May 14, 2013

Orbital Debris Assessment for
SporeSat on the
CRS SpX-3 / ELaNa-5 Mission
per NASA-STD 8719.14A

Sensitive But Unclassified (SBU)

REFERENCES:

A. *NASA Procedural Requirements for Limiting Orbital Debris Generation*, NPR 8715.6A, 5 February 2008
B. *Process for Limiting Orbital Debris*, NASA-STD-8719.14A, 25 May 2012
C. *P-POD Status SpX-3 Agreement History* (Orbital Information), ISS_CM_019 Rev 01/2011
D. McKissock, Barbara, Patricia Loyselle, and Elisa Vogel. *Guidelines on Lithium-ion Battery Use in Space Applications*. Tech. no. RP-08-75. NASA Glenn Research Center Cleveland, Ohio
E. *UL Standard for Safety for Lithium Batteries, UL 1642*. UL Standard. 4th ed. Northbrook, IL, Underwriters Laboratories, 2007
F. Kwas, Robert. Thermal Analysis of ELaNa-4 CubeSat Batteries, ELVL-2012-0043254; Nov 2012
G. Range Safety User Requirements Manual Volume 3- Launch Vehicles, Payloads, and Ground Support Systems Requirements, AFSCM 91-710 V3.
H. *UL Standard for Safety for Household and Commercial Batteries, UL 2054*. UL Standard. 2nd ed. Northbrook, IL, Underwriters Laboratories, 2005
I. Opiela, John. "RE: DAS 2.0 Orbital Lifetime Inquiry" April 5, 2013. E-mail.

The intent of this report is to satisfy the orbital debris requirements listed in ref. (a) for the SporeSat CubeSat on the ELaNa-5 auxiliary mission launching in conjunction with the SpX-3 primary payload. Sections 1 through 8 of ref. (b) are addressed in this document; sections 9 through 14 fall under the requirements levied on the launch vehicle compliance assessment and are not presented here.

The following table summarizes the compliance status of the SporeSat CubeSat as part of the ELaNa-5 auxiliary payload mission flown on SpX-3. This mission is fully compliant with all applicable requirements.

Table 1: Orbital Debris Requirement Compliance Matrix

Requirement	Compliance Assessment	Comments
4.3-1a	Compliant	Lifetime of debris is days
4.3-1b	Compliant	Lifetime of debris is days
4.3-2	Not applicable	No planned debris release
4.4-1	Compliant	On board energy source (batteries) incapable of debris-producing failure
4.4-2	Compliant	On board energy source (batteries) incapable of debris-producing failure
4.4-3	Not applicable	No planned breakups
4.4-4	Not applicable	No planned breakups
4.5-1	Compliant	
4.5-2	Not applicable	
4.6-1(a)	Compliant	Worst case lifetime 0.2yrs
4.6-1(b)	Not applicable	
4.6-1(c)	Not applicable	
4.6-2	Not applicable	
4.6-3	Not applicable	
4.6-4	Not applicable	Passive disposal
4.6-5	Compliant	
4.7-1	Compliant	Non-credible risk of human casualty
4.8-1	Compliant	No planned tether release

Section 1: Program Management and Mission Overview

The ELaNa-5 mission is sponsored by the Space Operations Mission Directorate at NASA Headquarters. The Program Executive is Jason Crusan. Responsible program/project manager and senior scientific and management personnel are as follows:

SporeSat: Andres Martinez, Project Manager

Table 2: Program Milestone Schedule

Program Milestone Schedule	
Task	**Date**
CubeSat Selection	7/1/12
CubeSat Build, Test, and Integration	July 2012 to July 2013
MRR	7/23/13
CubeSat Delivery/integration at Cal Poly	9/16/12
P-POD Integration into LV	10/28/13
Launch	12/9/13

The ELaNa-5 mission will deploy 5 pico-satellites (or CubeSats) as a secondary payload on the mission. The ELaNa-5 mission will be launched as an auxiliary payload on the SpX-3 mission on a Falcon 9 launch vehicle from Cape Canaveral Air Force Station. The current launch date is in December 2013. The five CubeSats will be ejected from a P-POD carrier attached to the launch vehicle, placing the CubeSats in an orbit approximately 325 X 325 km at inclination of 51.6 deg (ref. (c)).

Section 2: Spacecraft Description - SporeSat

SporeSat's objectives are to gain deeper knowledge of the mechanism of cell gravity sensing by studying the activation of plant gravity sensing and electrophysical signaling in a single-cell model system (*Ceratopteris richardii*) using a "lab-on-a-chip" microsensor technology platform.

