ORBITAL DEBRIS MITIGATION AND CUBESATS

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ABSTRACT

The 2019 Update to the United States Government Orbital Debris Mitigation Standard Practices (ODMSP) included CubeSats for the first time as a special class of space operations. This is the first governmental-level policy document that calls for CubeSats to follow quantitative recommendations for orbital debris mitigation. While CubeSats were never exempt from such recommendations, mission designers often under assess CubeSats due to their small size and historically low level of stored energy. Qualitative assessments of debris potential are less applicable as miniaturized energy systems (propulsive and electrical) become more available and as the "CubeSat" label is applied to larger payloads. Of particular interest to the long-term evolution of the debris environment is the likelihood of accidental explosion or collision; we must also consider the risk to the human population from reentering spacecraft. We discuss the on-orbit history of CubeSats and present guidance to assist in designing for future compliance with the new standard practices.

1 INTRODUCTION

The United States Government Orbital Debris Mitigation Standard Practices (ODMSP) were originally established to "address the increase in orbital debris in the near-Earth space environment" [1]. When the ODMSP were first adopted in 2001, the practices described in the brief document were adequate to mitigate the growth of the debris problem at that time, but have since been overcome by several significant changes: intentional and unintentional satellite collisions, the advent of large constellations, and launch and deployment of large numbers of small satellites.

The original ODMSP consisted of four objectives:

1. To minimize the generation of mission related debris, and minimize its lifetime;
2. To minimize the likelihood of accidental explosions during and after completion of mission operations;
3. To minimize the likelihood of collision with a 10 cm-sized object while on orbit; and
4. Conduct postmission disposal to minimize impact on future space operations.

These standard practices have been successful in slowing the growth of the orbital debris population over the past 20 years, but it had become clear by the mid-2010s that they were no longer sufficient. In 2018, NASA was tasked with leading an interagency team in an effort to update the ODMSP to address changes in both the environment and in operational practices [2].

Since the first CubeSat standard was released in 1999, CubeSats have become an extremely popular form factor for smaller-scale space projects, with government, industry, academia, and even secondary schools joining the action. As of January 2021, over 1350 CubeSats have successfully made it to orbit [3].

With the increased popularity of CubeSats, starting in the 2010s, the interagency working group updating the ODMSP decided to add a new objective to the ODMSP: Objective 5 – Special Classes of Space Operations [4]. This is the first governmental-level policy document that specifically calls out small satellites, including CubeSats, as a special class of space operations, with its own opportunities and challenges. Objective 5-2 reminds CubeSat projects that they should follow all the standard practices for spacecraft. Because spacecraft smaller than 1U are difficult to track and may be released in large numbers, Objective 5-2, parts a and b, emphasize the 25-year lifetime limit and a new limit, similar to the limit on mission-related debris, of an object-time less than 100 object-years per mission.

In addition to supporting the update to the ODMSP in 2018-2019, NASA has maintained its own document implementing the ODMSP, namely NASA Technical Standard 8719.14, Process for Limiting Orbital Debris, Revision B [5] (currently under review for Rev. C). That document provides technical requirements for limiting the creation of long-lived orbital debris that can be a mission-ending threat for generations to come.

Far from limiting CubeSats, NASA encourages their use through Small Business Innovation Research solicitations and through its CubeSat Launch Initiative. NASA is interested in development of small satellite propulsion and power systems, up to 27U, for use in all Earth orbit regimes and beyond. From 2009 to 2019, NASA awarded over $2.1M to Phase I & II studies of CubeSat propulsion systems, and about $3M for studies of electrical power systems [6].

Companies are developing and selling a variety of propulsion and power systems intended for use in

CubeSats. Propulsion products tailored to CubeSats include technologies such as cold gas, warm gas, electrostatic spray, liquid monopropellant, and multiple ion and plasma technologies that use solid, liquid, or gaseous propellant. Propulsion systems require varying amounts of electrical power, and may include pressure vessels and dense metal components. Electrical power generation typically uses solar photovoltaic arrays, either body-mounted or deployed. Power storage typically uses some form of rechargeable lithium-ion battery.

As CubeSat missions expand to include larger, more-capable systems, and move out of lower low Earth orbit (LEO) altitudes (less than about 500 km), the old thought that "it is too small to cause any harm" may no longer apply. The revised ODMSP and its implementations point out that standard debris mitigation assessment methods apply to CubeSats as well as larger spacecraft. Current methods and software tools can and therefore, should be used to assess compliance of CubeSat missions with orbital debris mitigation requirements.

