbound Planetary Spacecraft (http://nodis3.gsfc.nasa.gov/).

NPR 8020.12, Planetary Protection Provisions for Robotic Extraterrestrial Missions (http://nodis3.gsfc.nasa.gov/).

NASA Handbook 8719.14, Handbook for Limiting Orbital Debris

U.S. Air Force Space and Missile Center (SMC) Orbital Debris Handbook, (July, 2002) (http://stinet.dtic.mil/cgi-bin/GetTRDoc?AD=ADA435172&Location=U2&doc=GetTRDoc.pdf).

JSC-27862, Postmission Disposal of Upper Stages (December 1998) (available through the NASA ODPO).

Debris Assessment Software (DAS) (www.orbitaldebris.jsc.nasa.gov).

# 3. ACRONYMS AND DEFINITIONS

## 3.1 Acronyms

| | |
|---|---|
| CDR | Critical Design Review |
| COPUOS | Committee on the Peaceful Uses of Outer Space |
| DAS | Debris Assessment Software |
| EOM | End of Mission |
| EOMP | End of Mission Plan |
| ESA | European Space Agency |
| GEO | Geosynchronous Earth Orbit |
| GTO | Geosynchronous Transfer Orbit |
| HEO | High Earth Orbit |
| HQ | Headquarters |
| IADC | Inter-Agency Space Debris Coordination Committee |
| ISO | International Organization for Standardization |
| LEO | Low Earth Orbit |
| MEO | Medium Earth Orbit |
| ODA | Orbital Debris Assessment |
| ODAR | Orbital Debris Assessment Report |
| ODPO | NASA Orbital Debris Program Office |
| OSMA | Office of Safety and Mission Assurance |
| OSTP | Office of Science and Technology Policy |
| PDR | Preliminary Design Review |
| sfu | Solar Flux Unit |
| SMA | Safety and Mission Assurance |
| SSN | Space Surveillance Network |

| | |
|---|---|
| SSO | Sun Synchronous Orbit |
| STSC | Scientific and Technical Subcommittee |
| TNT | Trinitrotoluene |

## 3.2 Definitions

*Apogee*: The point in the orbit that is the farthest from the center of the Earth. The apogee altitude is the distance of the apogee point above the surface of the Earth.

*Apsis (pl. apsides)*: The point in the orbit where a satellite is at the lowest altitude (perigee) or at the highest altitude (apogee). The line connecting apogee and perigee is the *line of apsides*.

*Argument of perigee*: The angle between the line extending from the center of the Earth to the ascending node of an orbit and the line extending from the center of the Earth to the perigee point in the orbit measured from the ascending node in the direction of motion of the satellite.

*Ascending node*: The point in the orbit where a satellite crosses the Earth's equatorial plane in passing from the southern hemisphere to the northern hemisphere.

*Cratering flux*: The number of impacts per square meter per year of objects which will leave a crater at least as large as a specified diameter.

*Debris flux*: The number of impacts per square meter per year expected on a randomly oriented planar surface of an orbiting space structure.

*Debris flux to limiting size:* The number of impacts per square meter per year of debris objects of a specified diameter or larger.

*ΔV*: The change in the velocity vector caused by thrust measured in units of meters per second.

*Disposal:* An end-of-mission process for moving a spacecraft (if necessary) to an orbit considered acceptable for orbital debris limitation.

*Eccentricity*: The apogee altitude minus perigee altitude of an orbit divided by twice the semi major axis. Eccentricity is zero for circular orbits and less than one for all elliptical orbits.

*f10*: An index of solar activity; often a 13-month running average of the energy flux from the Sun measured at a wavelength of 10.7 cm, expressed in units of $10^4$ janskys.

*Geosynchronous Earth Orbit (GEO)*: An orbit with a period equal to the sidereal day. A circular GEO with 0° inclination is a geostationary orbit; i.e., the nadir point is fixed on the Earth's surface. The normal altitude of a circular GEO is 35,786 km and the inclination is normally +/- 15 degrees latitude.

Geosynchronous Transfer Orbit (GTO): A highly eccentric orbit with perigee normally within or near the LEO region altitude and apogee near or above GEO altitude.

High Earth Orbit (HEO): An orbit with a mean altitude greater than 2000 km or, equivalently, an orbit with a period greater than 127 minutes.

Inclination: The angle an orbital plane makes with the Earth's equatorial plane.

Jansky: A unit of electromagnetic power density equal to $10^{-26}$ watts/$m^2$/Hz.

Launch vehicle: Any space transportation mode, including expendable launch vehicles (ELVs), reusable launch vehicles (RLVs), and the Space Shuttle.

Line of apsides: The line connecting the apogee and perigee points in an orbit. This line passes through the center of the Earth.

Line of nodes: The line formed by the intersection of the orbit plane with the Earth's equatorial plane. This line passes through the center of the Earth. The ascending node is the point where a satellite crosses the equator from the southern hemisphere to the northern hemisphere.

Low Earth Orbit (LEO): An orbit with a mean altitude less than or equal to 2000 km, or equivalently, an orbit with a period less than or equal to 127 minutes.

Meteoroids: Naturally occurring particulates associated with solar system formation or evolution processes. Meteoroid material is often associated with asteroid breakup or material released from comets.

Mission operations: All activities executed by the spacecraft; includes design mission, primary mission, secondary mission, extended mission, and disposal.

Orbital debris: Artificial objects, including derelict spacecraft and spent launch vehicle orbital stages, left in orbit which no longer serve a useful purpose. In this document, only debris of diameter 1 mm and larger is considered. If liquids are to be released, they should explicitly be shown to be compliant with all mitigation requirements.

Orbital lifetime: The length of time an object remains in orbit. Objects in LEO or passing through LEO lose energy as they pass through the Earth's upper atmosphere, eventually getting low enough in altitude that the atmosphere removes them from orbit.

Orbital Stage: A part of the launch vehicle left in a parking, transfer, or final orbit during or after payload insertion; includes liquid propellant systems, solid rocket motors, and any propulsive unit jettisoned from a spacecraft.

Passivation: The process of removing stored energy from a space structure at EOM which could result in an explosion or deflagration of the space structure to preclude generation of new orbital debris after End of Mission. This includes removing energy in the form of electrical, pressure, mechanical, or chemical. See paragraph 4.4.4.1.2 for more details on passivation.

*Penetration debris flux:* The number of impacts per square meter per year that will penetrate a surface of specified orientation with specified materials and structural characteristics.

*Perigee*: The point in the orbit that is nearest to the center of the Earth. The perigee altitude is the distance of the perigee point above the surface of the Earth.

*Postmission Disposal*: The orbit/location where a spacecraft/launch vehicle is left after passivation at EOM.

*Right ascension of ascending node*: The angle between the line extending from the center of the Earth to the ascending node of an orbit and the line extending from the center of the Earth to the vernal equinox, measured from the vernal equinox eastward in the Earth's equatorial plane.

*Semi-major axis*: Half the sum of the distances of apogee and perigee from the center of the Earth. Half the length of the major axis of the elliptical orbit.

*Semi-synchronous Orbit (SSO):* An orbit with approximately a 12-hour period. A circular SSO is at an altitude of approximately 20,200 km.

*Solar flux unit (sfu)*: Equal to $10^4$ janskys measured at a wavelength of 10.7 cm.

*Space debris:* General class of debris, including both meteoroids and orbital debris.

*Space Structures*: Spacecraft and launch vehicle orbital stages. This includes all components contained within the object such as instruments and fuel.

*Spacecraft*: This includes all components contained within a space borne payload such as instruments and fuel.

*Stabilized*: When the spacecraft maintains its orientation along one or more axes.

*Vernal equinox:* The direction of the Sun in space when it passes from the southern hemisphere to the northern hemisphere (on March 20 or 21) and appears to cross the Earth's equator. The vernal equinox is the reference point for measuring angular distance along the Earth's equatorial plane (right ascension) and one of two angles usually used to locate objects in orbit (the other being declination).

# 4. REQUIREMENTS

## 4.1 Objectives of Orbital Debris Assessments and Planning

a. It is U.S. and NASA policy to limit the generation of orbital debris, consistent with mission requirements and cost effectiveness. NPR 8715.6 requires that each program or project conduct a formal assessment for the potential to generate orbital debris.

b. Each program or project should attempt to meet all pertinent requirements for its spacecraft, launch vehicle orbital stage(s), and objects released during nominal operations. It is understood, however, that satisfying these requirements must be balanced with the necessity to meet mission requirements and to control costs. If a requirement cannot be met because of an overriding conflict with mission requirements, technical capabilities, or prohibitive cost impact, then a waiver can be requested through the NASA Program Manager per NPR 8715.3 Section 1.13 with the ODAR containing the appropriate rationale and justification.

c. The NASA ODPO is staffed and funded to provide support to programs either as an Agency overhead or cost reimbursable function. The SMA organization at each Center and NASA Headquarters can also assist programs and projects with the preparation of the required ODARs and EOMPs. Programs/projects shall use the orbital debris modeling tools provided by the NASA ODPO in assessing orbital debris generation and risk in Earth orbit (Requirement 56346).

## 4.2 Conducting Debris Assessments: An Overview

The objective of an Orbital Debris program is to limit the generation of debris in orbit and the risk to human life due to generated orbital debris through prevention and analyses. Debris can damage other spacecraft, provide false scientific readings, and become a hazard to spacecraft, people in orbit, and people on the ground. In addition to limiting generation of debris in Earth orbit, NASA requires that the generation of debris be limited in lunar orbit. NASA should also limit debris generated at the Earth-Sun Lagrange points and in orbit around other celestial bodies.

Limiting orbital debris involves the following:

- Limiting the generation of debris associated with normal space operations;
- Limiting the probability of impact with other objects in orbit;
- Limiting the consequences of impact with existing orbital debris or meteoroids;
- Limiting the debris hazard posed by tether systems;
- Depleting onboard energy sources after completion of mission;
- Limiting orbital lifetime in LEO after mission completion or maneuvering to a disposal orbit; and
- Limiting the human casualty risk from space system components surviving reentry as a result of postmission disposal.

*Note: NASA-HDBK 8719.14 serves as a reference document to assist orbital debris practioners and program/project management in understanding orbital debris. Topics in NASA-HDBK 8719.14 include the OD environment, measurements, modeling, shielding,* *mitigation, and reentry. It is strongly encouraged that the NASA-HDBK be used with the implementation of NPR 8715.6 and NASA-STD 8719.14.*

### 4.2.1 ODA and ODARs

a. The detailed requirements and evaluation methods for ODARs are presented in Sections 4.3 through 4.8.

b. The orbital debris assessment covers the following broad areas:

- The potential for generating debris during normal operations or malfunction conditions;
- The potential for generating debris from a collision with debris or orbiting space systems; and
- Postmission disposal.

c. These broad areas are categorized into seven issues that are addressed in the assessment:

- Debris released during normal operations;
- Debris generated by explosions and intentional breakups;
- Debris generated by on-orbit collisions during mission operations;
- Reliable disposal of spacecraft and launch vehicle orbital stages after mission completion;
- Structural components impacting the Earth following postmission disposal by atmospheric reentry;
- Disposal of spacecraft and launch vehicle stages in orbits about the Moon; and
- Debris generated by on-orbit collisions with a tether system.

d. The assessment shall be organized in an ODAR using Appendix A, Section A.1 (Requirement 56371).

e. ODAs being performed on components or portions of a spacecraft shall document the assessment in the abbreviated ODAR using Appendix A.3 (Requirement 56372).

f. It is strongly encouraged that programs limit the regeneration of existing programmatic assessments, but rather include it as an attachment to the ODAR.

g. NPR 8715.6 specifies the timing of deliveries of ODARs to NASA.

h. Although ODARs are not required until PDR, it is advisable for each program or project to consider potential orbital debris issues during concept development (Phase A) and development of preliminary requirements, specifications, and designs (Phase B) to estimate and minimize potential cost impacts.

i. NASA programs/projects that are flying as Space Shuttle, International Space Station (ISS), and Constellation Program payloads that remain encapsulated by the Space Shuttle/ISS (i.e., not exposed to outer space environment) are exempted from performing orbital debris assessments. Space Shuttle/ISS/Constellation payloads which are temporarily deployed and retrieved into the

ISS or on the same Space Shuttle or Constellation flight shall provide an abbreviated Orbital Debris Assessment (ODA) Report (ODAR) per this NASA-STD (Requirement 56376).

### 4.2.2 EOMP

An EOMP is developed for limiting debris generation and limiting risk to the public and other active spacecraft during decommissioning, and disposal of all space objects.

a. The EOMP is a living document. It is developed during the later stages of mission development to ensure that design and operational use do not preclude a safe decommissioning and disposal. The EOMP identifies milestones in the operational life of the mission which affect the EOM processing. After those milestones, the EOMP and the health of the critical items defined in the EOMP shall be evaluated and updated so that NASA management understands the constraints and options available at EOM for limiting orbital debris (Requirement 56379).

b. The EOMP shall be organized using Appendix B, Section B.1 (Requirement 56380).

c. The EOMP shall contain a statement covering what actions must be undertaken in the event of reductions of capabilities or consumables which may significantly and predictably threaten the ability to carry out the EOMP (Requirement 56381). This includes reduction of system capability to "single string" unless expressly agreed otherwise.

d. It is strongly encouraged that programs limit the regeneration of existing programmatic information, but rather include the ODAR and other assessments as attachments.

e. NPR 8715.6 specifies the timing of deliveries of EOMPs to NASA.

f. An EOMP may include other aspects of the EOM process (final disposition of data and hardware, for example) if the program finds that the EOMP is the most convenient means of recording this information. Other applicable sections may be placed after the sections specified in Appendix B.

### 4.2.3 Structure of the Requirements in this Document

a. Each of Sections 4.3 through 4.8 covers a separate orbital debris technical area. Table 4.2-1 defines the organization for each technical area. Table 4.2-2 lists each orbital debris technical area. Note: In Table 4.2-1, the '4.x' is a pointer to sections 4.3 to 4.8.

**Table 4.2-1: Orbital Debris Technical Area Organization**

| | |
|---|---|
| Section 4.x.1 | Definition of the Area |
| Section 4.x.2 | Requirements for the Area |
| Section 4.x.3 | Rationale for the Area Requirements |
| Section 4.x.4 | Methods to Assess Compliance |
| Section 4.x.5 | Brief Summary of Mitigation Measures Used in NASA for this Area |

b. The sections titled "Method to Assess Compliance" (Sections 4.x.4) provide detailed steps for how compliance with each requirement is determined and measured. Actual compliance can be verified with the specially designed DAS (DAS 2.0 or higher) for operations in Earth orbit. Both the software and its documentation can be downloaded from the Internet at www.orbitaldebris.jsc.nasa.gov. NASA ODPO contact personnel are also identified at this web site. The models in DAS support the approach and techniques described in this NASA-STD. If methods or models other than DAS are used, a full description of the models used will need to be added to ODAR Front Matter (See Appendix A Section A.1.

c. Table 4.2-2 provides a summary of each of the technical requirements which need to be addressed in the ODAR.

**Table 4.2-2: Orbital Debris Technical Area Issues and Corresponding Requirements**
(Note: Requirement applicability is indicated in the introduction to each requirement area in sections 4.3 – 4.8.)

| Debris Assessment Issues | Reqm't | Requirement Summary | Comments |
|---|---|---|---|
| Release of debris during normal mission operations | 4.3-1 and 4.3-2 | • Limit number and orbital lifetime of debris passing through LEO<br>• Limit lifetime of objects passing near GEO | Requirement includes staging components, deployment hardware, or other objects that are known to be released during normal operations. |
| Accidental explosions | 4.4-1 and 4.4-2 | • Limit probability of accidental explosion during mission operations<br>• Passivate to limit probability of accidental explosion after EOM | Requirement addresses systems and components such as range safety systems, pressurized volumes, residual propellants, and batteries. |
| Intentional breakups | 4.4-3 and 4.4-4 | • Limit number, size, and orbital lifetime of debris larger than 1 mm and 10 cm<br>• Assess risk to other programs for times immediately after a test when the debris cloud contains regions of high debris density | Intentional breakups include tests involving collisions or explosions of flight systems and intentional breakup during space system reentry to reduce the amount of debris reaching the surface of the Earth. |

| Debris Assessment Issues | Reqm't | Requirement Summary | Comments |
|---|---|---|---|
| Collisions with large objects during orbital lifetime | 4.5-1 | Assess probability of collision with intact space systems or large debris (>10cm) | Collisions with intact space systems or large debris may create a large number of debris fragments that pose a risk to other operating spacecraft. A significant probability of collision may necessitate design or operational changes. |
| Collisions with small debris during mission operations | 4.5-2 | Assess and limit the probability of damage to critical components as a result of impact with small debris | Damage by small debris impacts can result in failure to perform postmission disposal. A significant probability of damage may necessitate shielding, use of redundant systems, or other design or operational options. |
| Postmission disposal | 4.6-1, 4.6-2, 4.6-3, and 4.6-4 | • Remove spacecraft and orbital stages from LEO to reduce collision threat to future space operations<br>• Remove spacecraft and orbital stages from GEO to reduce collision threat to future space operations<br>• Govern intermediate disposal orbits<br>• Assess reliability of postmission disposal<br>• Assess options for disposal beyond Earth's orbit | The accumulation of spacecraft and orbital stages in Earth orbit increases the likelihood of future collisions and debris generation. The orbital lifetimes of spacecraft and orbital stages in LEO and near GEO must be limited. The removal of objects at the EOM is preferred, but specific disposal orbits may be used. |
| EOM Planning | 4.6-5 | • Develop an EOMP addressing how the spacecraft will be decommissioned and disposed of. This includes:<br>• Passivation of all energy systems | The planning for demise, decommissioning, and disposal of all space objects is key to limiting space debris. |

| Debris Assessment Issues | Reqm't | Requirement Summary | Comments |
|---|---|---|---|
| Reentry Debris Casualty Risk | 4.7-1 | Limit number and size of debris fragments that survive atmospheric reentry | This requirement limits human casualty expectation. |
| Collision risk posed by tether systems | 4.8-1 | • Assess the probability of collision with resident space objects and limit orbital lifetime<br>• Mitigate the effects of severed tether systems | Tether systems may pose special collision hazards with other objects in orbit. Severed tethers may create additional hazards and hinder disposal plans. |

### 4.2.4 Deviations to ODARs and EOMPs

Requirements for submission of ODARs and EOMPs are contained in NPR 8715.6. Any deviation/waivers/exceptions from the requirements for ODAR and EOMPs stated in this NASA-STD require NASA management approval per NPR 8715.6.

## 4.3 Assessment of Debris Released During Normal Operations

Orbital debris analyses assess the amount of launch vehicle and spacecraft debris released in normal operations. This requirement area applies to all space structures while in Earth orbit and is recommended for lunar and Mars orbital operations.