Upon deployment from the P-POD, SporeSat will deploy antennae and the beacon will be activated. The spacecraft will stabilize for up to 15 days then execute the experiment, which will last approximately 96 hours. Data download will continue after experiment is complete.

The SporeSat structure is made of Al 2024. It contains all standard commercial off the shelf (COTS) materials, electrical components, PCBs and solar cells. The high-speed radio uses a ceramic patch antenna. Titanium fasteners are present in the design; see Section 7 for reentry analysis.

SporeSat incorporates a 1 atm container of integration phase retained air, critical to the science objectives. The maximum expected temperature of 136°F (ref. (f)) produces 16 psia on orbit, based on a 1 atm integration pressure. Successful heritage flights, GeneSat-1 and PharmaSat, and ground testing to 22 psia in a vacuum chamber for 24 hrs have demonstrated this container design poses no credible risk of debris producing ruptures. SporeSat contains no hazardous or exotic materials.

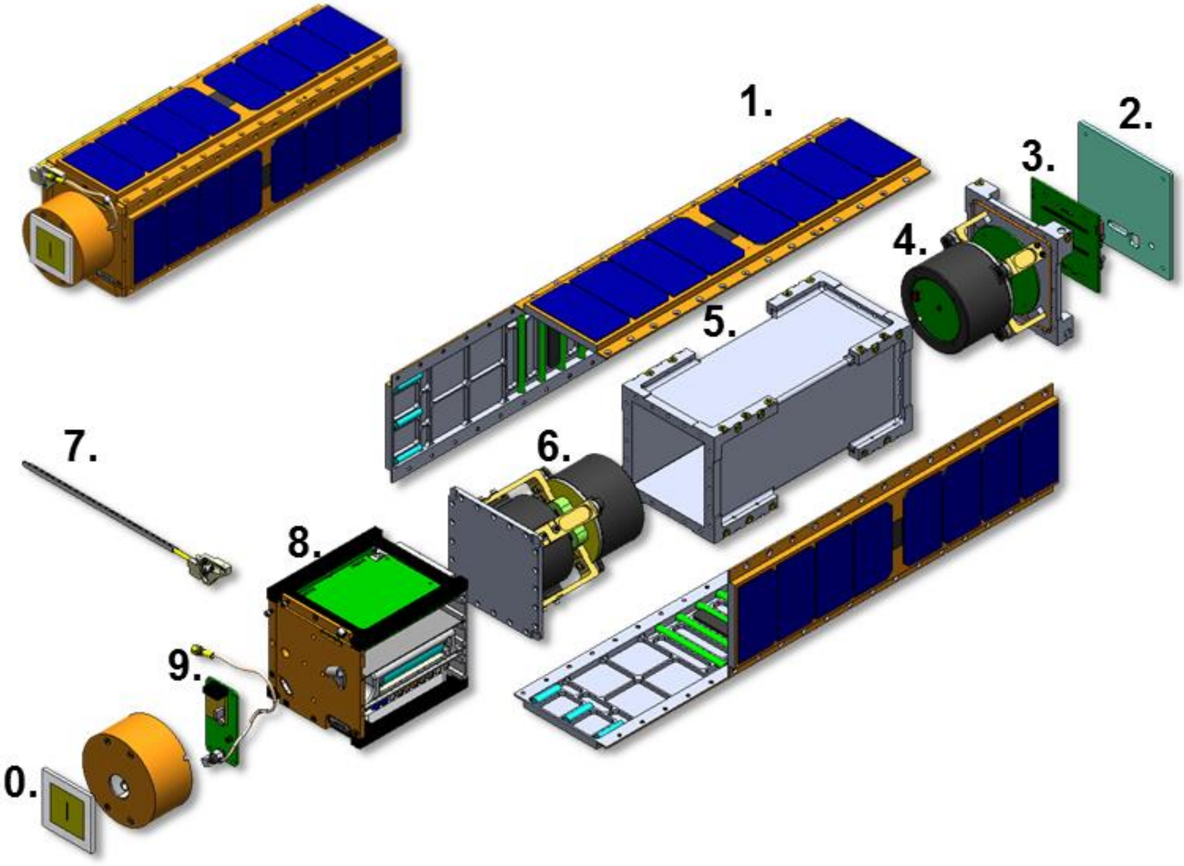
The electrical power storage system consists of common lithium-ion batteries with over-charge/current protection circuitry. The lithium batteries carry the UL-listing number MH12210.

