Orbital Debris Briefing

J.-C. Liou, PhD
Chief Scientist for Orbital Debris
National Aeronautics and Space Administration

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Outline

- **History of orbital debris (OD) mitigation policies and requirements**
  - NASA, U.S. Government, and the international community

- **Comparisons between NASA orbital debris mitigation requirements and others**

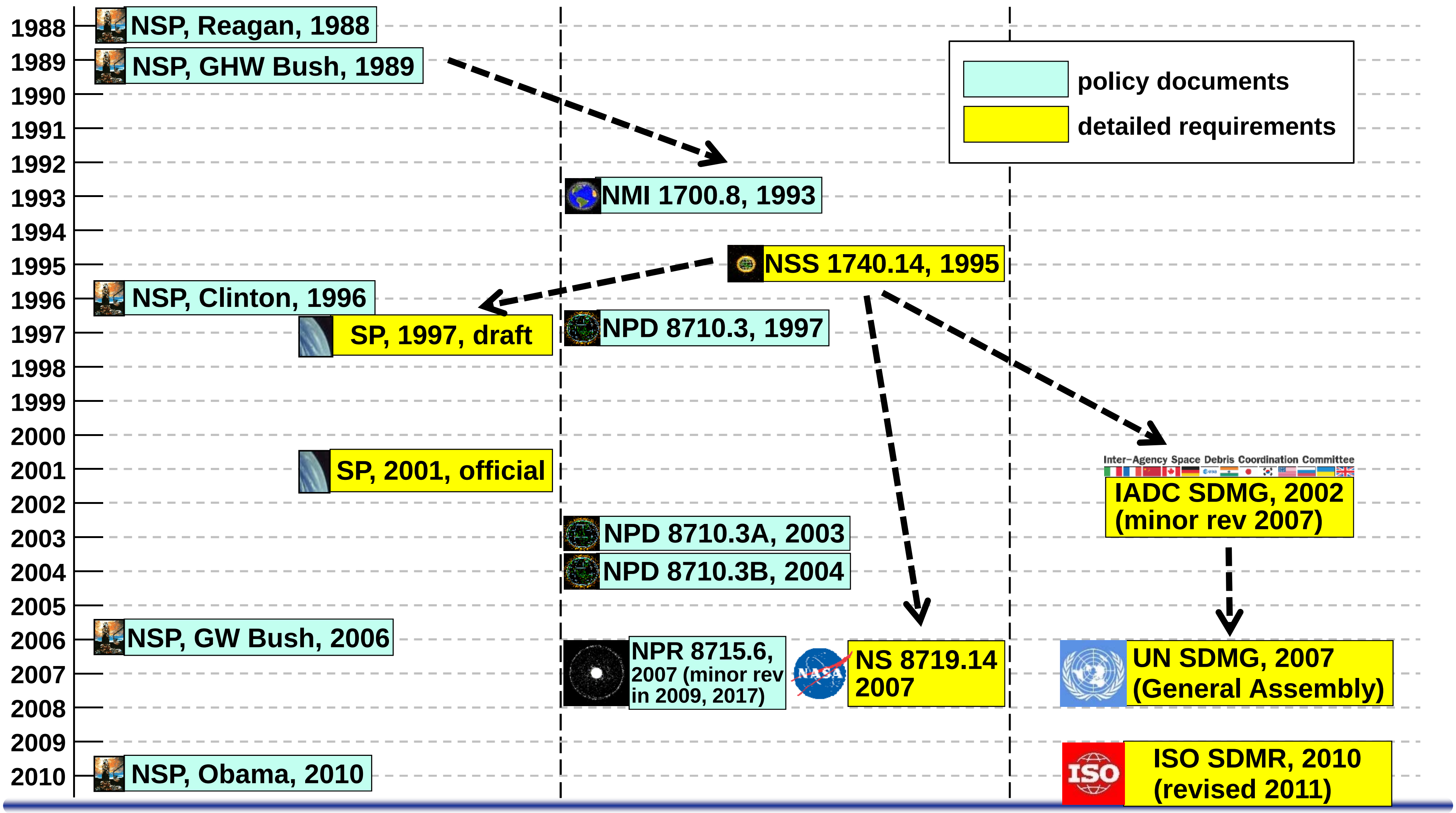
- **2008-2017 NASA mission compliance with U.S. Government Orbital Debris Mitigation Standard Practices**