2 CUBESATS AND EXPLOSION PROBABILITY

Projects must take steps to limit the probability of accidental explosion both during and after mission operations. ODMSP Objective 2-1 states that "the integrated probability of debris-generating explosions for all credible failure modes of each spacecraft and upper stage (excluding small particle impacts) is less than 0.001 (1 in 1,000) during deployment and mission operations." Objective 2-2 states that, after operations, "[a]ll on-board sources of stored energy of a spacecraft or upper stage should be depleted or safed when they are no longer required…" NASA's Process for Limiting Orbital Debris applies these Objectives to objects orbiting Earth or the Moon.

Meeting Objective 2-1 usually involves listing the credible failure modes that could lead to a debris-releasing event, then combining the probabilities of each event occurring during the operational period. The project uses known component or assembly failure statistics to perform "failure mode and effects analyses, probabilistic risk assessments, or other appropriate analyses" [5], yielding the integrated probability of explosion. Projects may find it challenging to obtain numerical failure probabilities from suppliers of low-cost, low-volume, or new-technology components. Since explosion during the mission also relates to mission assurance, projects already should be familiar with this process; the explosion probability and threshold are part of the probability of overall mission success.

Objective 2-2, known as post-mission passivation, does not include a probability threshold, but simply the description "depleted or safed." The difficulties encountered by projects with passivation requirements are magnified in CubeSats. Small CubeSat projects may be unaware of the requirements or otherwise neglect to include the hardware, software, and procedures to disconnect solar arrays, permanently deplete batteries, and vent pressure vessels. These additions may also introduce possible new points of failure: inadvertent activation could end the mission.

To date, no known on-orbit breakups of CubeSats have occurred. Exact causes of failure are generally not possible to obtain. Most CubeSat early failures are thought to be related to insufficient rigor in hardware integration and integrated testing, likely the result of cost and schedule pressures and, particularly for educational projects, limited experience [6]. The easiest path to compliance with the accidental explosion requirements is to procure high-quality components or subsystems from a verified supply chain, and complete rigorous pre-launch, test-as-you-fly tests.

If complete depletion/disconnection (hard passivation) is not possible, energy generation and storage should be controlled (soft passivation) "to a level which cannot cause an explosion or deflagration large enough to release orbital debris or break up the spacecraft" [5]. Even demonstrating the "control to a level" approach becomes difficult when CubeSats are larger than 3U, carry more energy (electrical, chemical, and pressure), and operate in longer-lived orbits. In the absence of suitable test data (including hypervelocity test results), projects may turn to components' flight history and similarity. For the small energies remaining at end-of-mission, a project may be able to show that the energy released by a battery or tank explosion will not exceed the structural limits of their spacecraft, or a small-particle impact will not cause a tank or battery explosion.

The CubeSat Design Specification (CDS), created by the California Polytechnic State University and Stanford University, provides a standardized CubeSat template including mechanical, electrical, and testing requirements for CubeSats. The CDS is not a regulatory document, referring the reader to regulatory agencies and the launch service provider for such requirements. CDS revision 13 [7] specifies a limit of 100 Wh for the total chemical energy in a CubeSat, mirroring the U.S. Federal Aviation Administration limit for carry-on, rechargeable Li-ion batteries. The CDS draft revision 14 [8] allows more flexibility in stored energy by changing this specification to a recommendation. While the U.S. Department of Transportation rule [9] limiting Li-ion cells and batteries to no more than 30% state of charge (SOC) is only applied to bulk air cargo, the 30% SOC limit appears as a safety guideline or rule-of-thumb in other arenas. Tests performed by Joshi, et al. [10] show that in some cases thermal runaway of Li-ion cells is possible at 30% SOC. In their range of tests (thermal and external short circuit), 15% was the highest SOC which produced no fire. Disconnection of solar panels is recommended so that discharged batteries do not recharge after the end of mission.

3 CUBESATS AND ORBIT LIFETIME

The end of a productive mission is not the end for orbital debris mitigation; for any mission to be successful, it must plan to safely dispose of any spacecraft or upper stage. ODMSP Objective 4-1 outlines several disposal methods that are in use today, including, for the first time, immediate removal as the preferred option in Objective 4-1.a. This would entail placing the spacecraft on a direct reentry trajectory (or, much less frequently, a heliocentric, Earth-escape trajectory). If a mission cannot budget the resources for this type of postmission disposal, Objective 4-1.b recommends that the orbital lifetime be limited to “as short as practicable but no more than 25 years after completion of mission” (i.e., the 25-year rule).

Few CubeSats are maneuverable, especially when considering the functional requirements for effective collision avoidance (e.g., the ability to apply a delta-V in a short period of time). With the rise of large constellations in LEO, such as the Starlink constellation around 550 km altitude and the planned Kepler constellation around 575 km altitude, CubeSat designers and operators should consider deploying and operating below those zones of high density operations.