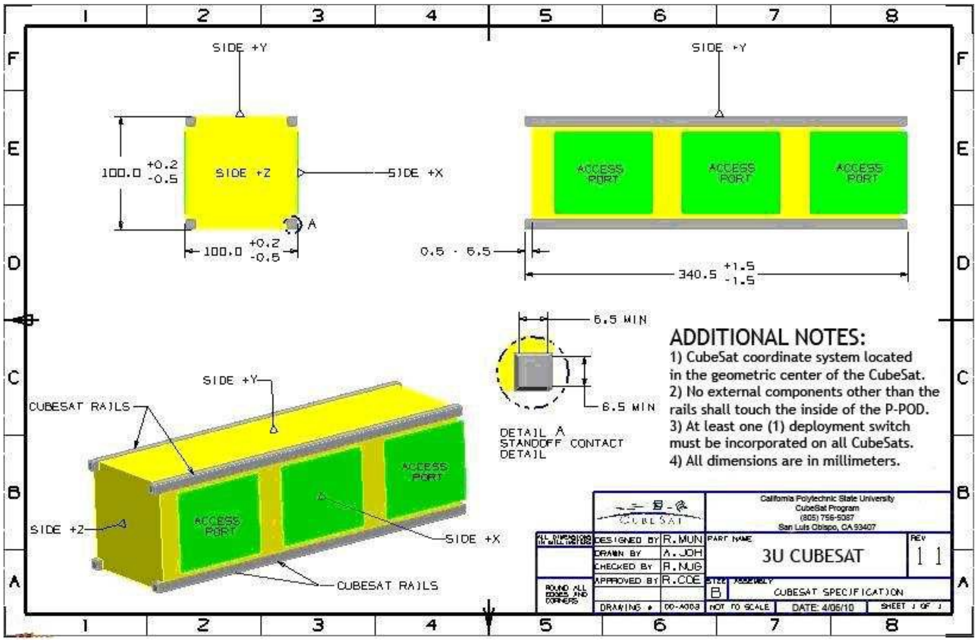
Table 3: ELaNa-5 CubeSats

CubeSat Quantity	CubeSat size	CubeSat Names	CubeSat Masses (kg)
1	1U (10 cm X 10 cm X 30 cm)	SporeSat	5.3

SporeSat CubeSat Description
NASA Ames Research Center – 3U

1. Solar Body Panels 4ea.
2. Close Out Panel
3. Bus Interface PCB
4. Front Panel Assembly
5. Atmospheric Pressure Enclosure
6. Back Panel Assembly
7. Transponder Antenna
8. Avionics Bus
9. Transponder PCB
10. Patch Antenna





ADDITIONAL NOTES:

1) CubeSat coordinate system located in the geometric center of the CubeSat.
2) No external components other than the rails shall touch the inside of the P-POD.
3) At least one (1) deployment switch must be incorporated on all CubeSats.
4) All dimensions are in millimeters.

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ALL DIMENSIONS IN MILLIMETERS
DESIGNED BY R. MUN
DRAWN BY A. JOH
CHECKED BY R. NUG
APPROVED BY R. COE
ROUND ALL EDGES AND CORNERS
DRAWING # 00-A008
PART NAME 3U CUBESAT
REV 11
SIZE B
ASSEMBLY CUBESAT SPECIFICATION
NOT TO SCALE
DATE: 4/05/10
SHEET 1 OF 1

Figure 2: 3U CubeSat Specification

Section 3: Assessment of Spacecraft Debris Released during Normal Operations

Section 3 provides rationale/necessity for release of each object, time of release of each object relative to launch vehicle separation, release velocity of each object with respect to CubeSat, 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), and an assessment of spacecraft compliance with Requirements 4.3-1 and 4.3-2.

No releases are planned on the SporeSat mission therefore this section is not applicable.

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

Malfunction of lithium ion or lithium polymer batteries and/or associated control circuitry has been identified as a potential cause for spacecraft breakup during deployment and mission operations.

While no passivation of batteries will be attempted, natural degradation of the solar cell and battery properties will occur over the post mission period, which may be as long as 0.2 years. These conditions pose a possible increased chance of undesired battery energy release. The battery capacity for storage will degrade over time, possibly leading to changes in the acceptable charge rate for the cells. Individual cells may also change properties at different rates due to time degradation and temperature changes. The control circuit may also malfunction as a result of exposure to the space environment over long periods of time. The cell pressure relief vents could be blocked by small contaminants. Any of these individual or combined effects may theoretically cause an electro-chemical reaction that result in rapid energy release in the form of combustion.