History of OD Mitigation Policies, Requirements, and Guidelines

- Orbital debris is any human-made object in orbit about the Earth that no longer serves any useful purpose
- International community prefers to use the term “Space Debris”

History of OD Mitigation Policies, Requirements, and Guidelines

U.S. OD Mitigation Policy and Standard Practices | NASA OD Mitigation Policy and Requirements | International OD Mitigation Guidelines



OD Mitigation at NASA

- **NASA was the first organization in the world to develop OD mitigation policy and guidelines in the 1990s**
  - NASA Management Instruction (NMI) 1700.8 "Policy for Limiting Orbital Debris Generation" was established in 1993
  - NASA Safety Standard (NSS) 1740.14 "Guidelines and Assessment Procedures for Limiting Orbital Debris" established the first detailed set of mitigation guidelines for NASA missions in 1995

- **The current NASA OD mitigation policy is documented in NASA Procedural Requirements for Limiting Orbital Debris, NPR 8715.6 revB (2017)**
  - Specific mission requirements are defined in NASA Technical Standard NS 8719.14, Process for Limiting Orbital Debris (2007)

U.S. Government OD Mitigation Standard Practices (1/3)

- **NASA and DOD led the effort to establish the U.S. Government (USG) OD Mitigation Standard Practices (approved in 2001)**
- **The U.S. National Space Policies of 2006 and 2010 direct agencies and departments to implement the USG OD Mitigation Standard Practices**
- **The 2013 National Transportation Policy directs the Secretary of Transportation to execute exclusive authority to address orbital debris mitigation practices for U.S.-licensed commercial launches through its licensing procedures**

U.S. Government OD Mitigation Standard Practices (2/3)

Orbital debris poses a risk to continued reliable use of space-based services and operations and to the safety of persons and property in space and on Earth. The United States shall seek to minimize the creation of orbital debris by government and non-government operations in space in order to preserve the space environment for future generations. Toward that end:

- *Departments and agencies shall continue to follow the United States Government Orbital Debris Mitigation Standard Practices, consistent with mission requirements and cost effectiveness, in the procurement and operation of spacecraft, launch services, and the operation of tests and experiments in space;*

(National Space Policy of the United States of America, 2006)