### 4.3.1 Definition of Released Debris Technical Area

a. The goal is that in all operational orbits, space systems are designed not to release debris during normal operations. Where this is not feasible, any release of debris needs to be minimized in number, area, and orbital lifetime.

b. Historically, debris has been released as an incidental part of normal space operations. This type of debris is referred to as operational or mission-related debris and includes such objects as sensor covers, tie-down straps, explosive bolt fragments, attitude control devices, and dual payload attachment fittings. Space systems need to be designed to avoid the creation of any operational or mission-related debris. If the release of debris is unavoidable, the release should be done in a manner that limits the risk to other users of space. Debris 1 mm in diameter (about 1 mg) and larger for LEO and 5 cm (about 100 gm) and larger for GEO is a source of concern because these debris have sufficient energy to critically damage an operating spacecraft. Large debris can create a cloud of secondary debris fragments in the event of a collision with another resident space object.

c. The probability of a future collision occurring with debris depends on the number and size of the debris and on the length of time the debris remains in orbit. The requirements, therefore, limit the total number of such debris objects and their orbital lifetimes. Debris released during normal operations includes debris released during launch vehicle staging, payload separation, deployment, mission operations, and EOM passivation/disposal. Spacecraft and spent orbital stages, as intact structures, are not considered operational debris themselves and are addressed later in Sections 4.5 and 4.6.

d. Small debris, such as slag which is ejected during the burning of a solid rocket motor, and liquids dispersed from a spacecraft, are not covered by the requirements of this NASA-STD.

### 4.3.2 Requirements for the Control of Debris Released During Normal Operations

NASA programs and projects shall assess and limit the amount of debris released (Requirement 56396).

4.3.2.1 *Requirement 4.3-1: Debris passing through LEO:* For missions leaving debris in orbits passing through LEO, released debris with diameters of 1 mm or larger shall satisfy both Requirement 4.3-1a and Requirement 4.3-1b (Requirement 56397).

a. Requirement 4.3-1a: All debris released during the deployment, operation, and disposal phases shall be limited to a maximum orbital lifetime of 25 years from date of release (Requirement 56398).

b. Requirement 4.3-1b: The total object-time product shall be no larger than 100 object-years per mission (Requirement 56399). The object-time product is the sum of all debris of the total time spent below 2000 km altitude during the orbital lifetime of each object. (See section 4.3.4.2 for methods to calculate the object-time product.)

4.3.2.2 *Requirement 4.3-2: Debris passing near GEO:* For missions leaving debris in orbits with the potential of traversing GEO (GEO altitude +/- 200 km and +/- 15 degrees latitude), released debris with diameters of 5 cm or greater shall be left in orbits which will ensure that within 25 years after release the apogee will no longer exceed GEO - 200 km (Requirement 56400).

### 4.3.3 Rationale for Released Debris Area Requirements

a. The intent of Requirement 4.3-1 is to remove debris in LEO from the environment in a reasonable period of time. The 25-year removal time from LEO limits the growth of the debris environment over the next 100 years while limiting the cost burden to programs and projects. The limit of 25 years has been thoroughly researched and has been accepted by the U.S. Government and the major space agencies of the world.

b. Debris in orbits with perigee altitudes below 600 km will usually have orbital lifetimes of less than 25 years. This requirement will have the greatest impact on programs and projects with perigee altitudes above 700 km, where objects may remain in orbit naturally for hundreds of years.

c. Requirement 4.3-1b limits the total number of debris objects released while taking into account their orbital lifetimes. Based on historical precedent and practice, an acceptable level of risk for released debris damaging another operational spacecraft is $<10^{-6}$ (over the life of the decay). The value of 100 object-years was chosen because debris released during normal operations following this requirement will have a probability on the order of $10^{-6}$ of hitting and potentially damaging an average operating spacecraft.

d. Examples of LEO debris are the cover (0.3 kg and ~0.2 $m^2$) released from the SABER instrument on the TIMED spacecraft which was launched in 2001 and the Delta 2 Dual Payload Attachment Fitting (DPAF) employed on the ICESAT and CHIPSAT mission of 2003. In both cases the debris were left in orbits of less than 630 km and are expected to decay from orbit well within the 25-year requirement.

e. Debris that is not removed from GEO altitude may remain in the GEO environment for many thousands of years. Therefore, Requirement 4.3-2 limits the accumulation of debris at GEO altitudes and will help mitigate the development of a significant debris environment, as currently exists in LEO. The 200 km offset distance takes into account the operational requirements of GEO spacecraft (see Section 4.6). Special orbit propagation models are necessary to evaluate the evolution of disposal orbits to ensure that debris do not later interfere with GEO, as a result of solar and lunar gravitational perturbations and solar radiation pressure.

### 4.3.4 Methods to Assess Compliance

Compliance to section 4.3 requirements shall be documented in the ODAR and EOMP for all items/objects larger than 1 mm in LEO and 5 cm in GEO planned for release during all phases of flight (Requirement 56407).

#### 4.3.4.1 Debris Passing Through LEO: 25-Year Maximum Lifetime (Requirement 4.3-1a)

a. The amount of time a debris object will remain in orbit depends on its initial orbit, on the area-to-mass ratio of the debris, and on solar activity. For an object with an apogee altitude above 5,000 km, the orbit lifetime will also be affected by lunar and solar gravitational perturbations.

b. The steps in performing the ODA for this requirement are as follows:

(1) Determine the average cross-sectional area, area-to-mass ratio, and initial orbit for each debris piece released. The average cross-sectional area for atmospheric drag calculations for an object that is not stabilized in attitude is the cross-sectional area averaged over all aspect angles and is measured in square meters. The NASA ODPO's DAS provides a rigorous means of determining average cross-sectional area. It can be approximated as follows:

(a) For convex shaped debris, the average cross-sectional area is approximately 1/4 of the surface area. For a convex shape, all of the surface area elements are exposed to a complete hemisphere ($2\pi$ steradians) of deep space. Examples of convex shapes are spheres, plates, and cylinders.

(b) For non-convex shaped debris, an estimate of the average cross-sectional area may be obtained in two ways:

[1] For nearly convex shaped debris; i.e., debris for which there is almost no shielding of one surface element from the deep space environment by another, use 1/4 of the effective total surface area of the debris. The effective total surface area is the total surface area decreased by the surface area shielded from deep space. Examples of nearly convex shapes are two convex shapes attached by a connecting element such as a cable or a convex shaped debris object with an appendage.

[2] For complex debris shapes, determine the view, V, that yields the maximum cross-sectional area and denote the cross-sectional area as $A_{max}$. Let $A_1$ and $A_2$ be the cross-sectional areas for the two viewing directions orthogonal to V. Then define the average cross-sectional area as $(A_{max} + A_1 + A_2) / 2$.

(c) If the debris will assume a stable attitude relative to the velocity vector, the average cross-sectional area for atmospheric drag calculations is the cross-sectional area presented in the direction of motion.

(d) The area-to-mass ratio for the debris object is the average cross-sectional area ($m^2$) divided by the mass (kg).

(e) The initial debris orbit is the orbit of the object releasing the debris unless the release occurs with Δv greater than 10 meters per second. For debris released with significant Δv (typically greater than 10 meters per second), the initial debris orbit may be significantly different from that of the object releasing the debris. DAS can be used to calculate the initial orbit in this case.

(2) With the debris orbital parameters, area-to-mass ratio, and year of release into orbit, use DAS to determine the orbital lifetime. If the apogee of the debris is greater than 5000 km, then additional orbital data will be needed. DAS will prompt the user for this information. Assistance can also be obtained from the NASA ODPO at the NASA JSC.

#### 4.3.4.2 Debris Passing Through LEO: Total Object-Time Product (Requirement 4.3-1b)

a. The total object-time product is the sum, over all objects, of the orbit dwell time in LEO. "Orbit dwell time" is defined as the total time spent by an orbiting object below an altitude of 2000 km during its orbital lifetime. If the debris is in an orbit with apogee altitude below 2000 km, the orbit dwell time equals the orbital lifetime. The orbit dwell time for each object can be obtained directly using DAS and the orbital information collected for the evaluation of Requirement 4.3-1.

b. If the calculated orbit dwell time for debris is calculated to be 25 years, then no more than four such debris can be released to be compliant with the 100 object-years limit. Note that Requirement 4.3-1a limits the total orbital lifetime of a single piece of debris passing through LEO to 25 years, regardless of how much time per orbit is spent below 2000 km. If the orbital dwell time of the debris is only 20 years, then a total of up to five debris can be released and still satisfy Requirement 4.3-1b, as long as the maximum orbital lifetime of each debris does not exceed 25 years. Figure 4.3-1 depicts the relationship between perigee and apogee altitudes in determining orbital lifetime.

#### 4.3.4.3 Debris Passing Near Geosynchronous Altitude (Requirement 4.3-2)

a. In general, debris passing near GEO can be categorized as in nearly circular or in highly eccentric orbits. An example of the former would be debris released by a spacecraft after the spacecraft has already been inserted into an orbit near GEO. The GOES 2 spacecraft employed a design of this type. To ensure that the debris is compliant with Requirement 4.3-2, the spacecraft must be sufficiently above or below GEO at the time of debris release. DAS can determine the minimum altitude above GEO or the maximum altitude below GEO to ensure that the debris is not perturbed into GEO within 100 years.

b. Debris may also originate from a launch vehicle orbital stage which has directly inserted its payload into an orbit near GEO; e.g., the IUS upper stage used on the TDRS 7 mission. The goal is that no debris is released and that the orbital stages are sufficiently removed from GEO at the time of debris release to minimize the risk to other GEO objects, as described in the previous paragraph.

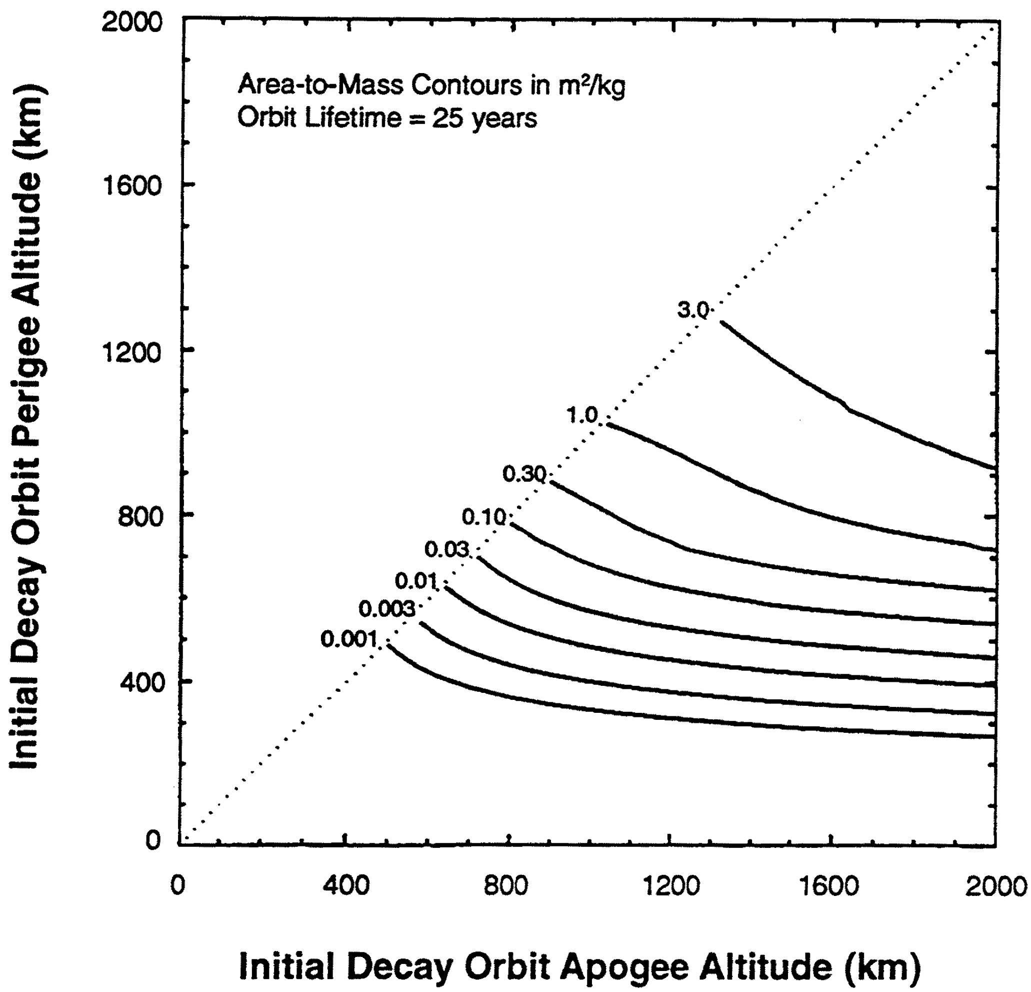


Figure 4.3-1. Maximum orbital parameters for sample area-to-mass values to ensure compliance with 25-year orbital lifetime limit under mean solar activity conditions and neglecting solar radiation effects

c. Debris may also be released into highly eccentric geosynchronous transfer orbits (GTO) with perigees near LEO or at higher altitudes and with apogees near GEO. (For debris with perigees passing through LEO, requirements 4.3-1a and 4.3-1b take precedence.) High perigee GTOs (above 2000 km) have been designed for use on several occasions by Proton launch vehicles and GOES 13. Debris released at the time of payload separation on a mission of this type would fall under Requirement 4.3-2. Debris can be left in an eccentric orbit traversing GEO, if orbital perturbations will cause the object to leave GEO within 25 years. DAS can be used to determine the long-term orbital perturbation effects for specific initial orbital conditions and, hence, to determine compliance with Requirement 4.3-2 by ensuring the debris will not reenter the GEO region within 100 years.

### 4.3.5 Brief Summary of Mitigation Measures Used in NASA for this Area

If a program or project does not fall within the above requirements, a number of mitigation measures may be taken. These include:

- Releasing debris in orbits with lower perigee altitude to reduce orbital lifetime;
- Designing debris with larger area-to-mass ratio to reduce orbital lifetime;
- Releasing debris under conditions in which lunar and solar perturbations will reduce lifetime; and
- Limiting release of debris by making design changes, changing operational procedures, or confining debris to prevent release into the environment.

Ground based simulations and testing can be used to better understand the characteristics and confinement approaches.

## 4.4 Assessment of Debris Generated by Explosions and Intentional Breakups

Orbital debris analyses assess accidental explosion probability and intentional breakups during and after completion of mission operations. Requirements 4.4-1, 4.4-2, and 4.4-3 are required for all space structures in Earth and lunar orbits (Requirement 56433). Requirement 4.4-3 is recommended for Earth-Sun Lagrange Points, Earth-Moon Lagrange points, and Mars operations.

Section 4.4 is not intended to mandate the use of techniques that could cause unreasonable passivation errors or malfunctions that involve nonreversible passivation methods.

### 4.4.1 Definition of the Explosion and Intentional Breakup Technical Area

a. Spacecraft and launch vehicle orbital stage explosions have been the primary contributor to the hazardous orbital debris environment. Some explosions have been accidental with onboard energy sources providing the energy such as residual propellants or pressurants left in orbital stages. However, some intentional breakups have occurred as tests or as a means of disposing of spacecraft.

b. In order to limit the risk to other space systems from accidental breakups after the completion of mission operations, all onboard sources of stored energy of a space system, such as residual propellants, batteries, high-pressure vessels, self-destructive devices, flywheels, and momentum wheels are depleted or safed when they are no longer required for mission operations or postmission disposal. Depletion should occur as soon as this operation does not pose an unacceptable risk to the payload (see section 4.6.2.5).

c. Meeting this requirement necessitates reliable designs to prevent explosions during operations as well as after operations are completed.

#### 4.4.1.1 Accidental Explosions

a. Accidental explosions of spent orbital stages have been the primary source of long-lived debris greater than 1 cm in diameter in LEO. The assessed source of energy for most of these events has been residual propellants, including liquid oxygen and hypergolic propellants. U.S. Delta 1 second stages were a principal source of such debris before corrective measures were implemented, but similar failures have been observed with European, Chinese, Russian, French, Indian, and Ukrainian orbital stages. Such failures have occurred as soon as a few hours and as long as 23 years after launch. The explosion of a 2-year-old Pegasus orbital stage in 1996 produced the greatest number of cataloged fragmentation debris to that date and was probably caused by the failure of a pressure regulation valve connecting a high pressure nitrogen supply with a lower pressure propellant tank. Several spacecraft breakups have been linked to battery failures.

b. Accidental explosions, primarily related to propulsion system malfunctions, during orbital deployment or orbital operations have also been documented. However, historically these events have attracted greater attention and more extensive preventive measures.

#### 4.4.1.2 Intentional Breakups

a. Intentional breakups have been used to reduce the amount of debris surviving the reentry of large space structures and in conjunction with on-orbit tests. An example of the latter was the deliberate structural limits testing of the second flight of the Saturn IVB stage in 1966.

b. An understanding of the approach taken in the evaluation for intentional breakups requires an understanding of the development of a debris cloud after breakup. Immediately after breakup, the debris cloud exhibits large spatial and temporal changes in the concentration of the debris. For example, near the inertial point in the orbit where the breakup occurred there may be no debris at times, while at other times the debris cloud densities may be orders of magnitude above the background. An operating spacecraft may have a small probability of colliding with the debris if the interaction were to occur randomly but a high probability of collision if it passes through a region of high density concentration. The test program can avoid having such high risk interactions by controlling the time and/or location of the test. However, because of the many orbital perturbations which affect space objects and because of the sensitivity of the debris cloud evolution to the exact time and location of the breakup event, the potential risk to other operating spacecraft can be determined accurately only a few days before the test. The assessment and control of this risk must be performed in conjunction with the Department of

Defense. This planning process needs to commence no later than 30 days before the planned breakup.

c. Within a few days after the breakup, the debris becomes more uniformly distributed within the cloud, and the cloud reaches a state called the pseudo-torus. Later, the debris cloud will expand and evolve into a shell distribution. By the time the debris cloud reaches the pseudo-torus state, the probability of collision between the debris cloud and other objects in space can be calculated assuming random encounters.

d. Secondary debris can also be generated by the collision of breakup debris with large operational and non-operational resident space objects. This risk is mitigated by placing limits on the numbers and orbital lifetime of breakup debris large enough to cause significant subsequent breakups.

### 4.4.2 Requirements for the Area

#### 4.4.2.1 Accidental Explosions

Orbital debris analyses assess the probability of accidental spacecraft and launch vehicle orbital stage explosion during and after completion of deployment and mission operations.

4.4.2.1.1 Requirement 4.4-1: Limiting the risk to other space systems from accidental explosions during deployment and mission operations while in orbit about Earth or the Moon: For each spacecraft and launch vehicle orbital stage employed for a mission, the program or project shall demonstrate, via failure mode and effects analyses or equivalent analyses, that the integrated probability of explosion for all credible failure modes of each spacecraft and launch vehicle is less than 0.001 (excluding small particle impacts) (Requirement 56449).

4.4.2.1.2 Requirement 4.4-2: Design for passivation after completion of mission operations while in orbit about Earth or the Moon: Design of all spacecraft and launch vehicle orbital stages shall include the ability to deplete all onboard sources of stored energy and disconnect all energy generation sources when they are no longer required for mission operations or postmission disposal or control to a level which can not cause an explosion or deflagration large enough to release orbital debris or break up the spacecraft (Requirement 56450).

#### 4.4.2.2 Intentional Breakups

Orbital debris analyses evaluate the effect of intentional breakups of spacecraft and launch vehicle orbital stages on other users of space.

4.4.2.2.1 *Requirement 4.4-3. Limiting the long-term risk to other space systems from planned breakups:* Planned explosions or intentional collisions shall:

a) Be conducted at an altitude such that for orbital debris fragments larger than 10 cm the object-time product does not exceed 100 object-years (Requirement 56453). For example, if the debris fragments greater than 10cm decay in the maximum allowed 1 year, a maximum of 100 such fragments can be generated by the breakup.

b) Not generate debris larger than 1 mm that shall remain in Earth orbit longer than one year (Requirement 56454).