There are NO plans for designed spacecraft breakups, explosions, or intentional collisions on the SporeSat mission.

Section 4 asks for a list of components, which shall be passivated at End of Mission (EOM), as well as the method of passivation and description of the components, which cannot be passivated. No passivation of components is planned at the End of Mission for SporeSat.

Since the batteries used do not present a debris generation hazard even in the event of rapid energy release (see assessment directly below), passivation of the batteries is not necessary in order to meet the requirement 4.4-2 (56450) for passivation of energy sources “to a level which cannot cause an explosion or deflagration large enough to release orbital debris or break up the spacecraft.” Because passivation is not necessary, and in the interest of not increasing the complexity of the CubeSat, there was no need to add this capability to the electrical power generation and storage systems.
Assessment of spacecraft compliance with Requirements 4.4-1 through 4.4-2 shows that the SporeSat is compliant. Requirements 4.4-3 and 4.4-4, addressing intentional break-ups are not applicable.

The following addresses requirement 4.4-2. The CubeSats that have been selected to fly on the SpX-3 mission have not been designed to disconnect their onboard storage energy devices (lithium ion and lithium polymer batteries). However, the CubeSat’s batteries still meet Req. 56450 by virtue of the fact that they cannot “cause an explosion or deflagration large enough to release orbital debris or break up the spacecraft”.

Table 4: SporeSat Battery Cells

CubeSat	Technology	Manufactor	Model	UL Listing Number
Sporesat	Lithium Ion	Panasonic	CGR 18650	MH12210

The batteries are all consumer-oriented devices. All battery cells have been recognized as Underwriters Laboratories (UL) tested and approved. Furthermore, safety devices incorporated in these batteries include pressure release valves, over current charge protection and over current discharge protection.

The fact that these batteries are UL recognized indicates that they have passed the UL standard testing procedures that characterize their explosive potential. Of particular concern to NASA Req. 56450 is UL Standard 1642, which specifically deals with the testing of lithium batteries. Section 20 Projectile Test of UL 1642 (ref. (e)) subjects the test battery to heat by flame while within an aluminum and steel wire mesh octagonal box, “[where the test battery] shall remain on the screen until it explodes or the cell or battery has ignited and burned out” (UL 1642 20.5). To pass the test, “no part of an exploding cell or battery shall penetrate the wire screen such that some or all of the cell or battery protrudes through the screen” (UL 1642 20.1).

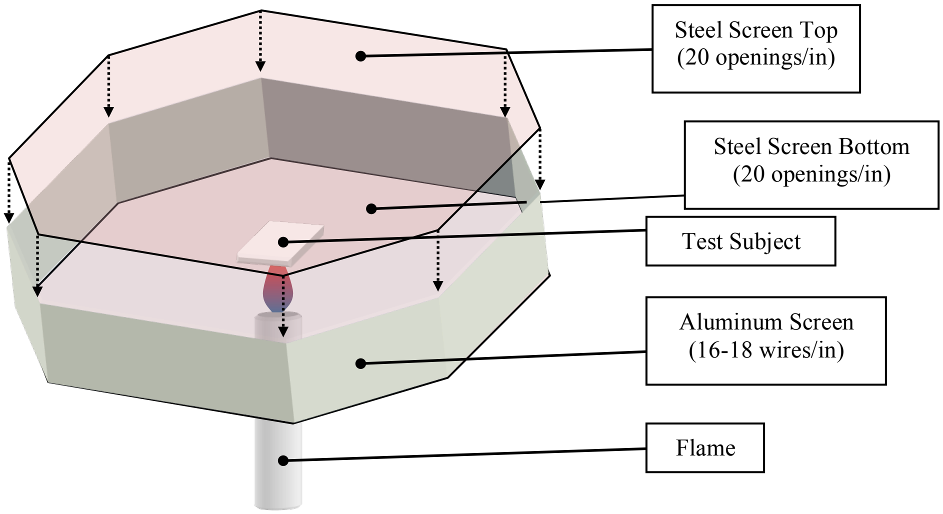

Figure 3: Underwriters Laboratory Explosion Test Apparatus

The batteries being launched via CubeSat will experience conditions on orbit that are generally much less severe that those seen during the UL test. While the source of failure would not be external heat on orbit, analysis of the expected mission thermal environment performed by NASA LSP Flight Analysis Division shows that given the very low power dissipation for CubeSats, the batteries will be exposed to a maximum temperature that is well below their 212^{o}F safe operation limit (ref. (f)). It is unlikely but possible that the continual charging with 2 to 6 W of average power from the solar panels over an orbital life span greater than 2 years may expose the two to four batteries (per CubeSat) to overcharging which could cause similar heat to be generated internally. Through the UL testing, it has been shown that these batteries do not cause an explosion that would cause a fragmentation of the spacecraft.