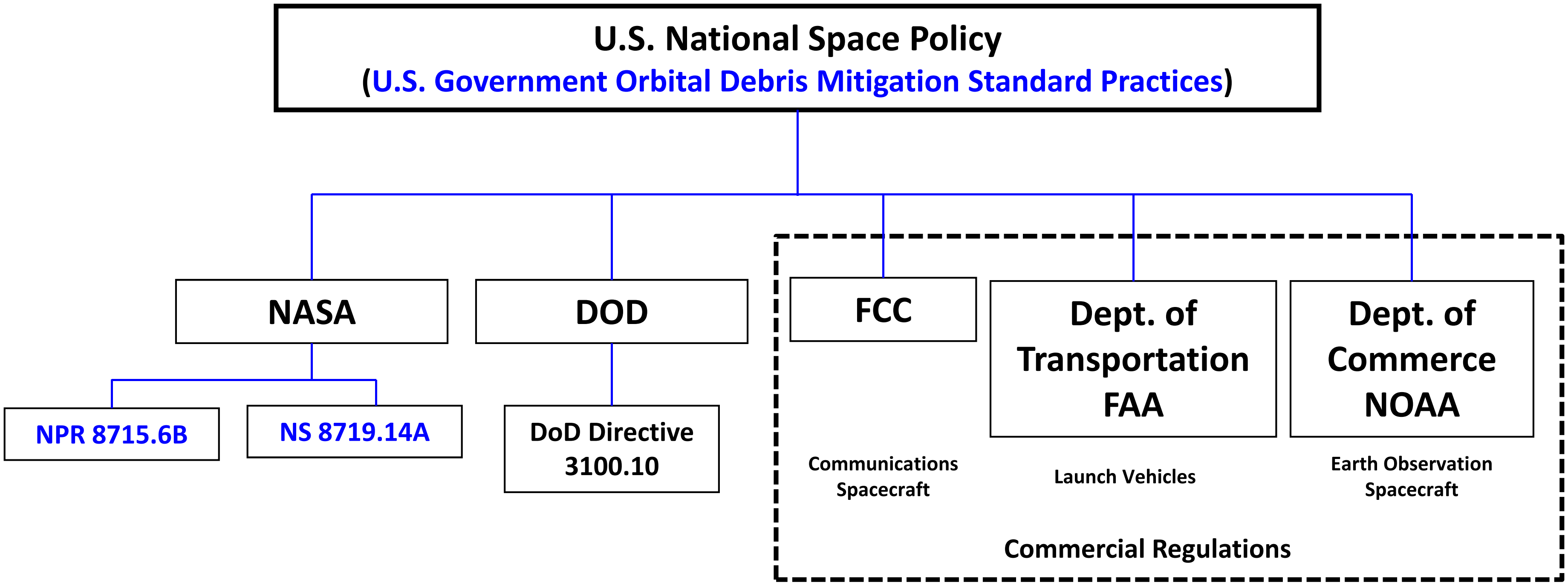
Preserve the Space Environment. For the purposes of minimizing debris and preserving the space environment for the responsible, peaceful, and safe use of all users, the United States shall:

- *Continue to follow the United States Government Orbital Debris Mitigation Standard Practices, consistent with mission requirements and cost effectiveness, in the procurement and operation of spacecraft, launch services, and the conduct of tests and experiments in space;*

(National Space Policy of the United States of America, 2010)

U.S. Government OD Mitigation Standard Practices (3/3)

- **Objectives of the USG OD Mitigation Standard Practices**
  - Control of debris released during normal operations
  - Minimizing debris generated by accidental explosions
  - Selections of safe flight profile and operational configuration
  - Postmission disposal of space structures



Inter-Agency Space Debris Coordination Committee (IADC)

- **The IADC is an international forum of national and multi-national space agencies for the coordination of activities related to space debris (SD)**
  – Current IADC members: ASI, CNES, CNSA, CSA, DLR, ESA, ISRO, JAXA, KARI, NASA, ROSCOSMOS, SSAU, and UKSA.
  – NASA represents the U.S. Government to the IADC. The NASA delegation also includes representatives from Dept. of State, OSD, AF, FAA, and FCC. The Orbital Debris Program Office (ODPO) leads the NASA delegation.
- **The IADC is recognized as the technical authority on SD by the international space community**
- **The IADC developed the first consensus on international SD mitigation guidelines in October 2002; subsequently submitted to the United Nations**

Space Debris at the United Nations (UN)

- **Space debris has been on the agenda of the Scientific and Technical Subcommittee (STSC) of the UN Committee on the Peaceful Uses of Outer Space (COPUOS) since 1994**

- **STSC Member States adopted a set of SD mitigation guidelines similar to the IADC guidelines in Feb. 2007, followed by adoption by COPUOS in Jun. 2007 and by the full UN General Assembly in Dec. 2007**
  - These are non-legally-binding, voluntary guidelines

- **There is an on-going effort by COPUOS to develop a new set of guidelines on the long-term sustainability of outer space activities (LTS)**

Comparisons between NASA OD Mitigation Requirements and Others

NASA, USG, and International OD Mitigation Requirements/Guidelines

- NASA has been the global pioneer and leader on orbital debris, being the first to identify the problem, to study the problem, and to develop mitigation measures to manage the problem
- NASA OD requirements are more quantitative and more strict than the USG OD Mitigation Standard Practices
- The USG OD Mitigation Standard Practices are more quantitative and more strict than the IADC and the UN SD Mitigation Guidelines
- Examples are provided in the following pages

Sample Comparison (1/4)