4.4.2.2.2 *Requirement 4.4-4: Limiting the short-term risk to other space systems from planned breakups:* Immediately before a planned explosion or intentional collision, the probability of debris, orbital or ballistic, larger than 1 mm colliding with any operating spacecraft within 24 hours of the breakup shall be verified to not exceed $10^{-6}$ (Requirement 56455).

### 4.4.3 Rationale for the Area Requirements

#### 4.4.3.1 Accidental Explosions

a. By keeping the probability of accidental explosion less than 0.001, the average probability of an operating spacecraft colliding with an explosion fragment larger than 1 mm from that space system will be less than $10^{-5}$ per "average spacecraft." An average spacecraft is a spacecraft of average size with average mission lifetime in circular orbit at an altitude through which explosion debris fragments that are 1 mm or larger would pass if an explosion occurred. The average probability of collision is the probability of collision averaged over the altitude that would be covered by the breakup cloud.

b. In cases where design and operational modifications have been made to remove stored energy sources, accidental explosions have been prevented. This process is called passivation. Onboard energy sources include chemical energy in the form of propellants (including a cold gas attitude control system), pressurants, explosives associated with range safety systems, pressurized volumes such as in sealed batteries, and kinetic energy devices such as control moment gyroscopes. An analysis should be done of pressurized systems which generally are not susceptible to fragmentation failures and their need to be passivated at EOM to mitigate the potential consequences of a later collision with a high speed object. For example, a cold gas attitude control system usually has a low probability for fragmentation failures, yet this system should still be passivated at EOM. The international adoption of passivation measures for both spacecraft and launch vehicle orbital stages has resulted in a significant curtailment in the rate of growth of the orbital debris population.

c. Passivation of all energy storage and charging systems should occur as soon as such operation does not pose an unacceptable risk to the mission (see section 4.6.2.5). In LEO, propellant depletion burns are normally designed to reduce the orbital lifetime of the vehicle to the maximum extent possible. Propellant depletion burns and compressed gas releases should also be designed to minimize the probability of accidental collision.

#### 4.4.3.2 Intentional Breakups

a. These requirements reflect the approach taken within the U.S. space program to limit the debris contribution from on-orbit tests. The P-78 (SOLWIND) ASAT test and the Delta-180 experiment are examples of missions reviewed by a safety panel for their near-term threat to operating spacecraft and for their long-term contribution to the orbital debris environment.

b. Debris released from an intentional breakup under Requirement 4.4-3 should not be a greater contributor to the long-term growth of the orbital debris environment than any debris released under requirements for normal operations (Requirement 4.3-1). The limit of 1 year for orbit lifetimes for debris larger than 1 mm prevents the accumulation of debris from intentional breakups.

c. The risk to other users from concentrations within the debris cloud which occur immediately after breakup is limited by Requirement 4.4-4 to no more than the risk represented by other debris deposition events such as release of operational debris.

### 4.4.4 Methods to Assess Compliance

Compliance to section 4.4 requirements shall be documented in the ODAR and EOMP for all phases of flight (Requirement 56465).

#### 4.4.4.1 Accidental Explosions

4.4.4.1.1 Limiting the Probability of Accidental Explosion (Requirement 4.4-1)

Documentation of the failure mode and effects analysis or some equivalent analysis of the credible failure modes that could lead to accidental explosion and their associated probability is included in the ODAR. Small particle impacts are not being considered here since they will be assessed in Section 4.5. If the probability of accidental explosion exceeds 0.001 for either a spacecraft or orbital stage, design or operational countermeasures will be needed to reduce the probability below the aforementioned limit.

4.4.4.1.2 Eliminating Stored Energy Sources (Requirement 4.4-2)

a. Documentation of the EOM sources or potential sources of stored energy that require passivation, and a plan for passivating these sources at EOM is included in the ODAR. Passivation procedures to be implemented might include;

- Burning residual propellants to depletion;
- Venting propellant lines and tanks;
- Venting pressurized systems;
- Discharging batteries, other energy storage systems, and preventing recharging;
- Depressurizing/discharging pressurized gas filled batteries;
- Deactivating range safety systems; and
- De-energizing control moment gyroscopes.

b. Residual propellants and other fluids, such as pressurants, should be depleted as thoroughly as possible, by either depletion burns or venting, to prevent accidental breakups by over pressurization or chemical reaction. Opening fluid vessels and lines to the space environment directly or indirectly at the conclusion of EOM passivation, is one way to reduce the possibility of a later explosion.

c. Depletion burns and ventings should not affect other space systems and should not increase the likelihood of fragmentation.

*Examples of potentially dangerous actions include a spin-up of the vehicle or inadvertent mixing of vented hypergolic propellants.*

*Note: The design of these depletion burns and ventings should minimize the probability of accidental collision with known objects in space.*

d. Leak-before-burst tank designs are beneficial but are not sufficient to prevent explosions in all scenarios. Therefore, such tanks should still be depressurized at the end of use. However, pressure vessels with pressure-relief mechanisms do not need to be depressurized if it can be shown that no plausible scenario exists in which the pressure-relief mechanism would be insufficient.

e. Small amounts of trapped fluids could remain in tanks or lines after venting or depletion burning. Design and operational procedures should minimize the amount of these trapped fluids.

f. Sealed heat pipes and passive nutation dampers need not be depressurized at EOM.

g. Batteries should be completely discharged and disconnected from their charging circuits. Electrical loads left connected to a battery can fail, leading to battery recharging if the charging circuit is not disconnected.

*Note: Paragraph 5.2.1(2) of the IADC Space Debris Mitigation Guidelines provides the additional direction for batteries: "At the end of operations battery charging lines should be de-activated."*

h. The removal of electrical energy inputs from rotational energy devices, such as a gyro, is usually sufficient to ensure the timely passivation of these units.

i. The ODAR and EOMP contain a full description of the passivation actions to be employed for all sources of stored energy and a notional timeline of when the actions take place. This plan identifies all passivation measures to include, at a minimum, spacecraft fuel depletion, propellant venting, disabling of battery charging systems, safing of bus and payloads, and any sources of stored energy that will remain. For example, an orbital stage main propulsion system depletion burn may be scheduled 15 minutes after separation of the payload, followed by a sequenced venting of the propellant and pressurant tanks thereafter.

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

#### 4.4.4.2 Intentional Breakups (Requirements 4.4-3 and 4.4-4)

a. The evaluation procedure for planned space object breakups uses Requirement 4.4-3 for long-term planning conducted during program development and uses Requirement 4.4-4 for near-term planning conducted shortly before the test. The objective of the long-term plan is to understand

and control the impact of the test on the space environment in general; that of the near-term plan is to control the risk of damage to operating spacecraft.

b. The steps for performing the evaluation are as follows:

(1) Define a breakup model for the test. A breakup model describes the debris created in the breakup process in terms of the distributions in size, mass, area-to-mass ratio, and velocity imparted at breakup. A standard breakup model used for debris environment evolution calculations may be acceptable for a test, or the breakup model may require taking into account specific characteristics of the planned test. Standard breakup models or support for defining specific breakup models for a given test may be obtained from the NASA ODPO at the NASA JSC.

(2) Calculate and sum the object-time products for the debris as derived from the breakup model and the state vector at the time of breakup. This procedure is described in detail in Section 4.3.3. DAS may be used to calculate initial state vectors for the debris fragments and the resulting orbit lifetimes, although use of a special model may be beneficial due to the large number of debris to be evaluated. Compare these summed products with the requirement of 100 object-years.

(3) Verify that no debris larger than 1 mm will have an orbital lifetime greater than one year.

(4) No later than 30 days prior to the planned breakup, coordinate with the Department of Defense (specifically, U.S. Strategic Command) to verify that immediately after the breakup no operating spacecraft will have a probability of collision greater than $10^{-6}$ with debris larger than 1 mm. Special software is generally required to analyze the debris cloud characteristics immediately after breakup. Contact the NASA ODPO at NASA JSC for assistance.

#### 4.4.5 Brief Summary of Mitigation Measures Used in NASA for this Area

To lower the risk associated with on-orbit breakups:

- Lower the altitude at which the breakup occurs. This is by far the most effective response for reducing both the near-term and long-term risk to other users of space.
- Lower the perigee altitude of the orbit of the breakup vehicle(s); and/or
- Adjust the time for performing the breakup to avoid spacecraft or large resident space object interactions with regions of high flux concentration.
- Deplete propellants and other stored energy sources as soon as practical.

### 4.5 Assessment of Debris Generated by On-orbit Collisions

Orbital debris analyses assess the ability of the design and mission profile of a space system to limit the probability of accidental collision with known resident space objects during the system's orbital lifetime. Requirement area 4.5 shall apply for all space structures in Earth and lunar orbits (Requirement 56500).

### 4.5.1 Definition of the Collision-induced Risk to Disposal Technical Area

a. Debris can be generated by random on-orbit collisions during and after mission operations. At issue are both the direct generation of debris by collision between the space vehicle and another large object in orbit and the indirect or potential generation of debris when collision with small debris damages the vehicle to prevent its disposal at EOM, making it more likely that the vehicle will be fragmented in a subsequent breakup.

b. While it remains intact, a spacecraft or launch vehicle orbital stage represents a small collision risk to other users of space; however, once it is fragmented by collision, the collision fragments present a risk to other users that may be orders of magnitude larger. Because of typically high collision velocities, debris objects much smaller than the spacecraft may cause severe fragmentation (referred to as a catastrophic collision). For purposes of evaluation, debris with a diameter of 10 cm and larger will be assumed to cause a catastrophic collision.

c. Catastrophic collisions during mission operations represent a direct source of debris, and the probability of this occurring is addressed by Requirement 4.5-1. However, if a spacecraft or launch vehicle orbital stage fails to perform its planned postmission disposal operations, it becomes a potential source of debris because a structure that is abandoned in orbit can subsequently experience catastrophic breakup by collision or explosion. The probability of such an event occurring as a result of a prior damaging impact with small debris is addressed by Requirement 4.5-2.

### 4.5.2 Requirements for the Collision-induced Risk to Disposal Area

NASA programs and projects shall assess and limit the probability that the operating space system becomes a source of debris if it collides with orbital debris or meteoroids (Requirement 56505).

4.5.2.1 *Requirement 4.5-1. Limiting debris generated by collisions with large objects when operating in Earth orbit:* For each spacecraft and launch vehicle orbital stage in or passing through LEO, the program or project shall demonstrate that, during the orbital lifetime of each spacecraft and orbital stage, the probability of accidental collision with space objects larger than 10 cm in diameter is less than 0.001 (Requirement 56506).

4.5.2.2 *Requirement 4.5-2. Limiting debris generated by collisions with small objects when operating in Earth or lunar orbit:* For each spacecraft, the program or project shall demonstrate that, during the mission of the spacecraft, the probability of accidental collision with orbital debris and meteoroids sufficient to prevent compliance with the applicable postmission disposal requirements is less than 0.01 (Requirement 56507).

### 4.5.3 Rationale for the Collision-induced Risk to Disposal Area Requirements

a. Requirement 4.5-1 limits the amount of debris that will be created by collisions between spacecraft or launch vehicle orbital stages in or passing through LEO and other large objects in orbit. By keeping the probability of collision between a spacecraft or orbital stage and other large objects to less than 0.001, the average probability of an operating spacecraft colliding with collision fragments larger than 1 mm from that spacecraft or orbital stage will be less than $10^{-6}$ per "average spacecraft." An average spacecraft is a spacecraft of average size with average mission lifetime in circular orbit at an altitude through which the fragments from such a collision would pass if the collision occurred. The average collision probability is the probability of collision averaged over the altitude that would be covered by the breakup cloud. Due to the exceptionally long orbital lifetimes of spacecraft and orbital stages in orbits near GEO, the disposal orbit constraints in section 4.6 limit, to the greatest practical extent, the probability of collision with other large objects.

b. Requirement 4.5-2 limits the probability of spacecraft being disabled and left in orbit at EOM, which would contribute to the long-term growth of the orbital debris environment by subsequent collision or explosion fragmentation. Due to the very short mission durations of some launch vehicle orbital stages, the probability of a disabling small debris impact on orbital stages is not significant.

### 4.5.4 Methods to Assess Compliance

Compliance to section 4.5 requirements shall be documented in the ODAR and EOMP for all phases of flight including the launch phase per applicability in Section 4.5 introduction (Requirement 56511).

The analyses documented in the ODAR and EOMP need to include not only collisions that produce large amounts of debris, but also collisions that will terminate a spacecraft's capability to perform postmission disposal. This documentation should also address methods being used to reduce risk such as mission re-selection or operational collision avoidance and any trade-offs between cost, mission requirements, and risk reduction for each method.

4.5.4.1 Collisions with Large Objects During Orbital Lifetime (Requirement 4.5-1)

a. For missions in or passing through LEO, the probability of a space system being hit by an intact structure or large debris object during its orbital lifetime, *P*, can be approximated by*

$$P = F * A * T \qquad (4.5\text{-}1)$$

where

$F$ = weighted cross-sectional area flux for the orbital debris environment exposure
$A$ = average cross-sectional area for the space system in $m^2$
$T$ = orbital lifetime in years

b. The weighted cross-sectional area flux is derived by evaluating the amount of time the vehicle spends in different altitudes during its orbital lifetime. This value is determined by DAS given the initial orbit, area-to-mass ratio, and the launch date of the vehicle. If the vehicle is maintained at a specific altitude during its mission and/or maneuvers to a different orbit for

* The exact expression for this probability is $P=1-e^{-FAT}$, which is approximated by Equation 4.5-1 when the product $F \times A \times T$ is less than 0.1

disposal at EOM, the probability of collision with large objects must be evaluated separately for the different orbits and then summed.

c. The average cross-sectional area is the cross-sectional area averaged over all aspects. For a simple convex space system, it is approximately 1/4 of the surface area. A simple convex spacecraft body with solar panel wings may be given an average cross-sectional area that is 1/4 of the sum of the surface area of the spacecraft body plus solar panels.

d. For highly irregular spacecraft shapes, an estimate of the average cross-sectional area may be obtained as follows: determine the view, *V*, that yields the maximum cross-sectional area and denote the cross-sectional area as $A_{max}$. Let $A_1$ and $A_2$ be the cross-sectional areas for the two viewing directions orthogonal to V. Then define the average cross-sectional area as $( A_{max} + A_1 + A_2 ) / 2$.

4.5.4.2 Collisions with Small Debris During Mission Operations (Requirement 4.5-2)

a. An impact with small (millimeter to centimeter or milligram to gram) meteoroids or orbital debris can cause considerable damage because the impacts usually occur at high velocity (~10 km/sec for debris, ~20 km/sec for meteoroids). An obvious failure mode caused by orbital debris or meteoroid impact is for the impact to puncture a propellant tank, causing leakage. Other failure modes include the loss of a critical attitude control sensor or a break in an electrical line.

b. Spacecraft design will consider and, consistent with cost effectiveness, limit the probability that collisions with debris smaller than 10 cm diameter will cause loss of control to prevent postmission disposal.

c. For this requirement, only subsystems which are vital to completing postmission disposal need to be addressed. This includes components needed for either controlled reentry or spacecraft passivation. However, the same methodology can be used to evaluate the vulnerability of the spacecraft instruments and mission-related hardware. This information can be used to verify the reliability of the mission with respect to orbital debris and meteoroid hazards.

d. Determining the vulnerability of a space system to impact with orbital debris or meteoroids can be a very complex process, in some cases requiring hypervelocity impact testing of components and materials that have been designed into the system. The objective of the following evaluation process is to help the user determine (1) if there may be a significant vulnerability to meteoroid or orbital debris impact, (2) which components are likely to be the most vulnerable, and (3) what simple design changes may be made to reduce vulnerability. DAS can provide valuable insight into these issues. If necessary, higher fidelity assessments, such as with the NASA BUMPER II model, may be warranted. The NASA ODPO can assist programs or projects with any questions in this area.

e. For operations in Earth orbit, DAS shall be used to determine whether damaging impacts by small particles could reasonably prevent successful postmission disposal operations (Requirement 56523). The software estimates the probability that meteoroid or orbital debris impacts will cause components critical to postmission disposal to fail. If this estimate shows that there is a significant probability of failure, a higher-fidelity analysis shall be used to guide any redesign and to validate any shielding design (Requirement 56524). DAS is not intended to be used to design shielding.

f. To estimate the probability that impacts with small meteoroids or orbital debris will prevent postmission disposal, the project will need to perform the following in order to provide necessary inputs into DAS:

(1) Identify the components critical for postmission disposal and the surface of the component that, when damaged by impact, will cause the component to fail. This surface is termed the "critical surface." Examples of critical components include propellant lines and propellant tanks, elements of the attitude control system and down-link communication system, batteries, and electrical power lines.

(2) Calculate the at-risk surface area for the critical surface of each critical component.

(a) To calculate the at-risk area for a critical surface, first determine those parts of the critical surface that will be the predominant contributor to failure. Those will likely be the parts that have the least protection from meteoroid or orbital debris impact and may be considered in two cases. In the case where the critical surface is equally protected by other spacecraft components, no part of the surface is the major contributor, and the at-risk area is the total area of the critical surface. In the case where some parts of the critical surface are less protected from impact than other parts, the at-risk area is the surface area of those parts of the critical surface most exposed to space.

(b) For example, if an electronics box is attached to the inside of the outer wall of the vehicle, the at-risk area will be the area of the box on the side attached to the outer wall. If the electronics box is attached to the exterior of the outer wall of the vehicle, the at-risk area will be the total area of the box, excluding the side attached to the outer wall.

(c) The area at risk is then corrected to give an average cross-sectional area at risk, depending on the orientation of the surface with respect to the spacecraft orientation. To perform this correction in DAS, the user will need to input the spacecraft orientation and the unit normal vector to the critical surface. Please consult the DAS users guide for more detail on how to define spacecraft orientation and surface vectors.

(3) For each at-risk surface element, identify vehicle components and structural materials between the surface and space that will help protect that surface. Other vehicle components and structural materials between a critical surface and the meteoroid/debris environment will shield the surface. Determine the material density and estimate the thickness of each layer of material acting as a shield in the direction where there is least material to act as a shield. DAS will independently model each layer of material based upon the user-defined characteristics of each layer and determine an overall risk for each critical surface.

(4) DAS will then calculate the expected number of incidents for failure of postmission disposal critical elements, $F_C$, by summing the expected number of failures for each critical surface, $h_i$, as determined by DAS. This sum is expressed as

$$F_c = \sum h_i \qquad (4.5\text{-}2)$$

(5) DAS calculates the probability of failure of one or more critical elements, $P_c$, as a result of impact with debris by

$$P_c = 1 - e^{-F_c} \approx F_c \qquad (4.5\text{-}3)$$

where the approximation in the last step is valid if $F_C \leq 0.1$.

### 4.5.5 Brief Summary of Mitigation Measures Used in NASA for this Area

a. If a spacecraft or orbital stage in LEO or passing through LEO has a high probability of colliding with large objects during its orbital lifetime, there are several mitigation measures that may be taken. These include:

- Changing the planned mission orbit altitude to reduce the expected collision probability;
- Changing the spacecraft design to reduce cross-sectional area and thereby reduce the expected collision probability; and
- Reducing the amount of time in orbit by selecting a lower disposal orbit.

b. There are many mitigation measures to reduce the probability that collisions with small debris will disable the spacecraft and prevent successful postmission disposal. These measures use the fact that the debris threat is directional (for orbital debris, highly directional) and that the directional distribution can be predicted with confidence. Design responses to reduce failure probability include addition of component and/or structural shielding, rearrangement of components to let less sensitive components shield more sensitive components, use of redundant components or systems, and compartmentalizing to confine damage. Since there are many alternatives to pursue for reducing vulnerability to impact with small debris, some of them requiring in-depth familiarity with hypervelocity impact effects, they will not be discussed further in this document. If a significant reduction in failure probability is required, it is advisable to contact the NASA ODPO at the NASA JSC.