A NASA Glenn Research Center guideline entitled Guidelines on Lithium-ion Battery Use in Space Applications (ref. (d)) explains that the hazards of Li-Ion cells in an overcharge situation result in the breakdown of the electrolyte found in Li-ion cells causing an increase in internal pressure, formation of flammable organic solvents, and the release of oxygen from the metal oxide structure. From a structural point of view a battery in an overcharge situation can expect breakage of cases, seals, mounting provisions, and internal components. The end result could be “unconstrained movement of the battery” (ref. (d), pg 13). This document clearly indicates that only battery deformation and the escape of combustible gasses will be seen in an overcharging situation, providing further support to the conclusion that CubeSat fragmentation due to explosion is not a credible scenario for this application. It is important to note that the NASA guide to Li-ion batteries makes no mention of these batteries causing explosions of any magnitude whatsoever.

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 takes into account both the mean cross sectional area and orbital lifetime.

The largest mean cross sectional area (CSA) of SporeSat is in the antenna-deployed configuration (maximum width of 29.1 cm with a total length of 38.3 cm):

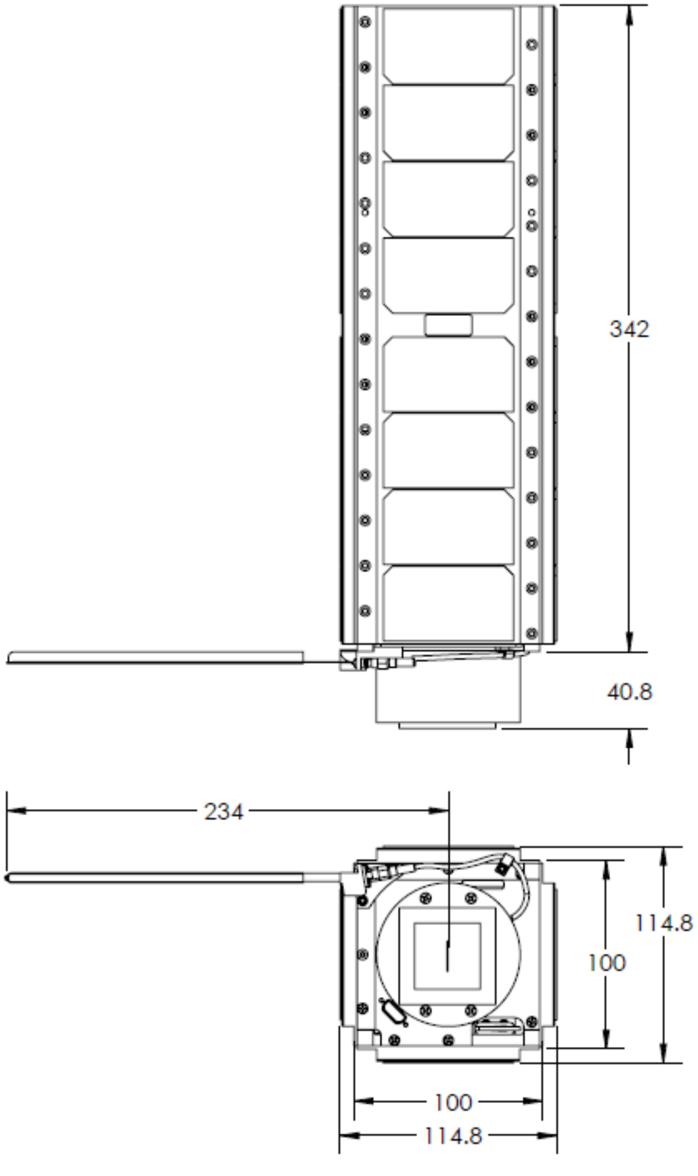

Figure 4: SporeSat deployed configuration (units in mm)

$$Mean\ CSA = \frac{\sum Surface\ Area}{4} = \frac{[2*(w*l)+4*(w*h)]}{4}$$

Equation 1: Mean Cross Sectional Area for Convex Objects

$$\boldsymbol{Mean\ CSA} = \frac{(\boldsymbol{A_{max}} + \boldsymbol{A_1} + \boldsymbol{A_1})}{\mathbf{2}}$$

Equation 2: Mean Cross Sectional Area for Complex Objects

All CubeSats evaluated for this ODAR are stowed in a convex configuration, indicating there are no elements of the CubeSats obscuring another element of the same CubeSats from view. Thus, mean CSA for all stowed CubeSats was calculated using Equation 1. This configuration renders the longest orbital life times for all CubeSats.