The 25-year rule for Low Earth orbit (LEO, the region below 2000 km altitude) postmission disposal

NASA	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.
USG	Leave the structure in an orbit in which, using conservative projections for solar activity, atmospheric drag will limit the lifetime to no longer than 25 years after completion of mission.
IADC	A spacecraft or orbital stage should be left in an orbit in which, using an accepted nominal projection for solar activity, atmospheric drag will limit the orbital lifetime after completion of operations. A study on the effect of post-mission orbital lifetime limitation on collision rate and debris population growth has been performed by the IADC. This IADC and some other studies and a number of existing national guidelines have found 25 years to be a reasonable and appropriate lifetime limit.
UN	Spacecraft and launch vehicle orbital stages that have terminated their operational phases in orbits that pass through the LEO region should be removed from orbit in a controlled fashion. If this is not possible, they should be disposed of in orbits that avoid their long-term presence in the LEO region.

Sample Comparison (2/4)

Minimizing debris generated by accidental explosions during missions

NASA	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.
USG	In developing the design of a spacecraft or upper stage, each program, via failure mode and effects analyses or equivalent analyses, should demonstrate either that there is no credible failure mode for accidental explosion, or, if such credible failure modes exist, design or operational procedures will limit the probability of the occurrence of such failure modes.
IADC	During the design of spacecraft or orbital stages, each program or project should demonstrate, using failure mode and effects analyses or an equivalent analysis, that there is no probable failure mode leading to accidental break-ups. If such failures cannot be excluded, the design or operational procedures should minimise the probability of their occurrence.
UN	Spacecraft and launch vehicle orbital stages should be designed to avoid failure modes which may lead to accidental break-ups. In cases where a condition leading to such a failure is detected, disposal and passivation measures should be planned and executed to avoid break-ups.

Sample Comparison (3/4)

Limiting human casualty risk from surviving reentry debris

NASA	For uncontrolled reentry, the risk of human casualty from surviving debris shall not exceed 0.0001 (1 in 10,000).
USG	If a space structure is to be disposed of by reentry into the Earth's atmosphere, the risk of human casualty will be less than 1 in 10,000.
IADC	If a spacecraft or orbital stage is to be disposed of by re-entry into the atmosphere, debris that survives to reach the surface of the Earth should not pose an undue risk to people or property.
UN	When making determinations regarding potential solutions for removing objects from LEO, due consideration should be given to ensuring that debris that survives to reach the surface of the Earth does not pose an undue risk to people or property, including through environmental pollution caused by hazardous substances.

Sample Comparison (4/4)

- **The French law, the national space agencies of Germany and Japan, and the European Space Agency have adopted quantitative OD requirements similar to those of NASA**
  - The 25-year rule, 0.001 accidental explosion probability limit, 1 in 10,000 reentry human casualty risk, 0.9 post-mission disposal reliability, *etc.*
- **The International Organization for Standardization (ISO) Space Debris Mitigation Requirements consist of many elements similar to the NASA OD requirements**
  - The 25-year rule, 0.001 accidental explosion probability limit, 0.9 post-mission disposal reliability, *etc*.
- **There is an on-going effort by the IADC to quantify several elements in its SD Mitigation Guidelines**
  - The 25-year rule, 0.001 accidental explosion probability limit, 1 in 10,000 reentry human casualty risk, *etc.*

Summary of NASA Mission Compliance With USG OD Mitigation Standard Practices

NASA Mission Compliance Summary

- **The U.S. National Space Policies of 2006 and 2010 direct agencies and departments to implement the USG OD Mitigation Standard Practices**

- **The June 2010 National Space policy requires the head of the sponsoring department or agency to approve exceptions to the USG OD Mitigation Standard Practices and notify the Secretary of State**

- **The following page is a summary of the January 2008 to September 2017 NASA mission compliance with the USG OD Mitigation Standard Practices**

Summary – by Missions
(Jan 2008 through Sep 2017)