## 4.6 Postmission Disposal of Space Structures

Spacecraft disposal can be accomplished by one of three methods:

- Atmospheric reentry,
- Maneuvering to a storage orbit, or
- Direct retrieval.

Requirement area 4.6 applies as follows:

a) Requirements 4.6-1, 4.6-2, and 4.6-3 are required for all space structures when in Earth orbit (Requirement 56545).

b) Requirement 4.6-4 is required for all space structure in orbit about the Earth (Requirement 56546).

c) Requirement 4.6-5 is required for all space structures in orbit about the Earth and the Moon (Requirement 56547).

### 4.6.1 Definition of the Postmission Disposal Technical Area

a. The historical practice of abandoning spacecraft and upper stages at EOM has allowed more than 2 million kg of debris to accumulate in LEO. A similar amount of mass now resides in GEO. If the growth of debris mass continues, collisions between these objects will eventually become a major source of small debris, posing a threat to space operations. The most effective means for preventing future collisions is the removal of all spacecraft and upper stages from the environment in a timely manner. These requirements represent an effective method for controlling the growth of the orbital debris environment, while taking into account cost and mission consequences to future programs.

b. The postmission disposal options are (1) natural or directed reentry into the atmosphere within a specified time frame, (2) maneuver to one of a set of disposal regions in which the space structures will pose little threat to future space operations, and (3) retrieval and return to Earth. The last option requires use of the Space Shuttle or similar vehicle and will generally not be an option, due to logistical constraints, cost, and crew safety.

c. In general, the most energy-efficient means for disposal of space structures in orbits below 1400 km is via maneuver to an orbit from which natural decay will occur within 25 years of EOM and 30 years from launch. For space structures in orbits between 1400 km and 2000 km, a maneuver to a storage orbit above 2000 km would likely be the best disposal option. Spacecraft and orbital stages in orbits near GEO are disposed of in super-synchronous disposal orbits with a minimum perigee based upon the vehicle characteristics, but typically about 300 km above GEO.

d. Special disposal maneuvers are normally not required in Medium Earth Orbit (MEO), although efforts should be made to avoid potential interference with known operational satellite constellations, especially the Global Positioning System.

e. The space structure disposal requirements in this section are consistent with the recommendations of the Inter-Agency Space Debris Coordination Committee (IADC), the U.S. Government Orbital Debris Mitigation Standard Practices, the International Telecommunications Union (ITU), the U.S. Federal Communications Commission (FCC), and other international and foreign organizations.

f. NASA space programs and projects shall plan for the disposal of spacecraft and launch vehicle orbital stages and space structures at the end of their respective missions. Postmission disposal shall be used to remove a space structure from Earth orbit in a timely manner or to leave a space structure in a disposal orbit where the structure will pose as small a threat as practical to other space systems.

g. Because of fuel gauging uncertainties near the EOM, a program is recommended to implement a maneuver strategy that reduces the risk of leaving the structure near an operational orbit.

### 4.6.2 Requirements for the Area

4.6.2.1 *Requirement 4.6-1. Disposal for space structures passing through LEO:* A spacecraft or orbital stage with a perigee altitude below 2000 km shall be disposed of by one of three methods: (Requirement 56557)

a. Atmospheric reentry option:

- Leave the space structure in an orbit in which natural forces will lead to atmospheric reentry within 25 years after the completion of mission but no more than 30 years after launch; or
- Maneuver the space structure into a controlled de-orbit trajectory as soon as practical after completion of mission.

b. Storage orbit option: Maneuver the space structure into an orbit with perigee altitude greater than 2000 km and apogee less than GEO - 500 km.

c. Direct retrieval: Retrieve the space structure and remove it from orbit within 10 years after completion of mission.

4.6.2.2 *Requirement 4.6-2. Disposal for space structures near GEO:* A spacecraft or orbital stage in an orbit near GEO shall be maneuvered at EOM to a disposal orbit above GEO with a predicted minimum altitude of GEO +200 km (35,986 km) for a period of at least 100 years after disposal (Requirement 56563).

4.6.2.3 *Requirement 4.6-3. Disposal for space structures between LEO and GEO*:

a) A spacecraft or orbital stage may be left in any orbit between 2000 km above the Earth's surface and 500 km below GEO (Requirement 56565).
b) A spacecraft or orbital stage shall not use nearly circular disposal orbits near regions of high value operational space structures, such as between 19,100 km and 20,200 km (Requirement 56566).

4.6.2.4 *Requirement 4.6-4. Reliability of postmission disposal operations in Earth orbit*: NASA space programs and projects shall ensure that all postmission disposal operations are designed for a probability of success as follows: (Requirement 56567)

a. For disposal maneuvers not associated with controlled reentry, the probability of success shall be no less than 0.90 at EOM.

b. For controlled reentry, the probability of success at the time of reentry burn shall be sufficiently high so as not to cause a violation of Requirement 4.7-1 pertaining to limiting the risk of human casualty.

4.6.2.5 *Requirement 4.6-5. Operational design for EOM passivation*:

a) All NASA spacecraft and launch vehicles in Earth and lunar orbit shall be passivated at EOM to the extent necessary to prevent breakup or further generation of orbital debris (Requirement 56571).
b) The timing, order, procedures, and verification methods for performing all depletions identified for Requirement 4.4-2 shall have been developed prior to launch (Requirement 56572).
c) The level of passivation shall be updated prior to implementation of the EOMP (Requirement 56573).
d) Passivation shall occur as soon as this operation(s) does not pose an unacceptable risk to the payload after EOM has been commenced (Requirement 56574).
e) Spacecraft and launch vehicles not operating in orbit about Earth or its moon are not required to be passivated at EOM, however passivation is recommended.

### 4.6.3 Rationale for the Area Requirements

a. The intent of Requirement 4.6-1a is to remove spacecraft and orbital stages in LEO from the environment in a reasonable period of time. The 25-year removal time from LEO limits the growth of the debris environment over the next 100 years, while limiting the cost burden to LEO programs. The 30-year limit recognizes a mean mission lifetime in LEO of five years. Missions with longer anticipated durations should plan on using disposal orbit lifetimes of less than 25 years. Spacecraft and orbital stages in mission orbits with mean altitudes below 600 km will usually have orbital lifetimes less than 25 years and will likely, therefore, automatically satisfy this requirement. This requirement will have the greatest impact on programs with mission orbit perigee altitudes above 700 km, where objects can remain in orbit for hundreds of years if abandoned at EOM.

b. The 25-year criterion of Requirement 4.6-1a is a maximum value, and, if possible, spacecraft and orbital stages use all available capabilities to minimize the time spent in LEO disposal orbits. For example, orbital stages have often used residual propellants to reduce orbital lifetimes to very short periods, only months or a few years.

c. In general, an elliptical disposal orbit offers the best solution for minimizing energy requirements and minimizing orbital lifetime. For example, if a space structure is in a sun-synchronous orbit of 800 km, less energy is required to ensure an orbital lifetime of less than 25 years if the space structure is left in an elliptical rather than a circular orbit. In some cases, the perigee of the disposal orbit will be within the orbital altitudes used for human space flight operations. Orbits less than 400 km are considered as in the orbital altitude of the ISS. However, this poses no risk to human space flight since the space structure will be monitored throughout its orbital lifetime by the U.S. Space Surveillance Network, and established collision avoidance procedures for human space flight will prevent any future collision potential. The vast majority of space objects decaying down through the lower portions of LEO never pose an actual threat to human space flight operations. Elliptical orbits also usually result in a lower integrated risk to human space flight than decaying circular orbits.

d. If disposal by controlled reentry into the atmosphere is chosen, the trajectory must be designed to ensure that the space structure does not skip in the upper regions of the atmosphere.

Therefore, the effective perigee of the reentry trajectory shall be no higher than 50 km (Requirement 56580). See Section 4.7 for additional guidance on controlled reentries.

e. In Requirement 4.6-1c only 10 years is allowed for planned retrieval after completion of the mission, which is shorter than the 25 years for orbital decay and atmospheric reentry in Requirement 4.6-1a. Retrieval may leave the space system in a higher altitude orbit where, in general, there is a higher probability per unit time that the system will be involved in a collision fragmentation, whereas transfer to an orbit with reduced lifetime lowers the perigee of the final orbit and reduces the probability per unit time that the system will be a source of collision fragments. To balance the risk of the system creating collision debris, the allowed period of time is therefore less for a system waiting to be retrieved.

f. Spacecraft that have terminated their mission shall be maneuvered far enough away from GEO so as not to cause interference with space systems still in geostationary orbit (Requirement 60158).

f.1 The minimum increase in perigee altitude at the end of re-orbiting shall ensure that the space structure does not come within GEO + 200 km for the next 100 years (Requirement 60159). A selected perigee of GEO +235 km + (1000·CR·A/m) and an eccentricity of less than 0.003 ($e<0.003$) will ensure that the space structure does not come within 200 km of GEO altitude (35,786 km) for at least 100 years (Figure 4.6-1). [CR = solar radiation pressure coefficient, typical values: 1-2, A = Area in $m^2$, and m = mass in kg]

g. The propulsion system for a GEO spacecraft should be designed not to be separated from the spacecraft. If there are unavoidable reasons that require separation, the propulsion system shall remain outside of the protected geosynchronous region (GEO altitude ±200 km) (Requirement 60160).

g.1. Regardless of whether it is separated or not, a propulsion system shall be designed for passivation (Requirement 60161).

h. In 1997 the IADC, whose members represent the world's major space agencies, completed a detailed study of GEO with an objective of developing a requirements-based recommendation for the disposal of space structures near GEO. The IADC concluded that a region within 200 km of GEO be preserved for the operation and relocation of GEO spacecraft. To ensure that disposed spacecraft and orbital stages do not stray into this region at a future date due to the perturbative effects of solar radiation pressure and solar and lunar gravitation, a formula was developed to determine the minimum distance above GEO for disposal orbits. The results are presented in Figure 4.6-1. This formula has been adopted by the FCC and the ITU.

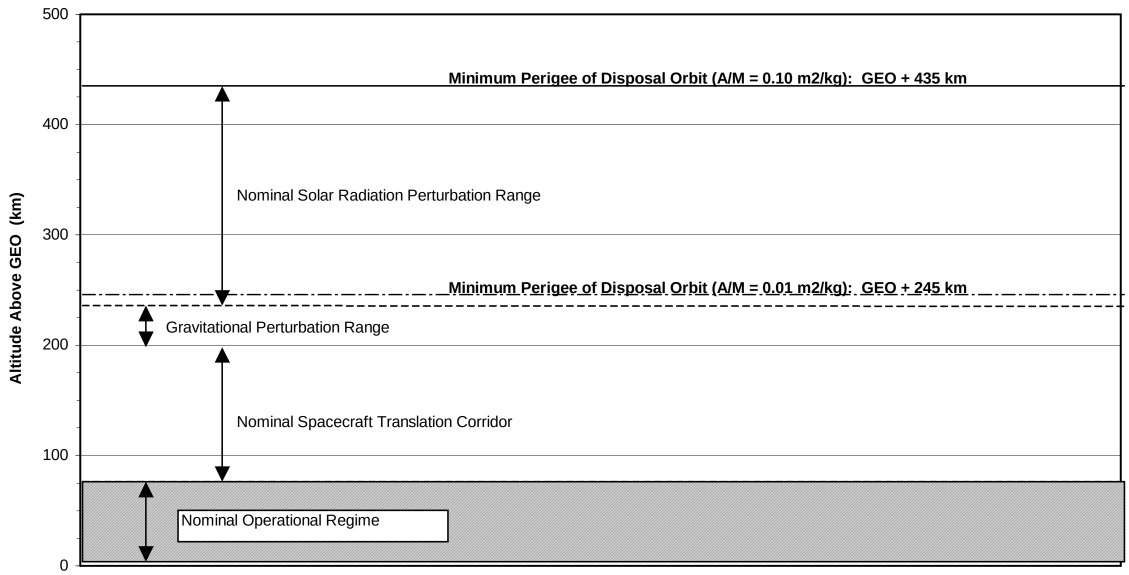


Figure 4.6-1: IADC Rationale for GEO minimum perigee equation

i. Recent studies have also indicated that disposal orbits with modest eccentricities near GEO can be perturbed over long periods into more elliptical orbits with perigees less than 200 km above GEO. Therefore, the initial eccentricity of a GEO disposal orbit should be less than 0.003. In selecting a disposal orbit, the specific initial orbital conditions can be evaluated to determine the long-term perturbative effects and consequent limitations on initial eccentricity.

j. Due to the relatively (compared with LEO) small amount of propellants needed to perform disposal maneuvers near GEO, propellant gauging issues can be important. An adequate amount of propellant shall be held in reserve to ensure that the desired disposal orbit is reached, usually through a series of maneuvers (Requirement 56586). This is even more important when orbits of very low eccentricity are needed. In accordance with Requirement 4.4-2, all propellants remaining after achieving the proper disposal orbit need to be vented or burned in a way that does not upset the disposal orbit.

k. From Requirement 4.6-3, disposal orbits between LEO and GEO need to have perigee altitudes above 2000 km. Objects in these orbits will have a low probability of collision (the current rate is less than 1 per 1000 years). If a collision does occur, then very little debris from that collision would come low enough to pose a significant threat to operational spacecraft in LEO since the region from 1500 km to 2000 km is little used. This disposal option will usually only be attractive for LEO spacecraft and orbital stages in orbits between 1400 km and 2000 km at EOM; at lower altitudes disposal orbits with orbital lifetimes of less than 25 years would be more cost-effective. Since missions between 1400 km and 2000 km are currently rare, the selection of this disposal option is infrequent.

l. Disposal orbits between LEO and GEO are also permitted for space structures in highly elliptical orbits like geosynchronous transfer orbits (GTO), but for most spacecraft and orbital stages in such orbits the use of a perigee-lowering maneuver or of natural perturbations to ensure an orbital lifetime of less than 25 years is more cost-effective than raising perigee to 2000 km. Disposal orbits between LEO and GEO strive to avoid potential interference with major satellite constellations, such as GPS. However, disposal orbits can briefly transit the altitude of such constellations during each revolution. For example, an orbital stage in a disposal orbit of 2500 km by 35,000 km at an inclination of 28.5 deg will regularly pass through the GPS altitude near 20,200 km but the potential for collision will be slight due to the very short dwell time in this region. Decommissioned spacecraft and orbital stages in nearly circular orbits need to avoid the region of 19,700 km to 20,700 km, which is +/- 500 km of semi-synchronous altitude.

m. When selecting a disposal orbit between LEO and GEO, a long-term (at least 100-year) orbital perturbation analysis shall be conducted (and documented in the ODAR/EOMP) to ensure that the disposal orbit is not altered, particularly by solar and lunar gravitational forces, in such a way that the disposed space structure will later penetrate LEO or GEO (Requirement 56589). Even nearly circular orbits in MEO can, under certain initial conditions, later experience severe changes in eccentricity, resulting in perigees within LEO or apogees within GEO.

n. Failure to execute a planned disposal maneuver or operation may further aggravate the orbital debris environment. For example, studies have shown that failure to satisfy Requirement 4.6-1 on a routine basis will result in a more rapid increase in the orbital debris population, which in turn will lead to on-orbit collisions producing even more debris. In addition, if a planned maneuver cannot be performed, a risk of vehicle explosion may be created from the unused propellants. Therefore, to satisfy Requirement 4.6-1, the space structure needs to be removed from used orbits to mitigate future collisions. For postmission disposal operations leading to a natural decay within 25 years or to a long-term storage orbit, the probability of success will be no less than 0.90. If a controlled deorbit is planned, the probability of success needs to be sufficiently high so as not to cause a violation of Requirement 4.7-1, which states the risk of human casualty from surviving debris not be less than 1:10,000.

o. All planned postmission maneuvers, including large, discrete maneuvers and continuous low-thrust maneuvers, shall be evaluated for potential collision risks with other resident space objects tracked by the U.S. Space Surveillance Network (Requirement 56591). Contact the NASA ODPO at JSC for assistance in requesting DoD support in maneuver planning.

p. If drag enhancement devices are planned to reduce the orbit lifetime, the ODAR will need to document that such devices will significantly reduce the collision risk of the system or will not cause spacecraft or large debris to fragment if a collision occurs while the system is decaying from orbit.

q. Due to the communication delays caused by extreme distances to Mars and other extraterrestrial bodies, NASA must be expeditious in its consideration of disposal orbits so as to not interfere with future missions to that body.

### 4.6.4 Methods to Assess Compliance

4.6.4.1 Limiting Orbit Lifetime Using Atmospheric Drag (Requirement 4.6-1a)

a. The amount of time a space structure will remain in orbit depends on its orbit, on the final area-to-mass ratio of the space structure, and on solar activity. For an orbit with apogee altitude above 5,000 km, the orbital lifetime will also be affected by lunar and solar gravitational perturbations. Follow the directions in Section 4.3 of this NASA-STD and in DAS to determine the optimum disposal orbit to satisfy Requirement 4.6-1a. Assistance is also available from the NASA ODPO at JSC.

b. Drag augmentation devices, such as inflatable balloons, increase the area-to-mass ratio of a space structure and, consequently, reduce its orbital lifetime. However, the use of such a device results in a larger collision cross-section, thereby increasing the probability of a collision during natural orbital decay. The increased collision probability should be documented in the ODAR/EOMP. This assessment needs to include the probable consequence of a hypervelocity impact between a resident space object, operational or non-operational, and the drag augmentation device.

c. Space structures using atmospheric drag and reentry for postmission disposal need to be evaluated for survival of structural fragments to the surface of the Earth. The requirement for this evaluation is presented in Section 4.7 of this NASA-STD.

d. A general plan for performing all postmission disposal maneuvers is included in the ODAR/EOMP. Coordination with the U.S. Space Surveillance Network prior to executing these maneuvers at EOM is required.

4.6.4.2 Other Postmission Disposal Options (Requirements 4.6-1b, 4.6-2 and 4.6-3)

Disposal options resulting in the space structure being left in long-lifetime orbits that will limit interference with future space operations are described in Requirements 4.6-1b, 4.6-2, and 4.6-3. DAS can be used to help design disposal orbits in accordance with Requirements 4.6-1b and 4.6-3. Whenever possible, disposal orbits should avoid the creation of a concentrated orbital debris. Between LEO and GEO, disposal orbits need to be chosen to reduce potential interference with operational satellite constellations. Long-term analysis of orbital stability for the selection of disposal orbit parameters needs to be documented in the EOMP. DAS will measure compliance with Requirement 4.6-3 by evaluating whether or not the orbit will reenter the GEO - 500 km within 100 years from EOM. As noted earlier in this Chapter, propellant gauging is an issue of particular importance for space structures in orbits near GEO.