CubeSats that deploy to altitudes above about 600 km typically will not be compliant with the well-known 25-year rule and thus need some type of postmission disposal maneuver, be it propulsive or a drag augmentation device such as a drag sail or tether. While these are flight-proven methods of reducing residual orbital lifetime, smallsat mission designers should also consider their potential impact on the overall environment when choosing a mission altitude. Tab. 1 lists common CubeSat form factors, the allowable mass for each form factor (per the latest draft CubeSat standard), and the corresponding area-to-mass ratio.

Table 1. Common CubeSat form factors, masses, and area-to-mass ratios.

Form Factor	Max Mass (kg)	A/m [m^2/kg]
1 U	2.0	7.50E-3
1.5 U	3.0	6.67E-3
2 U	4.0	8.33E-3
3 U	6.0	8.75E-3
6 U	12.0	4.58E-3
12 U	24.0	3.33E-3

With the mass and size of an initial spacecraft design, and an estimated launch date and deployment altitude, a mission designer can estimate the orbital lifetime. The NASA Orbital Debris Program Office (ODPO) has made available to the general public a tool called the Debris Assessment Software (DAS) [11]. Users interested in obtaining DAS need only complete a Software Usage Agreement to download the software free of charge.

DAS uses user-configured parameters such as area-to-mass ratio and initial orbital elements to compute an estimated orbital lifetime for a mission. Fig. 1 depicts the average orbit lifetime of CubeSats with several different form factors, computed using the tools in DAS. The figure shows the dramatic increase in orbital lifetime with initial orbit altitude. The horizontal line in Fig. 1 indicates the 25-year limit for space structure postmission lifetime. While there is a quantitative limit of 25 years for spacecraft and upper stages in LEO, CubeSat (and other smallsat) developers and operators are encouraged to minimize the postmission orbital lifetime to as short as practicable. The previously-mentioned large constellation deployment altitudes of 550 km and 575 km are also included in Fig. 1 as vertical lines; deploying CubeSats below these high-traffic altitudes is recommended, if at all possible.

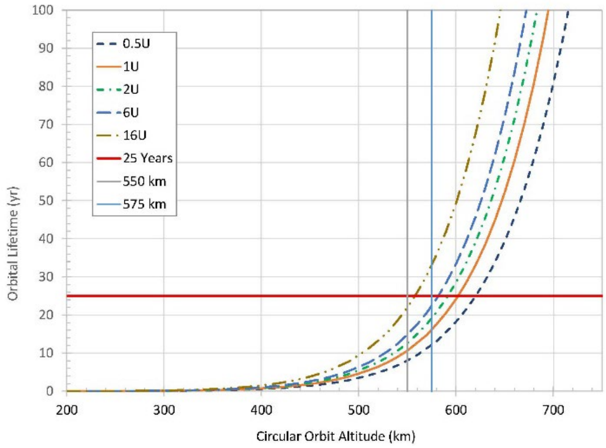

Figure 1. Typical orbit lifetime for CubeSats, as a function of initial circular orbit altitude.

In addition to the simple orbit lifetime limit specified in Objective 4-1, smallsat mission designers should be aware of a new standard practice in the new Objective 5-2: “For spacecraft smaller than 10 cm × 10 cm × 10 cm when fully deployed: […] the total spacecraft object-time product in LEO should be less than 100 object-years per mission.” This means that those missions that deploy femtosats or RFID tags must ensure that the lifetime of each object is short enough that the total object-time product does not exceed the 100-year limit. For example, a mission deploying 100 independent femtosats would need to ensure that each of the smaller objects has an orbit lifetime of 1 year or less.

4 REENTRY CASUALTY RISK

Another element of the orbital debris mitigation standard practices applies to CubeSat missions: the limiting of reentry human casualty risk to no more than 1:10,000 per mission. This is a design requirement and DAS can be used to analyze the reentry survivability of spacecraft components and assess the compliance of a mission with the casualty risk requirement.

Reentry analyses in DAS can be performed by anyone, but some aspects can be challenging, even for experienced users. Following the practices listed below will ensure the best results for DAS reentry analysis and is the best way to demonstrate compliance.

- Ensure that all components with masses greater than 15 grams are included in the parts list, regardless of material composition.
    - DAS version 3 can model up to 2500 unique components in a single run, allowing the simultaneous analysis of, for example, up to 100 CubeSats, each with 25 components. Missions with large numbers of satellites and components should note that the *reentry.csv* file can be edited manually in Excel and then loaded by DAS for a potentially easier workflow.
- Components that have one dimension that is much smaller than the other two should be modeled as flat plates.
    - For example, an object that is 0.5 m × 0.5 m × 0.05 m in size (approximately 10 times larger in two dimensions than in the third) should be a flat plate, not a box. On the other hand, an object 0.5 m × 0.5 m × 0.1 m in size (a ratio of around 5:1) may be better as a box.
- Components with two dimensions that are similar and one that is ~1.5 times larger should be modeled as a cylinder.
    - Most components will end up tumbling during reentry; square tubes will appear somewhat circular in terms of aeroheating and drag under these conditions. Even moderately non-square components may be best modeled as cylinders with the same hydraulic diameter (4×area/perimeter)
    - If an object has all three dimensions similar in magnitude, it is best modeled as a box, or potentially even a sphere.