Year	Spacecraft in Earth Orbit	Launch Vehicles
2008	GLAST, IBEX	Delta II, Pegasus, Delta II (Jason 2),
2009	NOAA-19, GOES-14, WISE	Delta II, Delta IV, Delta II, Atlas 5 (LRO), Delta II (Kepler)
2010	SDO, GOES-15, FASTSAT-HSV01	Atlas 5, Delta IV
2011	Aquarius, NPP	Delta II, Delta II, Atlas 5 (Juno), Delta II (GRAIL), Atlas 5 (MSL)
2012	NUSTAR, RBSP A, RBSP B	Pegasus, Atlas 5
2013	TDRS-11, Landsat-8, IRIS	Atlas 5, Atlas 5, Pegasus, Atlas 5 (MAVEN)
2014	TDRS-12, GPM, OCO-2	Atlas 5, Delta II
2015	SMAP, MMS (4 spacecraft)	Delta II, Atlas 5, Falcon 9 (DSCOVR)
2016	BEAM, GOES-R, CYGNSS (8 spacecraft)	Atlas 5, Pegasus, Falcon 9 (Jason 3), Atlas 5 (OSIRIS-Rex)
2017	TDRS-13	Atlas 5

- **Spacecraft or launch vehicles in full compliance with the USG OD Mitigation Standard Practices are in black**

Summary – Non-compliances
(Jan 2008 through Sep 2017)

- **End of Mission Passivation**
  - TDRS-11. TDRS-12, TDRS-13: tanks remain pressurized at 230 psi
  - SMAP: cannot drain batteries and cannot disconnect solar panels / batteries
  - CYGNSS: cannot disconnect solar panels / batteries
- **Postmission Orbital Lifetime (Requirement: <25 years)**
  - NOAA 19: 500 years
  - FASTSAT-HSV01: 75 years
  - IRIS Pegasus: 30 years
- **Reentry Human Casualty Risk (Requirement: <1 in 10,000)**
  - GLAST Delta II: 1 in 5,000
  - NOAA-19 Delta II: 1 in 9,100
  - Aquarius: 1 in 7,000
  - Aquarius Delta II: 1 in 5,000
  - NPP Delta II: 1 in 5000
  - RBSP A and B: 1 in 5,000
  - MMS Atlas 5: 1 in 600
  - BEAM: 1 in 5,100
  - CYGNSS Pegasus: 1 in 6,100

Concluding Remarks

- NASA monitors compliance at Agency-level performance reviews
- Each of NASA’s non-compliances was justified against mission requirements and cost effectiveness
- NASA is seeking improved compliance via careful consideration of heritage system compliance, controlled re-entry abilities, and improved management of non-compliance risks during the early mission design phase

Backup Charts

- USG OD Mitigation Standard Practices
- NASA Orbital Debris Mitigation Requirements (NS 8719.14A)
- Summary of 2008-2017 NASA Mission Compliance with NS 8719.14A

Four Objectives of USG OD Mitigation Standard Practices

- Control of debris released during normal operations
- Minimizing debris generated by accidental explosions
- Selection of safe flight profile and operational configuration
- Postmission disposal of space structures

USG OD Mitigation Standard Practices, Objective 1

OBJECTIVE

1. CONTROL OF DEBRIS RELEASED DURING NORMAL OPERATIONS

Programs and projects will assess and limit the amount of debris released in a planned manner during normal operations.

MITIGATION STANDARD PRACTICES

1-1. *In all operational orbit regimes:* Spacecraft and upper stages should be designed to eliminate or minimize debris released during normal operations. Each instance of planned release of debris larger than 5 mm in any dimension that remains on orbit for more than 25 years should be evaluated and justified on the basis of cost effectiveness and mission requirements.

USG OD Mitigation Standard Practices, Objective 2

OBJECTIVE

2. MINIMIZING DEBRIS GENERATED BY ACCIDENTAL EXPLOSIONS

Programs and projects will assess and limit the probability of accidental explosion during and after completion of mission operations.