4.6.4.3 Reliability of Postmission Disposal Operations (Requirement 4.6-4)

Compliance with Requirement 4.6-4 will be evaluated independent of DAS. The debris assessment includes two areas: (1) design or component failure which leads to loss of control during the mission and (2) failure of the postmission disposal system, including insufficient propellant to complete the disposal operation. Conventional failure modes and effects analysis or equivalent analysis are normally used to assess failures which could lead to loss of control during mission operations and postmission disposal. Note that the total reliability for postmission disposal operations not involving directed reentry is 0.90, while the probability of postmission disposal failure due only to small object impacts is 0.01 (Requirement 4.5-2). The probability of failure due to small object impacts need not be included in the 0.90 reliability determination. For controlled reentry, the probability of failure of the reentry maneuver will be multiplied by the human casualty risk to determine compliance with Requirement 4.7-1. No specific reliability benchmark for controlled reentry needs to be met for Requirement 4.6-4.

4.6.4.4 Development of an EOMP (Requirement 4.6-5)

a. Compliance with Requirement 4.6-5 will be based on the completeness of the document with regards to the data required per Appendix B.

b. The ODARs are considered as design documents and are basically final when the mission is launched. The EOMP is considered as an operational document and will need to be updated periodically until it is implemented at EOM.

c. As a living document, the EOMP will need to identify events/milestones in the operational life of the mission which affect the end of the mission processing. Those events/milestones include:

- Any event affecting the reliability of the space vehicle control systems. This includes the vehicles ability to maintain a safe/controllable attitude and flight path such as flywheels, solar arrays, and flight control computers.
- Any event affecting the reliability of the systems needed to passivate the vehicle upon decommissioning such as thrusters required to deplete fuel.
- Any event affecting the reliability of critical instruments to collect science. For example: the primary mission is photography and when the camera fails, the spacecraft can be decommissioned.
- Budgetary timelines/milestones.

d. An EOMP is required for all spacecraft being launched. For spacecraft operating in orbits around Earth, and Earth's moon, a full EOMP is required and updated periodically during the mission per Appendix B. For all other spacecraft, an abbreviated EOMP is required as a minimum per Appendix B.

e. EOMPs are not considered as complete until they are reviewed and signed by the sponsoring Mission Directorate Associate Administrator.

4.6.4.5 Planetary Protection

The EOMP will be considered as complete when the rationale for selection of disposal of the spacecraft at extraterrestrial bodies has been documented. For objects remaining in Earth orbit, this section is not applicable.

### 4.6.5 Brief Summary of Mitigation Measures Used in NASA for this Area

*Note: Sections a and b refer to Earth orbit only. Section c refers to all EOMPs.*

a. For a program or project that elects to limit orbital lifetime using atmospheric drag and reentry, several options are available:

- Lower the initial perigee altitude for the disposal orbit;

- When deploying LEO spacecraft to altitudes above 700 km, utilize a lower altitude staging orbit, followed by spacecraft raising maneuvers, to accelerate the orbital decay of launch vehicle stages, in particular those with no re-start capability;
- Increase the area-to-mass ratio for the structure using drag augmentation but be aware of the issues regarding collision potential with resident space objects;
- For highly elliptical orbits, restrict the initial right ascension of ascending node of the orbit plane relative to the initial right ascension of the Sun so that the average perigee altitude is lowered naturally; and/or
- To increase the probability that the postmission disposal maneuver will be successful, consider incorporating redundancy into the postmission disposal system.

b. Additional options and more detailed descriptions can be found in Postmission Disposal of Upper Stages, JSC-27862 (December 1998). Many of these options are also applicable for the disposal of spacecraft.

c. The review of EOMPs during the program's operational life will help meet the goals and intent of this NASA-STD while keeping NASA management aware of the associated risks and EOM constraints.

## 4.7 Survival of Debris From the Postmission Disposal Earth Atmospheric Reentry Option

Orbital debris analyses assess the risks associated with the disposal of a space vehicle in Earth's Atmosphere.

### 4.7.1 Definition of the Reentry Debris Casualty Risk Technical Area

The use of atmospheric reentry to limit the orbital lifetime of space structures in conformance with Requirement 4.6-1 results in the transfer of an orbital environment risk to a potential human casualty risk. This section presents the requirement that defines the maximum human casualty risk permitted for either a controlled or uncontrolled reentry. An uncontrolled reentry is defined as the atmospheric reentry of a space structure in which the surviving debris impact cannot be guaranteed to avoid landmasses. Requirement area 4.7 applies to all space structures in Earth orbital area (Requirement 56623).

### 4.7.2 Requirements for the Area

NASA space programs and projects that use atmospheric reentry as a means of disposal for space structures need to limit the amount of debris that can survive reentry and pose a threat to people on the surface of the Earth. This area applies to full spacecraft as well as jettisoned components.

*Requirement 4.7-1. Limit the risk of human casualty:* The potential for human casualty is assumed for any object with an impacting kinetic energy in excess of 15 joules:

a) For uncontrolled reentry, the risk of human casualty from surviving debris shall not exceed 0.0001 (1:10,000) (Requirement 56626).

b) For controlled reentry, the selected trajectory shall ensure that no surviving debris impact with a kinetic energy greater than 15 joules is closer than 370 km from foreign landmasses, or is within 50 km from the continental U.S., territories of the U.S., and the permanent ice pack of Antarctica (Requirement 56627).

c) For controlled reentries, the product of the probability of failure of the reentry burn (from Requirement 4.6-4.b) and the risk of human casualty assuming uncontrolled reentry shall not exceed 0.0001 (1:10,000) (Requirement 56628).

### 4.7.3 Rationale for the Area Requirements

a. In 1995 NASA established a policy of limiting the risk of world-wide human casualty from a single, uncontrolled reentering space structure to 1 in 10,000. In 1997 and again in 2001 this risk threshold was endorsed by its inclusion in the U.S. Government Orbital Debris Mitigation Standard Practices. The European Space Agency has also proposed, but not yet officially adopted, a reentry human casualty risk threshold of 1 in 10,000. The IADC is also examining this issue and is working to reach a consensus on an international requirement. To provide a reference for the reentry risk requirement, a 1999 study, sponsored by the NASA Office of Safety and Mission Assurance, compiled and compared U.S. Government-accepted human casualty risks in other transportation and non-transportation activities.

b. The principal factors in calculating the risk of human casualty from uncontrolled reentries include the number of debris expected to reach the surface of the Earth, the kinetic energy of each surviving debris, and the amount of the world population potentially at risk. The last factor is a function of both the orbital inclination of the space structure prior to reentry and the year in which the reentry occurs. To date, no casualties have been attributed to reentering artificial space structures.

c. Extensive human casualty studies by the U.S. Government, including ones by the Department of Defense and the Department of Energy, have examined the probability of injury and/or death from falling debris for a variety of impacting kinetic energies to humans. A kinetic energy threshold criterion of 15 joules is widely accepted as the minimum level for potential injury to an unprotected person.

d. The protection that a structure such as a single- or multi-story building or car provides an individual is dependent upon both the structure and the kinetic energy of the falling debris. Moreover, the typical degree of protection of a structure can be a function of the world region. It has been estimated that approximately 80% of the world's population is unprotected or in lightly-sheltered structures providing protection against falling debris with up to a few kilojoules (kJ) of kinetic energy. For the purpose of this NASA-STD, any debris with an impacting kinetic energy greater than 15 joules will be considered potentially hazardous for the majority of the world's population.

e. Impacting debris, particularly large debris, can also bounce or fall over, effectively increasing the impact zone and, therefore, the risk to people. However, this risk increase is countered by the conservatism of the aforementioned sheltering assumption.

#### 4.7.4 Methods to Assess Compliance

a. An important metric in the determination of risk from reentering debris is the debris casualty area. For a piece of debris that survives atmospheric reentry, the debris casualty area is the average debris cross-sectional area plus a factor for the cross-section of a standing individual. The total debris casualty area for a reentry event is the sum of the debris casualty areas for all debris pieces surviving atmospheric reentry. Equation 4.7-1 is used to calculate the total debris casualty area.

$$D_A = \sum_{i=1}^{N} \left(0.6 + \sqrt{A_i}\right)^2 \qquad (4.7\text{-}1)$$

where N is the number of objects that survive reentry and $A_i$ is the area of surviving pieces.

b. The average cross-sectional area of a standing individual, viewed from above, was taken to be 0.36 $m^2$. The 0.6 term is then the square root of this area.

c. The total human casualty expectation, E, is simply

$$E = D_A * P_D \qquad (4.7\text{-}2)$$

where $D_A$ is equal to the total casualty debris area and $P_D$ is equal to the total average population density for the particular orbit.

d. Due to the complexity of satellite reentry physics and material responses, NASA programs and projects shall employ either DAS or a higher fidelity model called ORSAT (Object Reentry Survival Analysis Tool) to determine compliance with Requirement 4.7-1 (Requirement 56639). The reentry risk assessment portion of DAS contains a simplified model which does not require expert knowledge in satellite reentry analyses. Due to the need to make some simplifications, the model is designed to be somewhat conservative. The degree of conservatism is actually a function of the vehicle and the materials under evaluation.

e. If a properly performed DAS reentry risk assessment indicates that the risk is less than 0.0001, then the vehicle is compliant with Requirement 4.7-1. If the DAS result indicates a risk greater than 0.0001, the vehicle may still be compliant, but an ORSAT assessment will be needed to determine the actual risk. ORSAT is fully documented, maintained, and operated by trained personnel at JSC. In addition, ORSAT has been validated by comparisons with recovered satellite debris and compares well with the European SCARAB (Spacecraft Atmospheric Reentry and Aerothermal Breakup) model.

f. For a controlled reentry, the DAS or ORSAT risk assessment is multiplied by the failure probability of the controlled reentry (from Requirement 4.6-4) in order to determine whether the overall risk of human casualty is less than 0.0001 (1:10,000). For example, if a failure modes and effects analysis determines that there exists a 10% probability of failure of the controlled reentry maneuver, then the risk to human casualty must be less than 0.001 (0.1 x 0.001 = 0.0001). If the probability of failure is 20%, the risk to human casualty must be less than 0.0005

(0.2 x 0.0005 = 0.0001). For both controlled and uncontrolled reentry, the DAS or ORSAT evaluation must be performed to determine compliance with Requirement 4.7-1.

g. In the DAS or ORSAT risk assessment, the assumptions used to model the reentry shall be documented in the ODAR and include the explanation of which items are assemblies and their sub assemblies and which items resulting in >15J impacts have been included (Requirement 56642).

h. For this technical area, it is suggested that illustrations and scenarios be used in the documentation of the analyses to assist in understanding the operations occurring.

### 4.7.5 Brief Summary of Mitigation Measures Used in NASA for this Area

If the amount of debris surviving reentry exceeds the requirement, then either the ground impact point is modified by a postmission disposal maneuver or measures are taken to reduce the amount of debris surviving reentry. Options to consider include:

a. Performing a controlled reentry. Maneuver the structure at EOM to a reentry trajectory with an effective perigee altitude no higher than 50 km to control the location of the reentry and ground impact points (see Section 4.6).

b. Using materials that are less likely to survive reentry, which is also known as 'design to demise.' Thermophysical and physical material properties of the space structure components, such as thermal conductivity, specific heat capacity, heat of fusion, melt temperature, heat of ablation, and density, have a significant effect on reentry survivability. In general, materials with high melting temperatures, like titanium, beryllium, and stainless steel, are more likely to survive than materials with low melting temperatures like aluminum. However, the configuration of the component is also very important.

c. Causing a structure to break up immediately prior to reentry. If the components of a space structure can be exposed individually to the environment prior to structural breakup altitude at about 80 km, then additional heating will take place, facilitating component demise. In the extreme, a deliberate detonation of the space structure (see Section 4.4) before normal breakup would not only expose the components sooner, but also create a large number of smaller debris more susceptible to demise. Such a breakup would normally take place at an altitude below 120 km, which would prevent any debris from remaining in orbit.

d. Maneuvering the structure at the end of the mission to a disposal orbit where reentry will not occur (see Section 4.6).

## 4.8 Additional Assessment Requirements for Tether Missions

Orbital debris analyses assess the potential hazard of tethered systems considering both an intact and severed system. Tethers are flexible long and narrow space structures with two of the dimensions much smaller than the third. The potential to damage operating spacecraft can be larger than would be expected solely from the tether mass and cross-sectional area. Requirement area 4.8 applies to all space structures using tethers in Earth or lunar orbits (Requirement 56648).

### 4.8.1 Definition of the Tether Technical Area

a. Programs using tethers must take extra measures to control the potential for damaging other systems. To limit risk to other users of space, tethers left in orbit after completion of mission or tether fragments created when meteoroids or orbital debris sever the tether are considered debris.

b. At the current time there is considerable uncertainty as to the final state of tethers or tether fragments that are not connected to end masses. If they remain extended, they may present a significant threat to operating spacecraft and a potential source of collision fragments from collisions with large debris.

### 4.8.2 Requirements for the Area

*Requirement 4.8-1. Mitigate the collision hazards of space tethers in Earth or Lunar orbits:* Intact tether systems in Earth and lunar orbit shall meet the requirements limiting the generation of orbital debris from on-orbit collisions (Requirements 4.5-1 and 4.5-2) and the requirements governing postmission disposal (Requirements 4.6-1 through 4.6-4) to the limits specified in those paragraphs. Due to the potential of tether systems being severed by orbital debris or meteoroids, all possible remnants of a severed tether system shall be compliant with the requirements for the collision, debris, and disposal of space structures (Requirement 56652).

### 4.8.3 Rationale for the Area Requirements

Due to their ability to sweep through large regions of space, tethers present an elevated risk to operating spacecraft. In addition, a tether collision with a large derelict spacecraft or orbital stage could create significant numbers of debris which, in turn, could pose risks to other resident space objects. Consequently, tethers or tether fragments left in orbit after completion of the mission require special consideration for the risks they may pose.

### 4.8.4 Methods to Assess Compliance

ODAR and EOMP assessments for tether systems are performed for both intact and severed conditions when performing trade-offs between alternative disposal strategies.

4.8.4.1 Limiting debris generated by tether collisions with large objects.

For known tether dimensions and mass, DAS will determine whether any tether has a probability of collision with large objects (10 cm or larger) less than 0.001.

4.8.4.2 Limiting debris generated by tether collisions with small objects

a. Requirement 4.5-2 is only applicable if the tether or tether system is required for postmission disposal. DAS can determine compliance for simple tethers only.

b. For missions in or passing through LEO, the probability, P, of a tether being hit by a small debris object during its mission lifetime can be approximated by the summation over debris/meteoroid diameter bins:

$$P = \sum f_i * A_{Ti} * T \qquad (4.8\text{-}1)$$

where

$f_i$ = weighted cross-sectional area flux for the debris environment at the midpoint of the tether for debris/meteoroid objects of diameter i. Note this is the differential flux, whereas orbital debris and meteoroid fluxes are typically given as cumulative fluxes (flux of a given diameter or larger). Differential flux can be estimated by dividing up the flux into diameter bins. The flux in each diameter bin is the cumulative flux for the diameter in that bin minus the cumulative flux of the diameter in the next larger bin.

$A_{Ti}$ = collision cross-section for the tether in $m^2$ (= cross sectional area of tether), and is also dependent on particle diameter (see below)

T = orbital lifetime in years

c. The weighted cross-sectional area flux is derived by evaluating the amount of time the vehicle spends in different altitudes during its mission.

d. The smallest diameter that can sever a particular tether is typically not a simple function but is analogous to ballistic equations for spacecraft surfaces that must be determined experimentally in a laboratory using hypervelocity gun tests. However, for the purposes of this requirement, the smallest particle (orbital debris or meteoroid) that can sever the tether is assumed to be 1/3 the diameter of the tether. Therefore the summation in Equation 4.8-1 need only start at the minimum diameter particle to sever the tether.

e. The collision cross-section for a tether will be

$$A_{Ti} = D_{Ti} * L \qquad (4.8\text{-}2)$$

where

$D_{Ti}$ = tether diameter in meters + diameter of orbital debris/meteoroid (for size diameter bin i) in meters

L = length of tether in meters

f. For more complex tether designs using braided, multi-strand, or Hoyt tethers, the ODAR/EOMP documents the analysis (outside of DAS) to demonstrate compliance. This is done by determining the diameter of debris sufficient to sever the complex tether and using Equations 4.8-1 and 4.8-2 to evaluate the probability of collision with small debris sufficient to sever the tether.

#### 4.8.4.3 Postmission Disposal of Tethers

Postmission disposal requirements include all tether fragments (Section 4.6). In the case of a single accidental severing, the tether may be assumed to be cut in two equal halves. To calculate the orbit lifetime of one tether fragment, the average cross-sectional area will be the cross-sectional area of the tether, as defined above, plus the cross-sectional area of one end mass. The mass of each tether fragment will be one-half the mass of the tether plus the mass of the respective end mass. The ratio of mass to area calculated in this way will be used as the area-to-mass ratio for orbital lifetime calculations in DAS.

### 4.8.5 Brief Summary of Mitigation Measures Used in NASA for this Area

One or more of the following options may prove helpful to ensure compliance with Requirement 4.8-1:

a. Detach the tether from the end masses at EOM to reduce the time the tether remains in orbit.

b. Plan to retract the tether at EOM.

c. Develop a tether design such that the tether will not be cut before mission completion, making the tether somewhat thicker, adding a protective cover to the tether, or constructing the tether as a ribbon or fiber matrix structure;

d. Perform the tether experiment at lower altitude.

# APPENDIX A. Orbital Debris Assessment Reports (ODAR)

## A.1 Format for ODARs

A.1.1 Delivery of the ODARs is governed by the requirements specified in NASA Procedural Requirements (NPR) 8715.6. The nominal schedule is:

- Delivery of "**PDR Draft ODAR**" prior to the program or project Preliminary Design Review (PDR) for the spacecraft or equivalent program/project development milestone. The purpose of preparing the report early in the design and development process is to ensure that orbital debris issues are identified early when resolutions are least costly to implement. Any orbital debris mitigation compliance issues should be addressed and resolved no later than the Critical Design Review (CDR) or equivalent program/project development milestone.
- Delivery of the "**CDR Draft ODAR**" 45 days prior to the program or project CDR for the spacecraft or equivalent program/project development milestone. The purpose of the CDR Draft is to update and clarify the issues and changes to the PDR Draft for any nonconformances which remain prior to beginning the launch approval process *(see NPR 8715.3 paragraph 1.13 for NASA SMA Waiver process)*.
- A "**Final ODAR**" submitted prior to the beginning of the launch approval process.

A.1.2 Draft (unsigned) ODARs shall be submitted in electronic form only (Requirement).

A.1.3 Final (signed) ODARs shall be delivered in both electronic and paper copies (Requirement).

A.1.4 Each ODAR delivery is reviewed by the OSMA and by the Space Operations Mission Directorate with technical assistance from the NASA Orbital Debris Program Office (ODPO). The Associate Administrator of the Mission Directorate sponsoring the mission is the final approving authority for the ODAR.

> *Note: Programs are encouraged to use existing program documentation for mission and spacecraft descriptions.*

A.1.5 When a spacecraft is jointly developed/built/operated by multiple organizations outside of the United States or is restricted by national defense or corporate proprietary restrictions, and the ODAR contains material restricted by export controls, such as international traffic of arms regulations (ITAR), then a full version of the ODAR material shall be prepared and delivered to the NASA ODPO in addition to the material being provided to organizations outside of NASA as permitted by ITAR and other data restrictions (Requirement)

A.1.6 Each ODAR shall follow the format below and include the content indicated at a minimum (Requirement).