Once a CubeSat has been ejected from the P-POD and deployables have been extended Equation 2 is utilized to determine the mean CSA. A_{max} is identified as the view that yields the maximum cross-sectional area. A_1 and A_2 are the two cross-sectional areas orthogonal to A_{max}. Refer to Figure 4 for dimensions used in these calculations

The SporeSat orbit at deployment is 325 km apogee altitude by 325 km perigee altitude, with an inclination of 51.6 degrees. With an area to mass (5.3 kg) ratio of $0.0091 m^2/kg$, DAS yields 0.2 years for orbit lifetime for its stowed state, which in turn is used to obtain the collision probability. Even with the variation in CubeSat design and orbital lifetime ELaNa-5 CubeSats see an average of $10^{-9.2}$ probability of collision. In the deployed configuration the highest probability of collision of $10^{-8.9}$. **Table 5** below provides complete results.

Table 5: SporeSat Orbital Lifetime & Collision Probability

CubeSat	SporeSat
Mass (kg)	5.3

Stowed	**Mean C/S Area (m^2)**	0.0481
	Area-to Mass (m^2/kg)	0.0091
	Orbital Lifetime (yrs)	0.2
	Probability of collision (10^X)	-8.9

Deployed	**Mean C/S Area (m^2)**	0.0523
	Area-to Mass (m^2/kg)	0.0099
	Orbital Lifetime (yrs)	0.1
	Probability of collision (10^X)	-9.15