Some CubeSat missions may find that their initial design is not compliant with the ground casualty risk requirement. In this case, two techniques can be used to move the design toward compliance. The first technique is “design for demise,” whereby components that survive reentry are swapped out for others that are made of materials that can still meet the mission objectives but will demise during reentry (e.g., instead of using carbon fiber, stainless steel, titanium, or tungsten, use fiberglass, aluminum or copper).

The second technique is “design for minimum casualty area”: if the components cannot be replaced by demisable ones with similar functionality, then designers can reduce the risk by joining components that survive into a larger, surviving assembly. An example of this could be a battery box with multiple cells, each of which survive with sufficient kinetic energy to pose a risk to the ground population; if the battery box is made of steel (or another high-temperature material) such that the box survives reentry, the total area contributing to casualty risk is reduced to the area of the box.

DAS can be used to explore both these strategies for ground casualty risk mitigation, through iterative design and analysis of spacecraft components. Designers should strongly consider performing this design and analysis activity early in the design process, when it is easiest and less expensive to make significant changes.

5 SUMMARY AND FUTURE DEVELOPMENTS

The development and adoption of the 2019 Update to the U.S. Government Orbital Debris Mitigation Standard Practices reflects the new era of spaceflight we are in, as well as an acknowledgment of the new classes of spacecraft operators. The new Objective 5 “Clarification and Additional Standard Practices for Certain Classes of Space Operations” establishes explicit guidelines for CubeSat (and other smallsat) operators for the first time, recognizing the challenges and opportunities inherent in their missions.

Since the establishment of the updated ODMSP in 2019, agencies throughout the U.S. government have begun to implement them through standards, instructions, and regulation. These implementations have already begun, with the Federal Communications Commission enacting new rules on orbital debris in April of 2020 [12], and other bodies such as the Department of Defense, NASA, and the FAA updating their documents soon. While the lower-level technical documents are being updated, further changes in operational practices or in the debris environment may still spur another update to the ODMSP in the future.

CubeSat designers and operators should be vigilant in the pre-launch testing, verification, and validation of their systems and subsystems to ensure both a successful mission and good stewardship of the orbital environment. In addition to building reliable spacecraft, designers and operators should analyze their mission plans to ensure they do not contribute to collision risk in high-traffic areas of near-Earth orbit, such as near (or above) altitudes of large constellation deployments or crewed space structures.

Freely-available guides such as the CubeSat Design Specification, and software tools such as the NASA DAS allow CubeSat designers to evaluate their compliance with the standard practices discussed here, as well as guide future missions in guaranteeing responsible spaceflight.

6 REFERENCES

1. U.S. Government Orbital Debris Mitigation Standard Practices (2001). Washington, D.C.
2. Space Policy Directive 3: National Space Traffic Management Policy (2018) Washington, D.C.
3. Nanosats Database [Online]. Available: nanosats.eu. [Accessed 23 February 2021].
4. U.S. Government Orbital Debris Mitigation Standard Practices, November 2019 Update (2019). Washington, D.C.,
5. Process for Limiting Orbital Debris, NASA-STD-8719.14B (2019) National Aeronautics and Space Administration, Washington, D.C.
6. Swartwout, M. (2020). CubeSat Mission Assurance Trends. In *2020 NEPP Electronics Technology Workshop*, Greenbelt, MD
7. CubeSat Design Specification, rev. 13 (2014). California Polytechnic State University, San Luis Obispo, CA
8. CubeSat Design Specification, rev. 14 DRAFT (2020) California Polytechnic State University, San Luis Obispo, CA
9. Hazardous Materials: Enhanced Safety Provisions for Lithium Batteries Transported by Aircraft, *49 CFR 173* (2019). Department of Transportation, Washington, D.C.
10. Joshi, T., Azam, S., Lopez, C., Kinyon, S., and Jeevarajan, J. (2020). Safety of Lithium-Ion Cells and Batteries at Different States-of-Charge, *Journal of the Electrochemical Society,* **167**(14)
11. "Debris Assessment Software, version 3.1.2," (2021) NASA: https://software.nasa.gov/software/MSC-26690-1.
12. "Orbital Debris in the New Space Age, Report and Order and Further Notice of Proposed Rulemaking," (2020) Federal Communication Commission, Washington, D.C.