MITIGATION STANDARD PRACTICES

2-1. *Limiting the risk to other space systems from accidental explosions during mission operations:* In developing the design of a spacecraft or upper stage, each program, via failure mode and effects analyses or equivalent analyses, should demonstrate either that there is no credible failure mode for accidental explosion, or, if such credible failure modes exist, design or operational procedures will limit the probability of the occurrence of such failure modes.

2-2. *Limiting the risk to other space systems from accidental explosions after completion of mission operations:* All on-board sources of stored energy of a spacecraft or upper stage should be depleted or safed when they are no longer required for mission operations or postmission disposal. Depletion should occur as soon as such an operation does not pose an unacceptable risk to the payload. Propellant depletion burns and compressed gas releases should be designed to minimize the probability of subsequent accidental collision and to minimize the impact of a subsequent accidental explosion.

USG OD Mitigation Standard Practices, Objective 3

OBJECTIVE

3. SELECTION OF SAFE FLIGHT PROFILE AND OPERATIONAL CONFIGURATION

Programs and projects will assess and limit the probability of operating space systems becoming a source of debris by collisions with man-made objects or meteoroids.

MITIGATION STANDARD PRACTICES

3-1. *Collision with large objects during orbital lifetime:* In developing the design and mission profile for a spacecraft or upper stage, a program will estimate and limit the probability of collision with known objects during orbital lifetime.

3-2. *Collision with small debris during mission operations:* Spacecraft design will consider and, consistent with cost effectiveness, limit the probability that collisions with debris smaller than 1 cm diameter will cause loss of control to prevent post-mission disposal.

3-3. *Tether systems* will be uniquely analyzed for both intact and severed conditions.

USG OD Mitigation Standard Practices, Objective 4

OBJECTIVE

4. POSTMISSION DISPOSAL OF SPACE STRUCTURES

Programs and projects will plan for, consistent with mission requirements, cost effective disposal procedures for launch vehicle components, upper stages, spacecraft, and other payloads at the end of mission life to minimize impact on future space operations.

MITIGATION STANDARD PRACTICES

4-1. *Disposal for final mission orbits:* A spacecraft or upper stage may be disposed of by one of three methods:

a. Atmospheric reentry option: Leave the structure in an orbit in which, using conservative projections for solar activity, atmospheric drag will limit the lifetime to no longer than 25 years after completion of mission. If drag enhancement devices are to be used to reduce the orbit lifetime, it should be demonstrated that such devices will significantly reduce the area-time product of the system or will not cause spacecraft or large debris to fragment if a collision occurs while the system is decaying from orbit. If a space structure is to be disposed of by reentry into the Earth's atmosphere, the risk of human casualty will be less than 1 in 10,000.

b. Maneuvering to a storage orbit: At end of life the structure may be relocated to one of the following storage regimes:

I. Between LEO and MEO: Maneuver to an orbit with perigee altitude above 2000 km and apogee altitude below 19,700 km (500 km below semi-synchronous altitude

II. Between MEO and GEO: Maneuver to an orbit with perigee altitude above 20,700 km and apogee altitude below 35,300 km (approximately 500 km above semi-synchronous altitude and 500 km below synchronous altitude.)

III. Above GEO: Maneuver to an orbit with perigee altitude above 36,100 km (approximately 300 km above synchronous altitude)

IV. Heliocentric, Earth-escape: Maneuver to remove the structure from Earth orbit, into a heliocentric orbit.

Because of fuel gauging uncertainties near the end of mission, a program should use a maneuver strategy that reduces the risk of leaving the structure near an operational orbit regime.

c. Direct retrieval: Retrieve the structure and remove it from orbit as soon as practical after completion of mission.

4-2. *Tether systems* will be uniquely analyzed for both intact and severed conditions when performing trade-offs between alternative disposal strategies.

NASA OD Mitigation Requirements

- **The current NASA OD mitigation policy is documented in NASA Procedural Requirements for Limiting Orbital Debris, NPR 8715.6 revB (2017)**

- **Specific mission requirements are defined in NASA Technical Standard NS 8719.14A, Process for Limiting Orbital Debris (2007)**

NS 8719.14A (1/9)

Control of Debris Released During Normal Operations

Req. 4.3-1: Debris passing through LEO – released debris with diameters of 1 mm or larger:

a. 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.

b. The total object-time product shall be no larger than 100 object-years per mission. The object-time product is the sum of all debris of the total time spent below 2,000 km altitude during the orbital lifetime of each object.