> *Note: To ease preparing and using the ODAR. orbital debris mitigation requirements for the spacecraft and launch vehicle are addressed in separate sections (Sections 2 through 8 and Sections 9 through 14, respectively).*

ODAR Cover and Front Matter

- Cover showing the document version and date of delivery
- Inside cover showing the signatures on that report. This shall include as a minimum: Document preparer(s), program management, NASA HQ program/project management, and the NASA HQ Office of Safety and Mission Assurance OD Manager.
- Signature page for the Final (Pre-launch) ODAR includes signature locations for the NASA Chief, Safety and Mission Assurance concurrence and the approval/risk acceptance of the sponsoring Mission Directorate Associate Administrator.
- Self assessment of the ODAR using the format in Appendix A.2 of this NASA-STD
- Statement of any restrictions on the data in the ODAR such as proprietary, ITAR, or export controls. If the document does not contain any restrictions, then a statement to that effect shall be included. If the document does contain restricted information, the restricted information shall be summarized and marked clearly on the page(s) where it occurs and on the cover.
- Document history page showing each version of the report. Reviews of the previous versions by the OSMA shall be included in this section.
- DAS version used, or if software and models other than DAS are used, a description of the software/model.

ODAR Section 1: Program Management and Mission Overview

- Identification of the Headquarters Mission Directorate sponsoring the mission and the Program Executive
- Identification of the responsible program/project manager and senior scientific and management personnel
- Identification of any foreign government or space agency participation in the mission and a summary of NASA's responsibility under the governing agreement(s)
- Clear schedule of mission design and development milestones from NASA mission selection through proposed launch date, including spacecraft PDR and CDR (or equivalent) dates
- Brief description of the mission
- Identification of the anticipated launch vehicle and launch site
- Identification of the proposed launch date and mission duration
- Description of the launch and deployment profile, including all parking, transfer, and operational orbits with apogee, perigee, and inclination
- Identification of any interaction or potential physical interference with other operational spacecraft

ODAR Section 2: Spacecraft Description

- Physical description of the spacecraft, including spacecraft bus, payload instrumentation, and all appendages, such as solar arrays, antennas, and instrument or attitude control booms
- Detailed illustration of the entire spacecraft in the mission operation configuration with clear overall dimensional markings and marked internal component locations

- Total spacecraft mass at launch, including all propellants and fluids
- Dry mass of spacecraft at launch, excluding solid rocket motor propellants
- Description of all propulsion systems (cold gas, mono-propellant, bi-propellant, electric, nuclear)
- Identification, including mass and pressure, of all fluids (liquids and gases) planned to be on board and a description of the fluid loading plan or strategies, excluding fluids in sealed heat pipes. Description of all fluid systems, including size, type, and qualifications of fluid containers such as propellant and pressurization tanks, including pressurized batteries
- Description of all active and/or passive attitude control systems with an indication of the normal attitude of the spacecraft with respect to the velocity vector
- Description of any range safety or other pyrotechnic devices
- Description of the electrical generation and storage system
- Identification of any other sources of stored energy not noted above
- Identification of any radioactive materials on board

ODAR Section 3: Assessment of Spacecraft Debris Released during Normal Operations

- Identification of any object (>1 mm) expected to be released from the spacecraft any time after launch, including object dimensions, mass, and material
- Rationale/necessity for release of each object
- Time of release of each object, relative to launch time
- Release velocity of each object with respect to spacecraft
- Expected orbital parameters (apogee, perigee, and inclination) of each object after release
- Calculated orbital lifetime of each object, including time spent in Low Earth Orbit (LEO)
- Assessment of spacecraft compliance with Requirements 4.3-1 and 4.3-2

ODAR Section 4: Assessment of Spacecraft Intentional Breakups and Potential for Explosions.

- Identification of all potential causes of spacecraft breakup during deployment and mission operations
- Summary of failure modes and effects analyses of all credible failure modes which may lead to an accidental explosion
- Detailed plan for any designed spacecraft breakup, including explosions and intentional collisions
- List of components which shall be passivated at End of Mission (EOM). List shall include method of passivation and amount which cannot be passivated.
- Rationale for all items which are required to be passivated, but can not be due to their design.
- Assessment of spacecraft compliance with Requirements 4.4-1 through 4.4-4

ODAR Section 5: Assessment of Spacecraft Potential for On-Orbit Collisions

- Calculation of spacecraft probability of collision with space objects larger than 10 cm in diameter during the orbital lifetime of the spacecraft

- Identification of all systems or components required to accomplish any postmission disposal operation, including passivation and maneuvering
- Calculation of spacecraft probability of collision with space objects, including orbital debris and meteoroids, of sufficient size to prevent postmission disposal
- Assessment of spacecraft compliance with Requirements 4.5-1 and 4.5-2

ODAR Section 6: Assessment of Spacecraft Postmission Disposal Plans and Procedures

- Description of spacecraft disposal option selected
- Plan for any spacecraft maneuvers required to accomplish postmission disposal
- Calculation of area-to-mass ratio after postmission disposal, if the controlled reentry option is not selected
- Assessment of spacecraft compliance with Requirements 4.6-1 through 4.6-5

ODAR Section 7: Assessment of Spacecraft Reentry Hazards

- Detailed description of spacecraft components by size, mass, material, shape, and original location on the space vehicle, if the atmospheric reentry option is selected
- Summary of objects expected to survive an uncontrolled reentry, using NASA Debris Assessment Software (DAS), NASA Object Reentry Survival Analysis Tool (ORSAT), or comparable software
- Calculation of probability of human casualty for the expected year of uncontrolled reentry and the spacecraft orbital inclination
- If appropriate, preliminary plan for spacecraft controlled reentry
- Assessment of spacecraft compliance with Requirement 4.7-1

ODAR Section 8: Assessment for Tether Missions

- Type of tether; e.g., momentum or electrodynamics
- Description of tether system, including (1) tether length, diameter, materials, and design (single strand, ribbon, multi-strand mesh), at a minimum and (2) end-mass size and mass
- Determination of minimum size of object that will cause the tether to be severed
- Tether mission plan, including duration and postmission disposal
- Probability of tether colliding with large space objects
- Probability of tether being severed during mission or after postmission disposal
- Maximum orbital lifetime of a severed tether fragment
- Assessment of compliance with Requirement 4.8-1

ODAR Section 9: Launch Vehicle Description

- Identification of launch vehicle to be used
- Identification of any non-basic upper stages to be used
- Identification of any launch vehicle stage which will be inserted into Earth orbit and left there

- Dry mass of each orbital stage after spacecraft deployment
- Detailed illustration of each orbital stage with clear dimensional markings and marked internal component locations

ODAR Section 10: Assessment of Launch Vehicle Debris Released During Normal Operations

- Identification of any object greater than 1 mm which will be released into Earth orbit from any stage, including, but not limited to, dual payload attachment fittings and stage separation devices
- Rationale/necessity for release of each object
- Time of release of each object, relative to launch time
- Release velocity of each object with respect to orbital stage
- Expected orbital parameters (apogee, perigee, and inclination) of each object after release
- Calculated orbital lifetime of each object, including time spent in Low Earth Orbit (LEO)
- Assessment of launch vehicle compliance with Requirements 4.3-1 and 4.3-2

ODAR Section 11: Assessment of Launch Vehicle Potential for Explosions and Intentional Breakups

- For Section 11, each orbital launch vehicle stage/piece shall be addressed separately
- Identification of all potential causes of launch vehicle in orbit breakup during all operations
- Summary of failure modes and effects analyses of all credible failure modes which may lead to an orbital stage accidental explosion
- Detailed plan for any designed orbital stage breakup, including explosions and intentional collisions
- Detailed plan, under normal EOM conditions and deployment malfunction scenario, for passivating (depleting all energy sources) each orbital stage, including the burning or release of all propellants and fluids
- Assessment of launch vehicle compliance with Requirements 4.4-1 through 4.4-4

ODAR Section 12: Assessment of Launch Vehicle Potential for On-orbit Collisions

- Calculation of each orbital stage probability of collision with space objects larger than 10 cm in diameter during the orbital lifetime of the stage
- Assessment of launch vehicle compliance with Requirement 4.5-1

ODAR Section 13: Assessment of Launch Vehicle Postmission Disposal Plans and Procedures

- Description of orbital stage disposal option selected
- Plan for any orbital stage maneuvers required to accomplish disposal after end of orbital stage mission
- Calculation of area-to-mass ratio after completion of all orbital stage operations, including disposal maneuvers, if the controlled reentry option is not selected
- Procedure for executing orbital stage disposal plan, including timeline from final shut-down of each orbital stage to completion of passivation and disposal operations

- Demonstration of reliability of orbital stage disposal operations
- Assessment of launch vehicle compliance with Requirements 4.6-1 through 4.6-4

ODAR Section 14: Assessment of Launch Vehicle Reentry Hazards

> *Note: If an ORSAT reentry hazard assessment has already been performed for an orbital stage, simply refer to that report and make any necessary adjustments for orbital inclination and year of reentry.*

- Detailed description of launch vehicle components by size, mass, material, and shape, if the atmospheric reentry option is selected, also indicate the location of that component within the vehicle.
- Summary of objects expected to survive an uncontrolled reentry, using NASA DAS, NASA ORSAT, or comparable software. If the version of the tool used is different from that cited in the cover section, then list it here
- Calculation of probability of human casualty for the expected year of uncontrolled reentry and the orbital stage inclination
- If appropriate, preliminary plan for launch vehicle controlled reentry
- Assessment of launch vehicle compliance with Requirement 4.7-1

## A.2 Review of ODARs

Each delivered ODAR will be reviewed by the OSMA and by the Space Operations Mission Directorate with technical assistance from the NASA ODPO. After the OSMA review, the check sheet in Figure A.2-1 will be returned to the Headquarters Sponsoring Mission Directorate Program Executive for distribution back to the program. OSMA will also provide a copy to the orbital debris lead at the Center supporting the program for assisting with corrective actions.

# Orbital Debris Assessment Report Evaluation: ___________ Mission

**(based upon ODAR _____ version, dated ________ , 200_)**

| Reqm't # | Launch Vehicle | | | | Spacecraft | | | Comments |
|---|---|---|---|---|---|---|---|---|
| | Compliant | Not Compliant | Incomplete | Standard Non Compliant | Compliant or N/A | Not Compliant | Incomplete | |
| 4.3-1.a | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | |
| 4.3-1.b | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | |
| 4.3-2 | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | |
| 4.4-1 | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | |
| 4.4-2 | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | |
| 4.4-3 | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | |
| 4.4-4 | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | |
| 4.5-1 | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | |
| 4.5-2 | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | |
| 4.6-1(a) | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | |
| 4.6-1(b) | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | |
| 4.6-1(c) | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | |

| Reqm't # | Launch Vehicle | | | | Spacecraft | | | Comments |
|---|---|---|---|---|---|---|---|---|
| | Compliant | Not Compliant | Incomplete | Standard Non Compliant | Compliant or N/A | Not Compliant | Incomplete | |
| 4.6-2 | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | |
| 4.6-3 | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | |
| 4.6-4 | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | |
| 4.6-5 | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | |
| 4.7-1 | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | ☐ | |
| 4.8-1 | | | | | ☐ | ☐ | ☐ | |

**Additional Comments:**

Reviewed by: _______________ on: ___/___/___

**Figure A.2-1: ODAR Review Check sheet**

## A.3 Abbreviated ODARs

A.3.1 For portions of spacecraft and missions where an abbreviated ODAR is required, Table A-1 lists the sections of the ODAR defined in Section A.1 that shall be included as a minimum (Requirement).

A.3.2 Abbreviated ODARs shall address and analyze the NASA portion of the program (Requirement).

A.3.3 Abbreviated ODARs are signed by the NASA Project Manager.

A.3.4 Final Abbreviated ODARs shall be delivered as a part of the hardware delivery turnover and sent to the NASA OSMA (Requirement).

A.3.5 Abbreviated ODARs shall be reviewed by the NASA Orbital Debris Program Office (Requirement).

A.3.6 Abbreviated ODARs do not require NASA HQ Office of Safety and Mission Assurance signatures.

**Table A-1: Mandatory Sections in an Abbreviated ODAR.**

| ODAR Section Name | Mandatory Portion of ODAR Section to include |
|---|---|
| ODAR Cover and Front Matter | All |
| ODAR Section 1: Program Management and Mission Overview | Program demographics and mission of items being delivered |
| ODAR Section 2: Spacecraft Description | Description of items being delivered |
| ODAR Section 3: Assessment of Spacecraft Debris Released during Normal Operations | Analysis of any material planned for release during normal operations |
| ODAR Section 4: Assessment of Spacecraft Potential for Explosions and Intentional Breakups | Summary of failure modes and effects analyses of all credible failure modes which may lead to an accidental explosion of the spacecraft from the delivered hardware.<br><br>List of components which shall be passivated at End of Mission (EOM). List shall include method of passivation and amount which cannot be passivated. |

| ODAR Section Name | Mandatory Portion of ODAR Section to include |
|---|---|
| ODAR Section 5: Assessment of Spacecraft Potential for On-Orbit Collisions | Not required |
| ODAR Section 6: Assessment of Spacecraft Postmission Disposal Plans and Procedures | Not required |
| ODAR Section 7: Assessment of Spacecraft Reentry Hazards | Summary of objects expected to survive an uncontrolled reentry, using NASA Debris Assessment Software (DAS), NASA Object Reentry Survival Analysis Tool (ORSAT), or comparable software |
| ODAR Section 8: Assessment for Tether Missions | If delivered hardware includes a tether, include all, otherwise not required. |
| ODAR Sections 9 through 14: Launch Vehicle | If delivered hardware is the launch vehicle, include all, otherwise not required. |

## APPENDIX B: End of Mission (EOM) Plans (EOMP)

The EOMP is a living document that grows with the program as it operates. Please note that it is recognized that the level of detail in the EOMP prior to launch may be limited and it is intended to only be complete as the EOM approaches.

### B.1 Format for EOMPs

B.1.1 Delivery of the EOMPs is governed by the requirements specified in NASA Procedural Requirements (NPR) 8715.6. The nominal schedule is:

- Delivery of "**Preliminary EOMP**" 45 days prior to the program or project Critical Design Review (CDR) for the spacecraft or equivalent program/project development milestone. The purpose of preparing the plan early in the operational development process is to ensure that EOM issues are identified early when resolutions are least costly to implement.
- Delivery of the "**Prelaunch EOMP**" 30 days prior to the launch of the mission. Formal acceptance of the risk associated with the nonconformances remaining in the EOMP is included as a part of the prelaunch risk acceptance.
- Delivery of updates to the EOMP (titled: "***[date]*** **Update to the EOMP**") is made at the major program operational milestones identified in the EOMP.
- The "**Final EOMP**" is delivered at 3 months prior to the expected implementation of the EOMP for spacecraft decommissioning/disposal.

> *NOTE: This is approximately the same time that the notice of intent to shutdown the spacecraft is delivered to the NASA Associate Administrator per NPD 8010.3A, Notification of Intent to Decommission or Terminate Operating Space Systems and Terminate Missions. It is desired that the EOMP accompany this letter.*

B.1.2 Draft (unsigned) EOMPs shall be submitted in electronic form only (Requirement).

B.1.3 Signed EOMPs shall be delivered in both electronic and paper copies (Requirement).

B.1.4 Each EOMP delivery is reviewed by the OSMA and by the Space Operations Mission Directorate with technical assistance from the NASA Orbital Debris Project Office (ODPO). The Associate Administrator of the Mission Directorate sponsoring the mission is the final approving authority for the EOMPs (as a minimum).

B.1.5 A copy of the Final ODAR shall be included in the delivery of the Final EOMP (Requirement).

B.1.6 When a spacecraft is jointly developed/built/operated by multiple organizations outside of the United States or is restricted by national defense or corporate proprietary restrictions, and the ODAR or the EOMP contains material restricted by export controls, such as international traffic of arms regulations (ITAR), then a full version of the ODAR and EOMP material shall be prepared and delivered to the NASA ODPO in addition to the material being provided to organizations outside of NASA as permitted by ITAR and other data restrictions (Requirement).

B.1.7. Each EOMP shall follow the format below and include the content indicated at a minimum (Requirement).

> *Note: Programs are encouraged to use existing program documentation and the ODAR for mission and spacecraft descriptions and identification of the EOM decommissioning issues. The below listing identifies the data needed prior to launch and additional data needed during EOMP updates.*

EOMP Cover and Front Matter

(all data is needed prior to launch)

- Cover showing the document version and date of delivery.
- Inside cover showing the signatures on the report. This shall include as a minimum: Document preparer(s), program management, NASA program management, NASA safety office reviewer, and NASA management signatures.
- Signature page for all EOMPs including signature locations for NASA program/project management and the sponsoring Mission Directorate Associate Administrator to accept the EOMP defined risk and signature locations for Safety and Mission Assurance concurrence to include the NASA HQ Office of Safety and Mission Assurance OD Manager; and the Chief, Safety and Mission Assurance for the pre-launch and final EOMPs.
- Self assessment of the EOMP using the format in Appendix B.2 of this NASA-STD for either the Preliminary and Prelaunch EOMPs (Figure B.2-1) or the operational Update or Final EOMPs (figure B.2-2).
- Statement of any restrictions on the data in the EOMP such as proprietary, ITAR, or export controls. If the document does not contain any restrictions, then a statement to that effect shall be included. If the document does contain restricted information, the restricted information shall be summarized and marked clearly on the page(s) where it occurs and on the cover.
- Document history page showing each version of the report. Reviews of the previous versions by the OSMA shall be included in this page.

EOMP Section 1: Program Management and Mission Overview

(data needed prior to launch)

- Identification of the Mission Directorate sponsoring the mission and the Program Executive
- Identification of the responsible program/project manager and senior scientific and management personnel
- Identification of any foreign government or space agency participation in any phase of the mission
- Clear schedule of mission operational milestones from launch through EOM
- Brief description of the mission (single paragraph)
- Description of operational orbits with apogee, perigee, and inclination

(data added during flight)

- Chronology of management reviews of the EOMP to include changes in spacecraft operability which may affect the ability to passivate and dispose per the plan in Section 6 of the EOMP

EOMP Section 2: Spacecraft Description

The ODAR Section 2 contains a full description of the spacecraft. Since the ODAR remains a reference, it does not need to be repeated here.