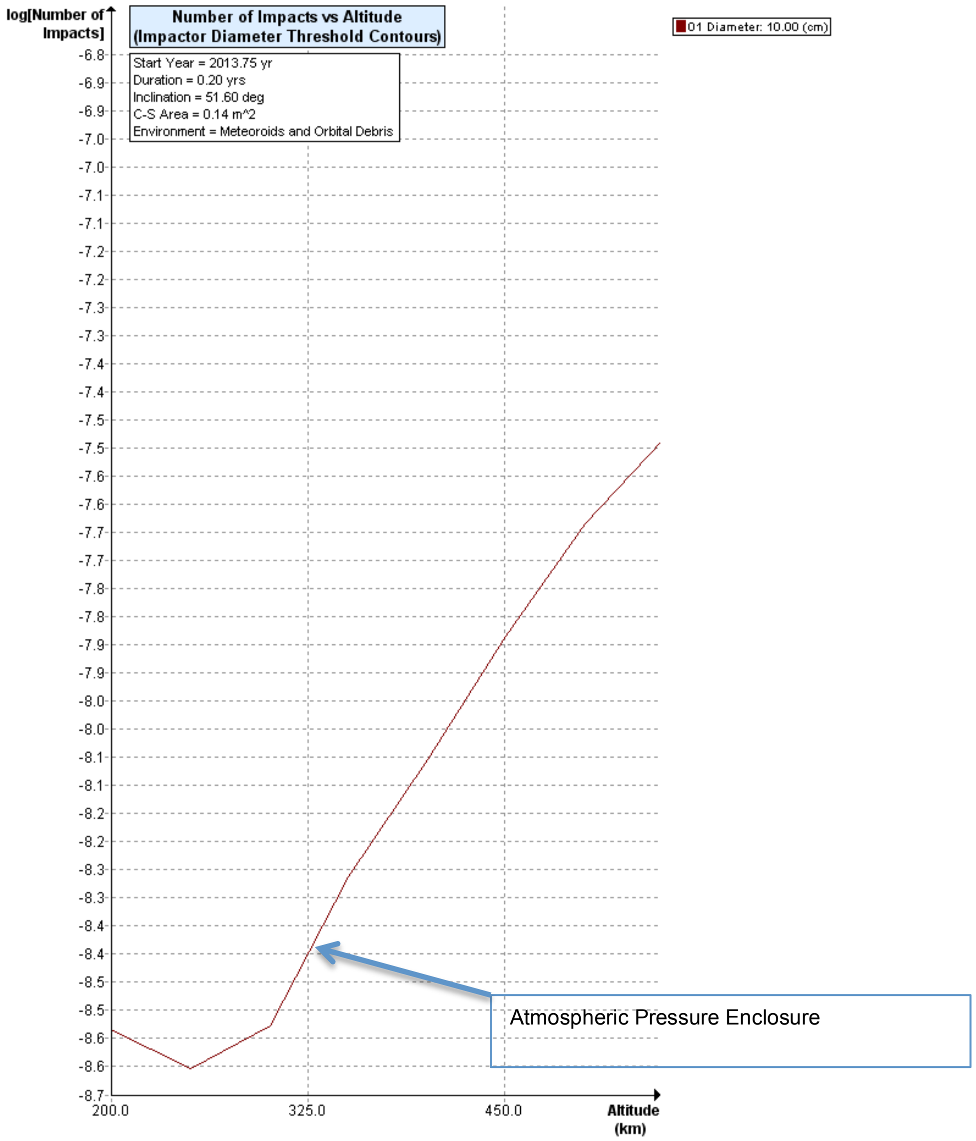

Figure 5: Highest Risk of Orbit Collision vs. Altitude (ALL-STAR/THEIA Deployed)

There will be no post-mission disposal operation. As such the identification of all systems and components required to accomplish post-mission disposal operation, including passivation and maneuvering, is not applicable.

The probability of SporeSat collision with debris and meteoroids greater than 10 cm in diameter and capable of preventing post-mission disposal is less than $10^{-8.9}$, for any configuration. This satisfies the 0.001 (10^{-6}) maximum probability requirement 4.5-1.

Since the CubeSats have no capability or plan for end-of-mission disposal, requirement 4.5-2 is not applicable.

Assessment of spacecraft compliance with Requirements 4.5-1 shows SporeSat to be compliant. Requirement 4.5-2 is not applicable to this mission.

Section 6: Assessment of Spacecraft Postmission Disposal Plans and Procedures

SporeSat will naturally decay from orbit within 25 years after end of the mission, satisfying requirement 4.6-1a detailing the spacecraft disposal option.

Planning for spacecraft maneuvers to accomplish postmission disposal is not applicable. Disposal is achieved via passive atmospheric reentry.

Calculating the area-to-mass ratio for the worst-case (smallest Area-to-Mass) post-mission disposal is calculated for is as follows:

$$\frac{\boldsymbol{Mean\ {}^{C}/_{S}\,Area\ (m^2)}}{\boldsymbol{Mass\ (kg)}} = \boldsymbol{Area - to - Mass\ (\frac{m^2}{kg})}$$

Equation 3: Area to Mass

$$\frac{0.0214m^2}{2.8\,kg} = 0.0076\frac{m^2}{kg}$$

DAS 2.0.2 Orbital Lifetime Calculations:

DAS inputs are: 325 km maximum perigee X 325 km maximum apogee altitudes with an inclination of 51.6 degrees at deployment in the year 2013. An area to mass ratio of 0.0076 m^2/kg..

Assessment results show compliance of SporeSat. This meets requirement 4.6-1. For the SporeSat orbital lifetime reference **Table 5**.

Section 7: Assessment of Spacecraft Reentry Hazards

A detailed assessment of the components to be flown on SporeSat was performed. The assessment used DAS 2.0, a conservative tool used by the NASA Orbital Debris Office to verify Requirement 4.7-1. The analysis is intended to provide a bounding analysis for characterizing the survivability of a CubeSat's component during re-entry. For example, when DAS shows a component surviving reentry it is not taking into account the material ablating away or charring due to oxidative heating. Both physical effects are experienced upon reentry and will decrease the mass and size of the real-life components as the reenter the atmosphere, reducing the risk they pose still further.

The following steps are used to identify and evaluate a components potential reentry risk relative to the 4.7-1 requirement of having less than 15 J of kinetic energy and a 1:10,000 probability of a human casualty in the event the survive reentry.

1. Low melting temperature (less than 1000 °C) components are identified as materials that would never survive reentry and pose no risk to human casualty. This is confirmed through DAS analysis that showed materials with melting temperatures equal to or below that of copper (1080 °C) will always demise upon reentry for any size component up to the dimensions of a 1U CubeSat.
2. The remaining high temperature materials are shown to meet the human casualty requirement through a bounding DAS analysis of the highest temperature components, generally stainless steel (1500°C). A component of similar dimensions and possessing a melting temperature between 1000 °C and 1500°C, can be expected to posses as negligible risk similar to stainless steel components. Probability of human casualty was calculated if a component exceeded 15J of energy upon reentry. See Table 6.

The SporeSat mission complies with Requirement 4.7-1, to have less than 1:10,000 risk of human casualty.