Req 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.

NS 8719.14A (2/9)

Limit Accidental Explosions

Req. 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).

Req. 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 and a plan 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.

NS 8719.14A (3/9)

Limit Intentional Breakups

Req. 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. For example, if the debris fragments greater than 10 cm 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 remains in Earth orbit longer than one year.

Req. 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}.

NS 8719.14A (4/9)

Limit Collisions with Large and Small Debris

Req. 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.

Req. 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.

NS 8719.14A (5/9)

Post-Mission Disposal

Req. 4.6-1: Disposal for space structures in or passing through LEO: A spacecraft or orbital stage with a perigee altitude below 2,000 km shall be disposed of by one of the following three methods:

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.

NS 8719.14A (6/9)

Post-Mission Disposal

Req. 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 perigee of GEO +200 km (35,986 km) or below GEO with an apogee of GEO – 200 km (35,586 km) for a period of at least 100 years after disposal.

Req. 4.6-3: Disposal for space structures between LEO and GEO:

a. A spacecraft or orbital stage shall be left in an orbit with a perigee greater than 2000 km above the Earth's surface and apogee less than 500 km below GEO.

b. A spacecraft or orbital stage shall not use nearly circular disposal orbits near regions of high value operational space structures, such as between 19,200 km and 20,700 km.

NS 8719.14A (7/9)

Post-Mission Disposal

Req. 4.6-4: Reliability of postmission disposal operations in Earth orbit: NASA space programs and projects shall ensure that all post mission disposal operations to meet Requirements 4.6-1, 4.6-2, and/or 4.6-3 are designed for a probability of success as follows:

a. Be no less than 0.90 at EOM.

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

NS 8719.14A (8/9)

Limit Debris Reentry Casualty Risk

Req. 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).

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.

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).

NS 8719.14A (9/9)

Limit Collision Risk Posed by Tether Missions

Req. 4.8-1: Mitigate the collision hazards of space tethers in Earth or Lunar orbits: Intact and remnants of severed 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.

NASA Mission Compliance Summary

- **NASA robotic space missions launched between January 2008 and September 2017 were examined to determine the degree of compliance with NASA OD mitigation requirements NS 8719.14A**
  - NOAA missions for which NASA was responsible for the design and construction of the spacecraft were also included
  - Shuttle missions and Commercial Resupply Services (CRS) missions to ISS were **not** included
- **CubeSats were not included**
  - All NASA CubeSats launched through September 2017 complied with the 25-year rule
- **Each of NASA's non-compliances must be justified against mission requirements and cost effectiveness**

Statistics – All Missions
(Jan 2008 through Sep 2017)

Year	Spacecraft launched	Spacecraft in full compliance	Compliance %
2008	2	1	50%
2009	6	2	33%
2010	3	1	33%
2011	6	5	83%
2012	3	1	33%
2013	5	4	80%
2014	3	1	33%
2015	6	1	17%
2016	11	2	18%
2017	1	0	0%
Total	46	18	39%

Launch vehicles	Launch vehicles in full compliance	Compliance %
3	2	67%
5	3	60%
2	1	50%
5	1	20&
2	1	50%
4	3	75%
2	2	100%
3	2	67%
4	1	25%
1	0	0%
31	16	52%

Summary – by Missions (All)
(Jan 2008 through Sep 2017)