(all data added during flight)

- Table of the following onboard the spacecraft at time of issue of EOMP version, expected at commencement of passivation, and expected at completion of passivation.
    - Fluids
    - Pyrotechnic devices
    - Electrical generation and storage system
    - Identification of any other sources of stored energy not noted above
    - Any radioactive materials
- List of changes in the propulsion systems and energy systems which have occurred since launch. Include a detailed illustration of the entire spacecraft in the EOM configuration with clear dimensional markings and marked internal component locations
- Total mass of post-passivation spacecraft, including all propellants and fluids
- Status of the major systems on board the spacecraft, including any changes in redundancy

EOMP Section 3: Assessment of Spacecraft Debris Released During and After Passivation

(data needed prior to launch)

- Identification of any solid object (>1 mm) expected to be released during passivation

(data added during flight)

- Identification of all objects (>1 mm) expected to be released (including fluids)
- Rationale/necessity for release of each object
- Time of release of each object, relative to passivation
- Release velocity of each object with respect to spacecraft
- Expected orbital parameters (apogee, perigee, and inclination) of each object after release
- Calculated orbital lifetime of each object, including time spent in Low Earth Orbit (LEO)
- Assessment of spacecraft compliance with Requirements 4.3-1 and 4.3-2

EOMP Section 4: Assessment of Spacecraft Potential for Explosions and Intentional Breakups

(data needed prior to launch)

- Identification of all potential causes of spacecraft breakup during passivation and after passivation
- Assessment of spacecraft compliance with Requirements 4.4-2 and 4.4-3

(data added during flight)

- Summary of remaining failure modes and effects analyses of all credible failure modes which may lead to an accidental explosion during passivation and after passivation.
- Assessment of spacecraft compliance with Requirements 4.4-1 through 4.4-4

EOMP Section 5: Assessment of Spacecraft Potential for On-orbit Collisions

(data needed prior to launch)

- Identification of all systems or components required to accomplish any postmission disposal operation, including passivation and maneuvering
- Evaluation of the vulnerability of systems required for postmission disposal to impacts by small space objects
- Assessment of EOM spacecraft compliance with Requirement 4.5-2

(data added during flight)

- Calculation of spacecraft probability of collision with space objects larger than 10 cm in diameter during the orbital lifetime of the spacecraft after passivation
- Assessment of EOM spacecraft compliance with Requirements 4.5-1 and 4.5-2

EOMP Section 6: Assessment of Spacecraft Postmission Disposal Plans and Procedures

(data needed prior to launch)

- Description of spacecraft disposal option selected
- Demonstration of reliability of postmission disposal operations
- Calculation of area-to-mass ratio after postmission disposal, if the controlled reentry option is not selected
- Assessment of spacecraft compliance with Requirements 4.6-1 through 4.6-5

(data added during flight)

- Plan for any spacecraft maneuvers required to accomplish postmission disposal
- Procedure for executing postmission disposal plan
- Detailed plan for passivating (depleting all energy sources) the spacecraft, including the burning or release of all propellants and fluids, the discharge of batteries, the disabling of charging circuits, and the de-energizing of rotational energy sources per requirement 4.4-2
- Assessment of spacecraft compliance with Requirements 4.6-1 through 4.6-5

EOMP Section 7: Assessment of Spacecraft Reentry Hazards

(all data added during flight)

- Detailed description of spacecraft components by size, mass, material, and shape, if the atmospheric reentry option is selected, includes assumptions for type of breakup

- Summary of objects expected to survive an uncontrolled reentry, using NASA Debris Assessment Software (DAS), NASA Object Reentry Survival Analysis Tool (ORSAT), or comparable software
- Calculation of probability of human casualty for uncontrolled reentry and the spacecraft orbital inclination, based on the expected date of reentry
- If appropriate, preliminary plan for spacecraft controlled reentry
- Assessment of spacecraft compliance with Requirement 4.7-1

EOMP Section 8: Assessment for Tether Missions

(all data added during flight)

- Description of tether system, including (1) tether length, diameter, materials, and design (single strand, ribbon, multi-strand mesh) at a minimum and (2) end-mass size and mass remaining at EOM
- Assessment of compliance with Requirement 4.8-1

EOMP Appendices: Additional EOM Data

- The Program may add additional appendices for documenting the final disposition of other program elements if it is felt that the EOMP is the most advantageous place for documenting them.

EOMP Addendum: Final ODAR

- For the Final EOMP, a copy of the Final ODAR shall be included for reference.

### B.2 Review of EOMPs

Each EOMP delivered will be reviewed by the OSMA with technical assistance from the NASA ODPO. After the OSMA review, the check sheet in Figure B.2-1 (prelaunch EOMP) or Figure B.2-2 (Final EOMP) will be returned to the Headquarters Sponsoring Mission Directorate Program Executive for distribution back to the program. OSMA will also provide a copy to the Center SMA organization supporting the program for assisting with corrective actions.

# Prelaunch EOMP Evaluation: ___________ Mission

**(based upon EOMP ________ version, dated ________ , 200_)**

| Reqm't # | Compliant or N/A | Not Compliant | Incomplete | Comments |
|---|---|---|---|---|
| 4.3-1.a | | | | |
| 4.3-1.b | | | | |
| 4.3-2 | | | | |
| 4.4-1 | | | | |
| 4.4-2 | ☐ | ☐ | ☐ | |
| 4.4-3 | ☐ | ☐ | ☐ | |
| 4.4-4 | | | | |
| 4.5-1 | | | | |
| 4.5-2 | ☐ | ☐ | ☐ | |
| 4.6-1(a) | ☐ | ☐ | ☐ | |
| 4.6-1(b) | ☐ | ☐ | ☐ | |
| 4.6-1(c) | ☐ | ☐ | ☐ | |
| 4.6-2 | ☐ | ☐ | ☐ | |
| 4.6-3 | ☐ | ☐ | ☐ | |
| 4.6-4 | ☐ | ☐ | ☐ | |
| 4.6-5 | | | | |
| 4.7-1 | | | | |
| 4.8-1 | | | | |

**Additional Comments:**

Reviewed by: ________________ on: ___/___/___

**Figure B.2-1: Prelaunch EOMP Review Check Sheet**

# Final EOMP Evaluation: ___________ Mission

**(based upon EOMP ________ version, dated ________ , 200_)**

| Reqm't # | Compliant | Not Compliant | Incomplete | Comments |
|---|---|---|---|---|
| 4.3-1.a | ☐ | ☐ | ☐ | |
| 4.3-1.b | ☐ | ☐ | ☐ | |
| 4.3-2 | ☐ | ☐ | ☐ | |
| 4.4-1 | | | | |
| 4.4-2 | ☐ | ☐ | ☐ | |
| 4.4-3 | ☐ | ☐ | ☐ | |
| 4.4-4 | ☐ | ☐ | ☐ | |
| 4.5-1 | ☐ | ☐ | ☐ | |
| 4.5-2 | ☐ | ☐ | ☐ | |
| 4.6-1(a) | ☐ | ☐ | ☐ | |
| 4.6-1(b) | ☐ | ☐ | ☐ | |
| 4.6-1(c) | ☐ | ☐ | ☐ | |
| 4.6-2 | ☐ | ☐ | ☐ | |
| 4.6-3 | ☐ | ☐ | ☐ | |
| 4.6-4 | ☐ | ☐ | ☐ | |
| 4.6-5 | ☐ | ☐ | ☐ | |
| 4.7-1 | ☐ | ☐ | ☐ | |
| 4.8-1 | ☐ | ☐ | ☐ | |

**Additional Comments:**

Reviewed by: _______________ on: ___/___/___

**Figure B.2-2: Final EOMP Review Check Sheet**

## APPENDIX C. BACKGROUND ON ORBITAL DEBRIS

*Note: NASA-HDBK 8719.14 serves as a reference document to assist orbital debris practioners and program/project management in understanding orbital debris. Topics in NASA-HDBK 8719.14 include the OD environment, measurements, modeling, shielding, mitigation, and reentry. It is strongly encouraged that the NASA-HDBK be used with the implementation of NPR 8715.6 and NASA-STD 8719.14.*

### C.1 Understanding the Threat of Orbital Debris

The threat of collision with orbital debris is an issue of growing concern as historically accepted practices and procedures have allowed artificial objects, some having the potential to explode, to accumulate in orbit. In the past, explosions have been the primary source of debris and are likely to continue to be so for the immediate future. However, current international modeling efforts indicate that even if there are no further space launches, collisions between resident space objects will eventually become the major source of debris. Collisional processes will lead to a large increase in the amount of orbital debris capable of damaging or disabling operating spacecraft.

The greatest risk in not controlling the debris environment is the onset of collisions between large objects. There are two reasons for this. First, once collisions begin to occur, it may be difficult to halt the process. Second, the energies in collisional breakup are much larger than in explosive breakup, in the megajoule (a few kilograms of TNT) to gigajoule (a few metric tons of TNT) range. This large amount of expended energy creates many more debris fragments in all size ranges and spreads the debris over many hundreds of kilometers of altitude. This debris may hit other satellite surfaces. Debris less than 1 mm in diameter, typically about 1 mg of mass, can penetrate an unshielded spacecraft surface and damage sensitive surfaces such as optics or thermal radiators; debris only 1 cm in diameter (~1 gm) can penetrate even a heavily shielded surface; and debris as small as 10 cm (1 kg) can cause a spacecraft to experience a severe breakup.

### C.2 The Presidential Directive to Limit Orbital Debris Generation

On February 11, 1988, President Reagan issued a Presidential Directive on national space policy which included a requirement to limit the accumulation of orbital debris. This directive was the foundation for a coordinated effort among U.S. agencies and other nations to increase the understanding of the hazards caused by orbital debris and to establish effective techniques to manage the orbital debris environment. Under Presidents Bush and Clinton orbital debris continued to be a concern.

In 1993 the Executive Branch Office of Science and Technology Policy (OSTP) directed that the 1989 U.S. Government Interagency Report be updated. The updated report was released in 1995 and directed Government agencies to develop a coordinated orbital debris work plan, to consult with U.S. industry, and to continue efforts to achieve international consensus on dealing with the orbital debris problem. In 1997 NASA and the Department of Defense developed a draft set of U.S. Government Orbital Debris Mitigation Standard Practices, derived in large measure from NASA Safety Standard 1740.14, the predecessor of this current NASA-STD. These standard practices were coordinated among all relevant U.S. Government agencies and adopted in

February 2001. The Department of Defense and its subordinate organizations, including U.S. Strategic Command, Air Force Space Command, and the National Reconnaissance Office, have now issued their own orbital debris mitigation requirements. U.S. regulatory agencies, particularly the Department of Transportation and the Federal Communications Commission, have also addressed orbital debris mitigation within their own spheres of responsibility.

### C.3 International Orbital Debris Efforts

As a result of the 1989 OSTP direction to promote international cooperation in the area of orbital debris, NASA formalized bilateral consultations with the European Space Agency (ESA), the former Soviet Union, and Japan. These efforts led to the establishment in 1993 of the Inter-Agency Space Debris Coordination Committee (IADC), whose membership comprises the major space agencies of the world. From an initial membership of only four, the IADC has grown to 11 members, including the space agencies from 10 countries (U.S., Russia, China, Japan, India, France, Germany, Italy, United Kingdom, and Ukraine) and ESA. In October 2002, the IADC adopted a consensus set of space debris mitigation guidelines, which are very similar to and consistent with this NASA-STD (the mitigation guidelines can be found at www.iadc-online.org).

In 1993, after a multi-year effort, the International Academy of Astronautics released a position paper on orbital debris. The paper focused on the present status of orbital debris, debris control options, and methods of debris control. The position paper was updated and re-released in 2001.

Orbital debris mitigation guidelines have been issued in a number of space agencies of other countries, including Russia, France, and Japan. ESA released a draft *Space Debris Mitigation Handbook* in 1999 with a revision in 2002. These requirements bear strong similarities to one another and to U.S. orbital debris mitigation requirements.

This current NASA-STD, in part, reflects the evolution of international thinking on orbital debris mitigation.

Space debris has been an item on the agenda of the Scientific and Technical Subcommittee (STSC) of the United Nations' Committee on the Peaceful Uses of Outer Space (COPUOS) since 1993. In 1999 the United Nations released its Technical Report on Space Debris, which summarized the then state-of-world knowledge on orbital debris measurements, modeling, and mitigation. In February 2003 the STSC began discussions about an international set of orbital debris mitigation measures based upon the *IADC Space Debris Mitigation Guidelines* of 2002. The STSC and full COPUOS adopted a consensus set of orbital debris guidelines in 2007.

### C.4 A Theoretical Perspective on Managing Orbital Debris

Even though access to space and operations in space require a large expenditure of energy, any object left in space after it has performed its desired functions will still contain residual energy. This energy is composed in large part of kinetic energy and may also include additional stored energy, both chemical and mechanical. The kinetic energy results from both the high orbital velocity and the fact that objects are generally in different orbit planes. In the low Earth orbit region of space (up to 2,000 km altitude), average kinetic energy is about 50 megajoules per kilogram of mass in orbit.* The stored energy (in the form of momentum devices, residual propellant, pressurized containers, or batteries, for example) is minimal by comparison—usually much less than a megajoule per kilogram. These sources of stored energy, however, can cause their associated structures to fragment, producing numerous smaller fragments, each still containing the 50 megajoules of kinetic energy per kilogram of fragment mass. The large number of fragments, combined with the relatively high kinetic energy for each fragment, creates a risk to other spacecraft.

Fundamentally, the process of managing orbital debris is a process of managing this residual energy. Stored energy can be depleted before ending operations. Kinetic energy management, on the other hand, requires eliminating either mass or relative velocity. Since in most cases it is not possible to cause objects to orbit in a way which reduces the relative velocity, mass shall not remain long in a region where it can affect other space operations, either directly or by fragmentation. In some cases, mass will be removed from orbit by natural forces. For other cases specific removal actions must be planned. Even after debris control measures are instituted, however, there will be a residual debris environment from mass left in orbit before management of the environment began and from accidents occurring in orbit.

Therefore, a program mitigates its orbital debris contribution by controlling the energy it contributes to the orbital debris environment. The short-term environment can be managed by controlling the stored chemical and mechanical energy within a spacecraft. This requires reliable designs to prevent explosions during operations. To prevent explosions after completion of mission operations, residual energy such as pressure, propellant, or mechanical energy must be vented or depleted. If spacecraft remain in the environment long enough, they will eventually be converted into fragments as a result of collisions. Consequently, the long-term management of the environment requires that objects be removed from useful orbits at EOM. This also means that objects must have sufficient reliability against orbital debris and other hazards to ensure that they can be removed before any fragmentation occurs.

## C.5 Orbital Debris Modeling—Predicting the Probability of Collision

Since 1979, NASA has conducted a program which characterizes the current and future environment and which consists of a combination of models validated by measurements. A better understanding of the consequences of past space operations has resulted from this program. We now know that within the approximately 2,000 km altitude Low Earth Orbit (LEO) region there are many millions of very small orbital debris fragments (0.1 mm and smaller, produced from solid rocket motor firings and degradation of spacecraft surfaces) that can erode spacecraft surfaces. More than 1 million objects are larger than 1 mm and can cause operational failure if they strike sensitive areas on a spacecraft. Much of the orbital debris 1 mm and larger comes from the more than 200 accidental and intentional fragmentations which occurred between 1961 and 2005. There are more than 100,000 orbital debris objects larger than 1 cm that are likely to cause operational failure if they impact the main spacecraft bus; and there are more than 10,000 objects larger than 10 cm which could catastrophically fragment most space structures they strike.

* This is roughly 25 times the energy content of TNT.

In the current environment, the probability of spacecraft failures caused by collisions with debris remains slight. Evolutionary environment models, however, project that, unless measures are taken to limit the generation of debris, in the future, the failure probabilities will grow significantly. Thus, the hazard imposed by debris may become almost as significant a cause of spacecraft loss as component failure, even after routine techniques are adopted to protect spacecraft. The requirements defined in this NASA-STD provide constraints on debris generation that will limit the growth of the debris environment and, therefore, limit the potential of orbital debris becoming a significant hazard to future space operations.

## C.6 Orbital Debris Environment Models

During the 1980's, NASA orbital debris environment models were largely analytical in nature, relying on the official population of large (>10 cm) objects maintained by the U.S. Space Surveillance Network (SSN) and simple physics models representing estimates of debris from satellite breakups, surface degradation, and other sources. With the advent of the Space Shuttle, considerable new data on the very small (<1 mm) orbital debris population became available through examinations of returned spacecraft surfaces such as LDEF, EURECA, SFU, SMM, and the Mir Space Station, as well as inspections of the Space Shuttle itself. In 1990 NASA began a program of dedicated ground-based radar observations aimed at defining the intermediate (1 mm – 10 cm) orbital debris population. Today, NASA's LEO Orbital Debris Engineering Model 2000 (ORDEM2000) is largely empirical in nature. As an example, Figure C-1 below indicates the assessed flux of objects below 600 km in 1999, based upon a wide variety of data sources.

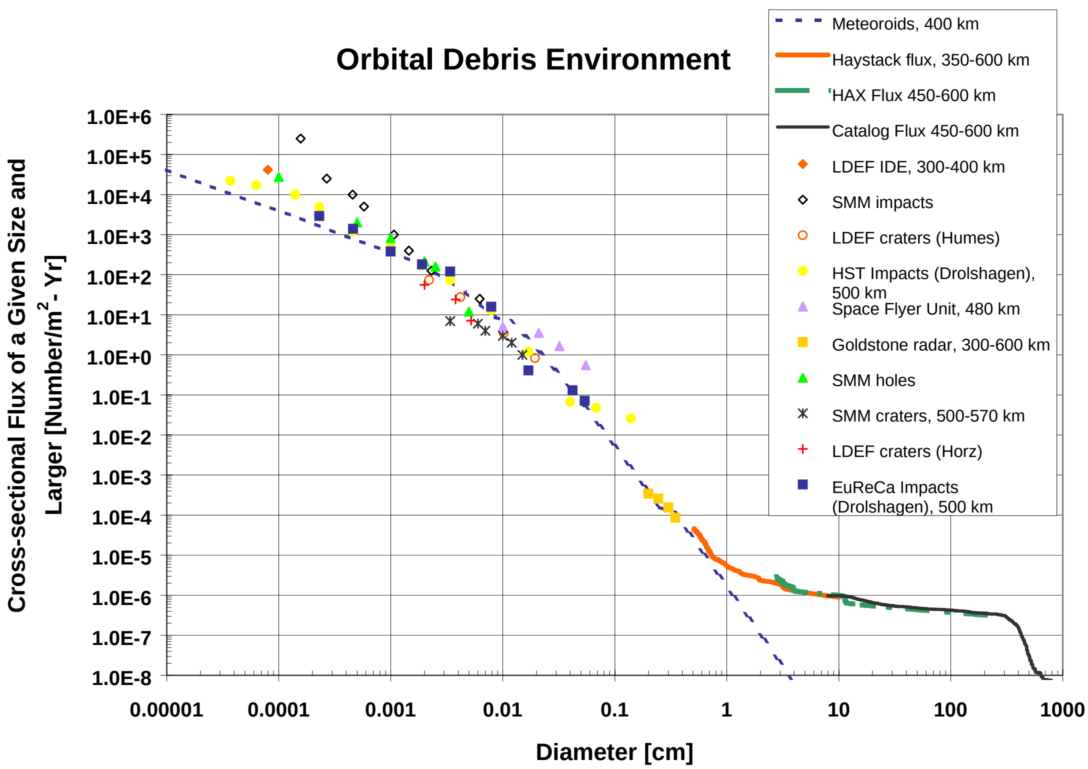


Figure C-1. Cross-sectional area flux below 600 km in 1999.

The characterization of the orbital debris population in Geosynchronous Earth Orbit (GEO) is of a lower fidelity than that in LEO. Ground-based sensors, both radar and optical, of the SSN are limited to tracking objects of approximately 1 m or larger. During the 1990's NASA and ESA began optical surveys of GEO with the objective of defining the debris population there to a sensitivity of 20-30 cm diameter. Subsequently, the IADC has undertaken periodic GEO debris observation campaigns. A few spacecraft detectors are also collecting information on very small (typically microns and tens of microns in diameter) debris.

In general, the GEO debris population is believed to be much more benign than that in LEO, primarily due to the much smaller number of assessed and postulated satellite breakups in GEO. In addition, GEO does not contain a large population of mm- and cm-sized sodium potassium particles, such as resides in LEO from the leakage of coolant from former Soviet nuclear reactors.