SporeSat has fasteners constructed out of titanium that have essentially zero joules of energy upon reaching the Earth's surface.

The majority of high temperature components demise upon reentry. The components that DAS conservatively identifies as reaching the ground have less than 15 joules of kinetic energy. No high temperature component will pose a risk to human casualty as defined by the Range Commander's Council (ref. (g)).

As documented in, Table 6, and the Appendix, the SporeSat mission is conservatively shown to be in compliance with Requirement 4.7-1 of NASA-STD-8719.14A.

See Appendix for a complete accounting of the survivability of SporeSat components.

Table 6: SporeSat Survivability DAS Analysis

CubeSat	ELaNa-5 Stainless Steel Components	Mass (g)	Length / Diameter (cm)	Width (cm)	Height (cm)	Demise Alt (km)	KE (J)
SporeSat	Patch Antennae	20.0	2.00	5.12	5.12	0	3
SporeSat	Beacon Antennae	1.4	0.14	2.37	20.70	0	<1 J
SporeSat	Sep Switch	5.0	0.50	2.05	1.50	0	1
SporeSat	Magnets	5.9	0.59	0.64	2.54	75	0
SporeSat	Hysteresis rods	21.8	2.18	0.64	7.00	74.8	0
SporeSat	Titanium Fasteners*	0.3	0.03	0.25	1.00	0	< 1J

Note: Components are modeled as stainless steel unless otherwise noted in component name.

Section 8: Assessment for Tether Missions

ELaNa-5 CubeSats will not be deploying any tethers.

ELaNa-5 CubeSats satisfy requirement 4.8-1.

Section 9-14

ODAR sections 9 through 14 for the launch vehicle are addressed in ref. (g), and are not covered here.

If you have any questions, please contact the undersigned at:

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Appendix Index:

Appendix A. ELaNa-5 Component List by CubeSat: SporeSat

CubeSat	Row Number	Name	External/Internal (Major/Minor Components)	Qty	Material	Body Type	Mass (g)	Diameter/ Width (mm)	Length (mm)	Height (mm)	Low Melting	Melting Temp (C)	Comment
SporeSat	1	SporeSat	External - Major	1	Aluminum 6061	Box	5300	115.32	382.78	113.22	Yes		Demises
SporeSat	2	Solar Panel Body	External - Major	4	AL6061	Panel	233	96.8	338	7.2	Yes		Demises
SporeSat	3	Beacon Can	External - Major	1	AL6061	Cylinder		76.2	38		Yes		Demises
SporeSat	4	Patch Antennae	External - Major	1	Ceramic	wafer	19.96	51.18	51.18	3.18	No	1400	
SporeSat	5	Beacon Antennae	External - Major	1	Steel	Strip	1.36	23.74	207	12.27	No	1500	
SporeSat	6	Sep Switch	External - Minor	1	Plastic/Steel	Box	4.99	20.5	15	6.6	No	1500	Negligable Risk
SporeSat	7	Atm Pressure Enclosure	Internal - Major	1	AL2024	Box	665	96	206.4	96	Yes		Demises
SporeSat	8	Avionics Bus	Internal - Major	1	AL/FR-4	Box	1771	97	153	97	Yes		Demises
SporeSat	9	Front Panel Assembly	Internal - Major	1	AL/FR-4	Box/Cylinder	383	96	102.6	96	Yes		Demises
SporeSat	10	Back Panel Assembly	Internal - major	1	AL/FR-4	Box/Cylinder	617	94	118	94	Yes		Demises
SporeSat	11	Batteries	Internal - Major	8	Li-ion	Cylinder	45	18.34	65		Yes		Demises
SporeSat	12	Magnets	Internal - Major	24	NdFeB	Cylinder	5.90	6.35	25.4		No	1300	Demises See **Error! Reference source not found.**
SporeSat	13	Hysteresis rods	Internal - Major	16	HyMu80	Cylinder	21.77	6.35	70		No	1454	Demises See **Error! Reference source not found.**
SporeSat	14	ISM Board	Internal - Major	1	FR-4	Board		53	89	15	Yes		Demises
SporeSat	15	Beacon Board	Internal - Major	1	FR-5	Board		32	67	13	Yes		Demises
SporeSat	16	C&DH Board	Internal - Major	1	FR-4	Board		85	107		Yes		Demises
SporeSat	17	Fasteners	Internal - Minor	48	Titanium	Cylinder	0.26	2.5	10		No	1670	**Error! Reference source not found.**
SporeSat	18	Cabling	Internal - Minor	AR	Copper alloy	Cylinder					Yes		Demises