Year	Spacecraft (full compliance in black)	Launch vehicles (full compliance in black)
2008	GLAST, IBEX	Delta II, Pegasus, Delta II (Jason 2)
2009	NOAA-19, Kepler, LRO, LCROSS, GOES-14, WISE	Delta II, Delta II, Atlas 5, Delta IV, Delta II
2010	SDO, GOES-15, FASTSAT-HSV01	Atlas 5, Delta IV
2011	Aquarius, JUNO, Grail A, Grail B, NPP, MSL	Delta II, Atlas 5, Delta II, Delta II, Atlas 5
2012	NUSTAR, RBSP A, RBSP B	Pegasus, Atlas 5
2013	TDRS-11, Landsat-8, IRIS, LADEE, MAVEN	Atlas 5, Atlas 5, Pegasus, Atlas 5
2014	TDRS-12, GPM, OCO-2	Atlas 5, Delta II
2015	SMAP, DSCOVR, MMS (4)	Delta II, Falcon 9, Atlas 5
2016	BEAM, OSIRIS-Rex, GOES-R, CYGNSS (8)	Atlas 5, Atlas 5, Pegasus, Falcon 9 (Jason 3)
2017	TDRS-13	Atlas 5

Non-Earth

Summary – by Missions (Earth Orbit)
(Jan 2008 through Sep 2017)

Year	Spacecraft in Earth Orbit	Launch Vehicles
2008	GLAST, IBEX	Delta II, Pegasus, Delta II (Jason 2)
2009	NOAA-19, GOES-14, WISE	Delta II, Delta IV, Delta II, Atlas 5 (LRO), Delta II (Kepler)
2010	SDO, GOES-15, FASTSAT-HSV01	Atlas 5, Delta IV
2011	Aquarius, NPP	Delta II, Delta II, Atlas 5 (Juno), Delta II (GRAIL), Atlas 5 (MSL)
2012	NUSTAR, RBSP A, RBSP B	Pegasus, Atlas 5
2013	TDRS-11, Landsat-8, IRIS	Atlas 5, Atlas 5, Pegasus, Atlas 5 (MAVEN)
2014	TDRS-12, GPM, OCO-2	Atlas 5, Delta II
2015	SMAP, MMS (4 spacecraft)	Delta II, Atlas 5, Falcon 9 (DSCOVR)
2016	BEAM, GOES-R, CYGNSS (8 spacecraft)	Atlas 5, Pegasus, Falcon 9 (Jason 3), Atlas 5 (OSIRIS-Rex)
2017	TDRS-13	Atlas 5

- **Spacecraft or launch vehicles in full compliance with NASA orbital debris requirements are in black**

Launch Vehicle Non-Compliances

- **Launch Vehicle Non-Compliances: 15**
  - Req 4.4-1 Operational Explosion Probability (Requirement: < 1 x 10^{-3}):
    - **8 Atlas Centaur Stages**
    - **Range of Probabilities: 1.5 x 10^{-3} to 2.0 x 10^{-3}, fleet waiver approved 11/2009 - 11/2019**
    - **Some Centaur stages are compliant due to mission profiles, *e.g.*, Landsat 8**
  - Req 4.6-1 Residual orbital lifetime (Requirement: < 25 years):
    - **1 Pegasus final stage: 30 years**
  - Req 4.7-1 Reentry risk (Requirement: < 1:10,000) :
    - **4 Delta II second stage: 1:5,000, fleet waiver approved 4/2009 - 4/2014**
    - **1 Atlas Centaur (MMS): 1:600**
    - **1 Pegasus (CYGNSS): 1:6,118**

Spacecraft Non-Compliances

- **28 spacecraft accounted for 32 non-compliances**
  - Req 4.4-1 Explosion Probability (Requirement: < 1×10^{-3}): 1 spacecraft
    - **IBEX: 4×10^{-4}**
  - Req 4.4-2 End of Mission Passivation: 22 spacecraft
    - **Batteries remain connected, tanks remain pressurized**
  - Req 4.6-1 Postmission Orbital Lifetime (Requirement: < 25 years): 2 spacecraft
    - **FASTSAT-HSV01: 75 years; NOAA-19: 500 years**
  - Req 4.6-4 Disposal Reliability (Requirement: > 0.9): 3 spacecraft
    - **OCO-2: 0.82; RBSP A and B: 0.765**
  - Req 4.7-1 Reentry Risk (Requirement: < 1:10,000): 4 spacecraft
    - **Aquarius: 1:7,000; RBSP A and B: 1:5,000; BEAM: 1:5,100**