Between LEO and GEO, the known debris environment consists primarily of derelict spacecraft and orbital stages and of a relatively few fragmentation debris. The true fragmentation debris population is undoubtedly larger but substantially less than that in LEO. In addition, micron-size and cm-size particles from the operation of solid rocket motors also exist, particularly in highly elliptical orbits. The smaller particles can be detected by the examination of LEO spacecraft surfaces, as was found on NASA's Long Duration Exposure Facility (LDEF).

## C.7 Placing Others at Risk

The growth in the amount of debris in space and the increasing hazard it poses demand that users of space exercise responsibility in both the design and operational phases of space missions. To decrease risks to others, space users shall avoid the following risk-creating events, to the greatest extent feasible:

*Explosions in orbit.* Explosions produce a large number of debris fragments capable of causing single-event failure of an operating spacecraft, as well as a still larger number of smaller debris fragments capable of degrading the performance of a spacecraft. The velocities imparted to the debris on breakup often create a risk to spacecraft operating hundreds of kilometers above or below the breakup altitude and can place debris in orbits with very long lifetimes.

*Damaging collisions with debris during mission operations.* This most likely will occur with a small piece of debris, leading to loss of control of the spacecraft. However, it could be a collision with a large piece of debris, leading to catastrophic breakup.

*Failure to remove a structure from orbit in a timely fashion at the end of useful life.* Failure to leave nonfunctional objects in short-lived (*e.g.*, <25 years) postmission orbits can lead to future collisions with large objects, which, in turn, can create large numbers of new debris.

*Leaving operational debris in the environment.* Such debris fragments, while small in number, are generally larger than 1 cm and represent a risk of single-event failure to operating spacecraft. These objects may remain in orbit for months to years if left at low altitude, for tens to hundreds of years if released at altitudes typical for Sun-synchronous missions, and for a virtually unlimited period of time if released above this altitude.

*Impacting the Earth's surface.* This danger occurs when components or structures from a spacecraft or orbital stage survive atmospheric reentry.

## Appendix D. Background On 25-Year Postmission Disposal Lifetimes

*Note: NASA-HDBK 8719.14 serves as a reference document to assist orbital debris practioners and program/project management in understanding orbital debris. Topics in NASA-HDBK 8719.14 include the OD environment, measurements, modeling, shielding, mitigation, and reentry. It is strongly encouraged that the NASA-HDBK be used with the implementation of NPR 8715.6 and NASA-STD 8719.14.*

### D.1 Brief Explanation

The 25-year requirement for postmission disposal has been established to limit debris growth while limiting the cost to low Earth orbiting programs. Since this requirement was first proposed by NASA in the 1990's, space agencies of other nations have adopted it, and the Inter-Agency Space Debris Coordination Committee (IADC) has endorsed it after a thorough technical assessment.

Specifically, the requirement was derived by first determining the debris environments that would result from postmission disposal requirement options, such as, no disposal time requirement, 50-year maximum postmission orbit lifetime, 25-year maximum postmission orbit lifetime, 10-year maximum postmission orbit lifetime, and immediate reentry. All options assumed that the annual launch of mass to orbit remained at the levels of the recent past. The option of no disposal orbital lifetime limit yielded an environment with significant debris growth. Time limits of 50 years, 25 years, 10 years, and immediate reentry yielded environments with much more modest debris growth (Figure D-1).

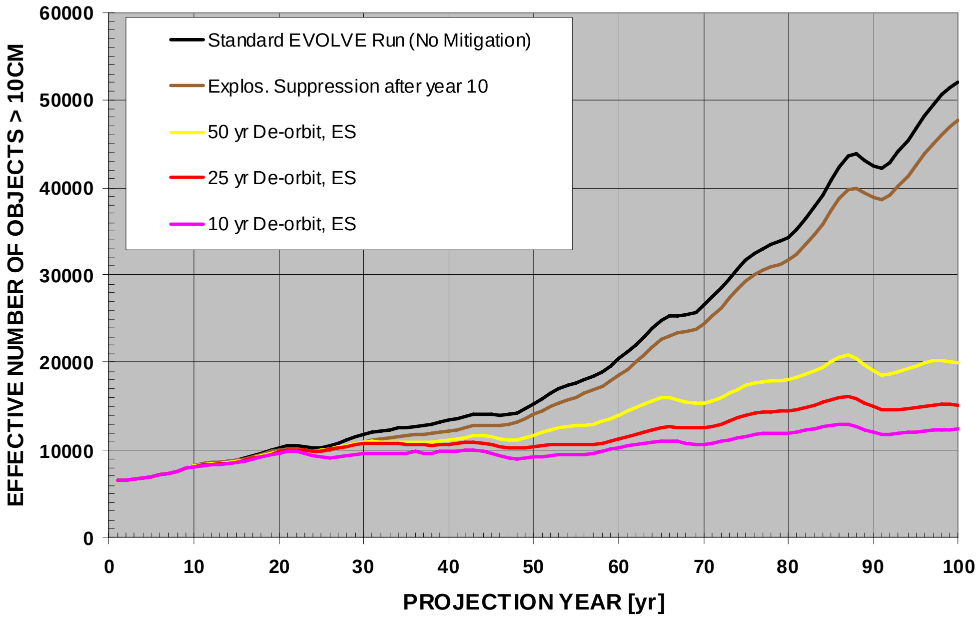


**Figure D-1. Effects on future debris environment from various postmission disposal options.**

Next, the propellant requirements to maneuver to orbits with maximum lifetimes of 50, 25, and 10 years, and immediate reentry were considered. It was found that there is a substantial propellant requirement (15-20% of final mission mass) to maneuver to immediate reentry. However, the propellant requirement for maneuver to either of the 50-year, 25-year, or 10-year orbits was substantially less (3-5% of final mission mass). Thus, these orbits are more attractive in terms of the propellant requirements imposed to maneuver to these lifetime orbits. In particular, the difference between the 50-year and the 25-year cases in percentage of spacecraft mass for propellants was very small, but the resultant effect on the environment was more pronounced.

Consequently, based on balancing the aim of limiting growth in the debris environment with the aim of limiting propellant costs and the complications imposed by performing a maneuver to a limited lifetime orbit, the 25-year requirement was selected.

### D.2 Detailed Explanation

Models of the orbital debris environment show that procedures must be instituted to limit accumulation of debris mass in orbit. For low Earth orbit programs or programs having systems in highly eccentric orbits, limiting this accumulation is best accomplished by limiting the orbit lifetimes of the systems after completion of mission. Requirement 4.6-1a implements this concept.

The 25-year lifetime allowed by Requirement 4.6-1a was determined by trading off the size of the postmission disposal maneuver delta velocity (ΔV) requirement with the effectiveness of reducing growth of the debris environment. The shorter the allowed postmission orbital lifetime, the less growth there will be in the debris environment but the larger the fraction of space programs that will require post mission disposal and the greater the ΔV requirement on affected programs. Longer postmission orbital lifetimes affect fewer programs but will allow more environment growth.

The ΔV required for postmission disposal from circular orbit is shown as a function of orbit altitude in Figure D-2. The ΔV calculation assumes a single, in-plane, horizontal burn against the satellite velocity vector. This operational procedure provides the maximum lowering of perigee in the disposal orbit and is the most efficient single-maneuver procedure for lowering perigee and reducing orbital lifetime. Figure D-2 also presents information relating ΔV to propellant mass requirements for a single burn maneuver; the numbers on the axes are the fraction of total system mass required for propellant for the postmission disposal maneuver.

The top curve in Figure D-2 shows the ΔV required for an example of targeted reentry. In this case the location of the reentry ground footprint is controlled by the location of the reentry burn. The second curve shows the ΔV requirement for a case of immediate reentry, in which reentry occurs within a few revolutions in the disposal orbit but where the location of the reentry footprint can be quite uncertain. These two cases are highly effective for debris environment control since the objects are removed from orbit within hours after completion of mission and therefore have almost no time to collisionally interact with other components of the debris environment. However, any program using either of these disposal options would have to perform a postmission disposal maneuver and, as can be seen from the propellant mass fraction axes, these maneuvers can require a propellant expenditure of up to 12% of the final mass of a space system orbiting at 1000 km.

Expending less ΔV than for the first two cases leads to disposal orbits in which the initial perigee altitude is higher and the disposal orbit lifetime is longer. There are five contours in Figure D-2 showing the ΔV required to transfer from circular orbit to an eccentric disposal orbit with the apogee altitude equal to the circular orbit altitude and the perigee altitude such that the system in the disposal orbit has a lifetime of 10, 25, or 50 years. Orbital lifetime in these cases depends on the area-to-mass ratio for the system being disposed of (expressed in units of $m^2$/kg); a constant level of solar activity of 130 solar flux units (sfu) is used for these calculations. (Note: 1 sfu is a solar radiation energy flux of $10^4$ Janskys or $10^{-22}$ watts/$m^2$/sec measured at a wavelength of 10.7 cm; nominal levels of solar activity are 75 sfu at a minimum in the solar cycle and 150-200 sfu at a peak in the solar cycle.) This value is a realistic average over an average solar cycle for orbital lifetime calculations. Orbital lifetime is inversely proportional to area-to-mass ratio.

Using Figure D-2, for the requirement case of 25 years, systems with an area-to-mass ratio of 0.01 $m^2$/kg and a mission orbit altitude below ~630 km or with an area-to-mass ratio of 0.05 $m^2$/kg and a mission orbit altitude below ~740 km will require no postmission disposal maneuver. As can be seen in Figure D-2, there is considerable reduction in ΔV in changing from targeted or immediate reentry to having an orbit with a 10-year lifetime, but there is relatively little further reduction in ΔV to change from a 10-year lifetime to a 25-year lifetime.

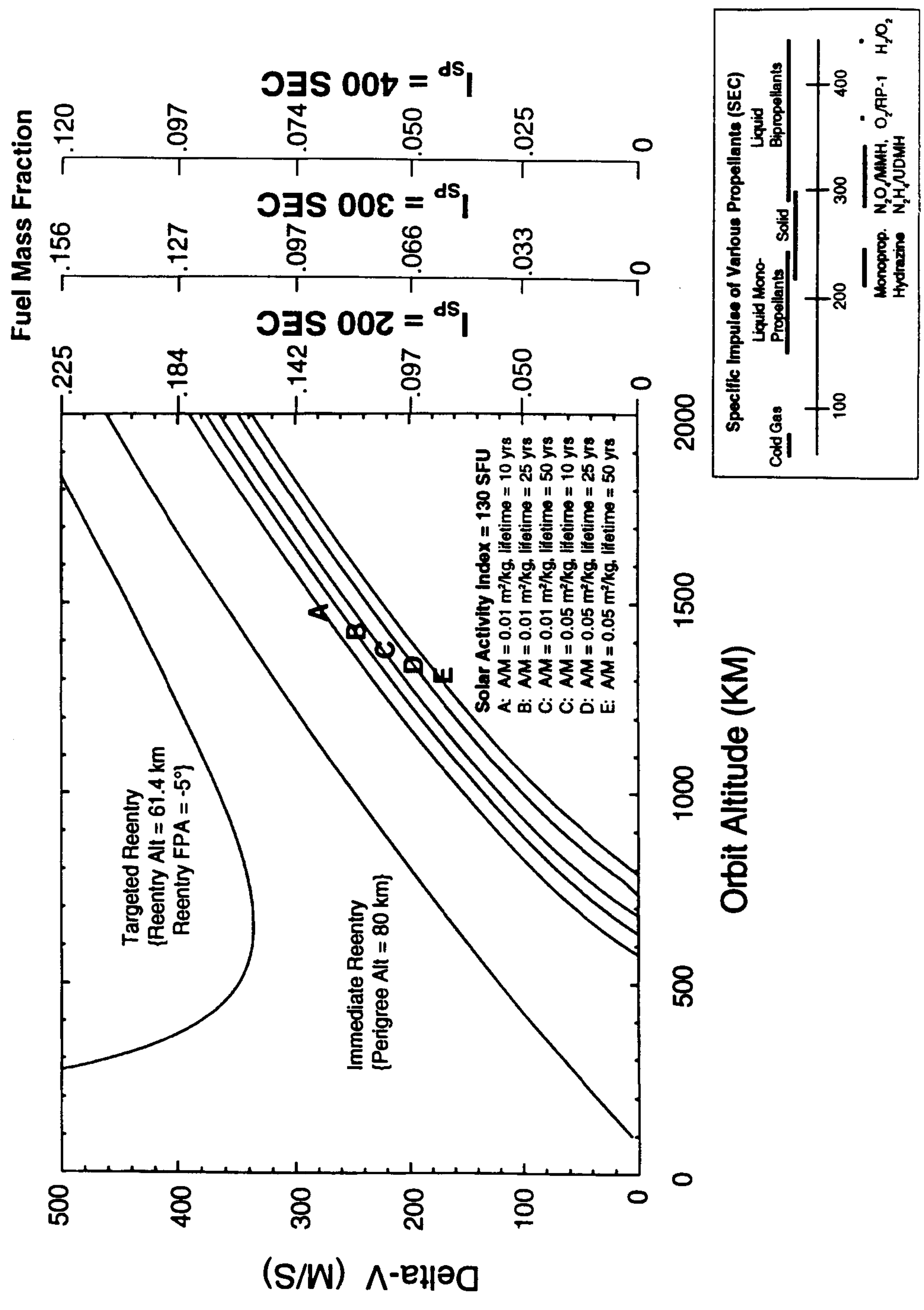


**Figure D-2. Delta-V Requirements for Disposal from Circular Orbit. Note that the targeted reentry curve is an example only; the maximum recommended perigee is 50 km (see Section 4.6)**

## APPENDIX E. Background On Human Casualty Expectation

*Note: NASA-HDBK 8719.14 serves as a reference document to assist orbital debris practioners and program/project management in understanding orbital debris. Topics in NASA-HDBK 8719.14 include the OD environment, measurements, modeling, shielding, mitigation, and reentry. It is strongly encouraged that the NASA-HDBK be used with the implementation of NPR 8715.6 and NASA-STD 8719.14.*

The risk of human casualty following an uncontrolled satellite reentry depends upon (1) the number and size of pieces that survive to the ground, (2) the orbit inclination for the reentering space system, and (3) the total average population underneath the spacecraft's orbit. In the risk assessment approach in this NASA-STD, the number and size of the debris pieces is considered in the debris casualty area calculation, and the total average population is dependent upon the orbit inclination for the reentering spacecraft. Figure E-1 shows the variation of average population density underneath the spacecraft with the spacecraft's orbital inclination for the years 2000 and 2050.

Following the development of both referenced Bouslog *et al.*, the risk is characterized by the expected number of human casualties, E, resulting from reentry using the equation

$$E = P\left[\frac{N_l}{A_l^L}\right]D_A \qquad \text{(E-1)}$$

where

$P$ = probability of impacting on a landmass = $A_\ell^L / A_\ell$

$A_\ell^L$ = land area within a latitude band bounded by ±l

$A_\ell$ = total surface area within a latitude band bounded by ±l = $4\pi R_e^2 \mathrm{Sin}(l)$

$N_\ell$ = population within a latitude band bounded by ±l

$R_e$ = radius of the Earth (m) = 6,378,145.0 m

Debris Casualty Area ($m^2$)

$$D_A = \sum_{i=1}^{N}\left(0.6 + \sqrt{A_i}\right)^2 \qquad \text{(E-2)}$$

where:

N = the number of objects

$A_i$ = average cross-sectional area of the $i^{th}$ surviving debris fragment ($m^2$)

The latitude band is related to the inclination of the orbit of the reentering object by

$\ell$ = orbit inclination for orbit inclinations ≤ 90°

$\ell$ = 180° - orbit inclination for orbit inclinations ≥ 90°

The quantity $N_l / A_l$ is the average area density for people within the latitude band.

The population density data (shown on Figure E-1) comes from an assessment conducted at Johnson Space Center in 2002 of world-wide population projection databases.

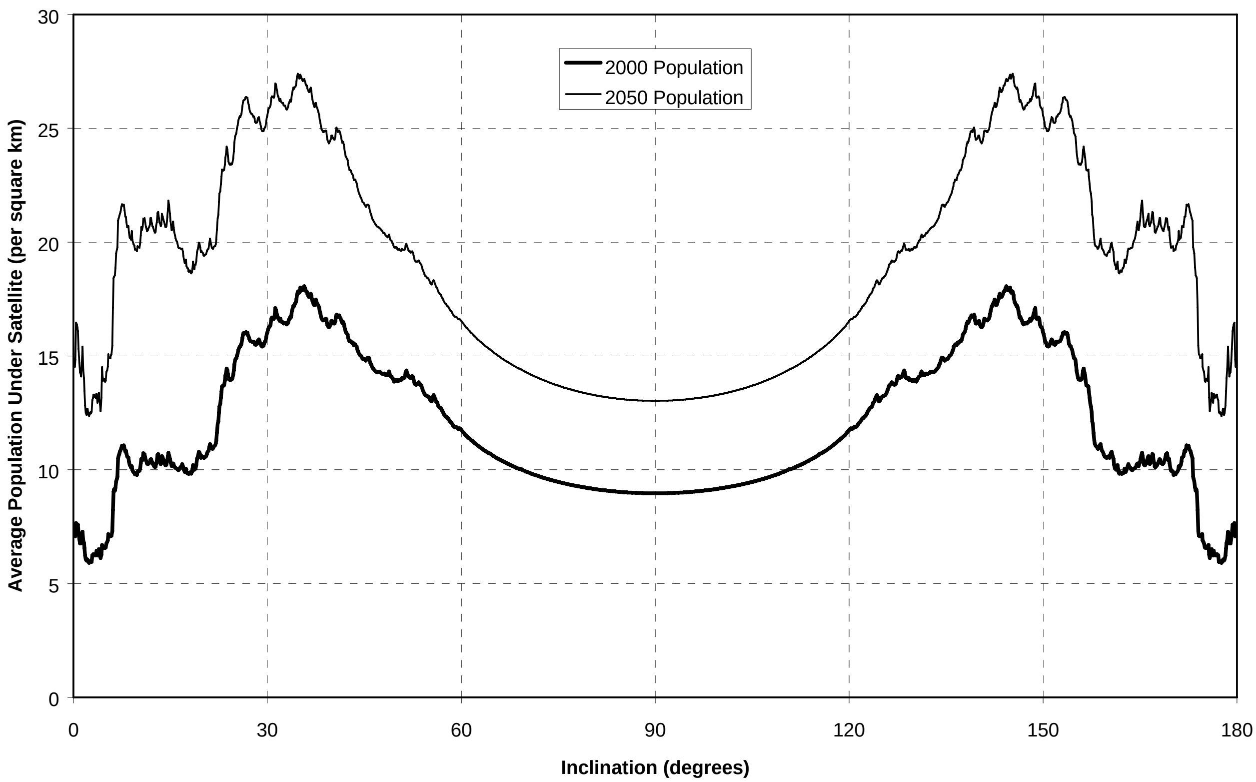


Figure E-1. Average Population Density as a Function of Orbital Inclination

## Appendix E References

E-1 Bouslog, S., K. Wang, B. Ross, and C. Madden, Reentry Survivability and Risk Analysis, NASA/JSC Technical Report JSC-27232, September, 1995.

E-2 Bouslog, S., B. Ross, and C. Madden, Space Debris Reentry Risk Analysis, Presented at the 32nd Aerosciences Meeting and Exhibit, Paper No. AIAA-94-0591, Reno, NV, January 10-13, 1994.