Orbital Debris Assessment for The SGSat CubeSat per NASA-STD 8719.14A

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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. 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
D. *UL Standard for Safety for Lithium Batteries, UL 1642*. UL Standard. 4th ed. Northbrook, IL, Underwriters Laboratories, 2007
E. *Range Safety User Requirements Manual Volume 3- Launch Vehicles, Payloads, and Ground Support Systems Requirements*, AFSCM 91-710 V3.
F. *UL Standard for Safety for Household and Commercial Batteries, UL 2054*. UL Standard. 2nd ed. Northbrook, IL, Underwriters Laboratories, 2005.
G. *Common Risk Criteria Standards for National Test Ranges*, Standard 321-10, December 2010.

The intent of this report is to satisfy the orbital debris requirements listed in ref. (a) for the SGSat CubeSat. Sections 1 through 8 of ref. (b) are addressed in this document; sections 9 through 14 fall under the requirements levied on the Department of Defense's Operationally Responsive Space Office and are not presented here.

The following table summarizes the compliance status of the SGSat CubeSat. SGSat is fully compliant with all applicable requirements.

Table 1: Orbital Debris Requirement Compliance Matrix

Requirement	Compliance Assessment	Comments
4.3-1a	Not applicable	No planned debris release
4.3-1b	Not applicable	No planned debris release
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 1.22 yrs
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

SGSat will be launching on the SpaceX CRS 10 mission; payload integration and coordination is being provided by NanoRacks LLC (NR).

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Program Milestone Schedule	
Task	Date
CubeSat Build, Test, and Integration	8/1/15 through 7/10/16
Pre-Ship Review	8/2/16
CubeSat Delivery to NR	9/2/16
Launch	11/21/16

Figure 1: Program Milestone Schedule

After ejection from the Nanoracks CubeSat Deployer (NRCSD), SGSat will be placed into an orbit approximately 403 x 404 km at an inclination of 51.6 deg.

Section 2: Spacecraft Description

Table 2: Basic CubeSat Physical Description

CubeSat Quantity	CubeSat size	CubeSat Name	CubeSat Mass (kg)
1	1U (10 cm X 10 cm X 10 cm)	SGSat	1.2

SGSat CubeSat Description
University of Kentucky – 1U

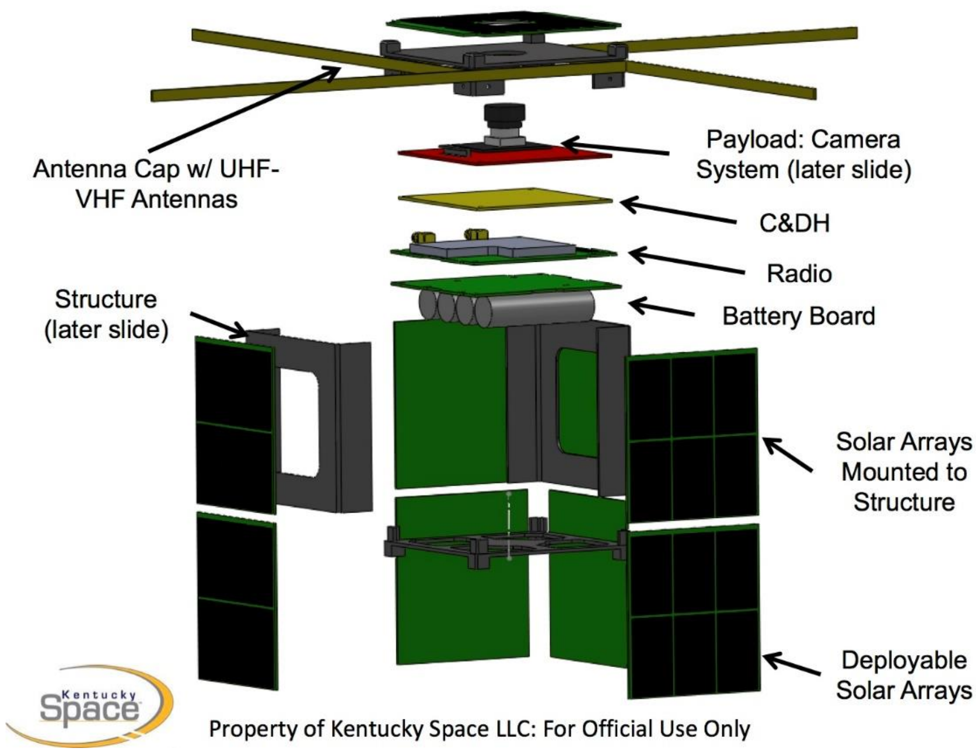

Figure 2:SGSat Expanded View

SGSat is a technology demonstrator that builds upon the resources developed for the KySat-2 mission. SGSat will validate a stellar gyro attitude determination system. SGSat will feature upgraded components developed by University of Kentucky.

Following deployment from NRCSD, the SGSat CubeSat will wait 30 minutes then release its deployable solar arrays and antenna. After 45 minutes the autonomous beacon will turn on, allowing ground stations to track and attempt to differentiate between the other objects.

The primary CubeSat structure is made of Aluminum 6061. It contains all standard commercial off the shelf (COTS) materials, electrical components, PCBs and solar cells.

There are no pressure vessels, hazardous or exotic materials.

The electrical power storage system consists of common lithium-ion batteries with over-charge/current protection circuitry. See Table 3: SGSat CubeSat Cells for UL Listing.

Section 3: Assessment of Spacecraft Debris Released during Normal Operations

The assessment of spacecraft debris requires the identification of any object (>1 mm) expected to be released from the spacecraft any time after launch, including object dimensions, mass, and material.

The section 3 requires 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), and an assessment of spacecraft compliance with Requirements 4.3-1 and 4.3-2.

No releases are planned on the SGSat CubeSat 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 2.5 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 SGSat 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 the SGSat CubeSat.

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 CubeSats, there was no need to add this capability to their electrical power generation and storage systems.

Assessment of spacecraft compliance with Requirements 4.4-1 through 4.4-4 shows that the SGSat CubeSat is compliant. Requirements 4.4-3 and 4.4-4 are not applicable.

The following addresses requirement 4.4-2. SGSat has not been designed to disconnect 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”.

The battery cells utilize lithium ion technology and are compliant with Underwriters Laboratory (UL) Standard 1642

Table 3: SGSat CubeSat Cells

CubeSat	Technology	Manufacturer	Model	UL Listing Number
SGSat	Li-Ion Polymer	E-ONE MOLI ENERGY LIMITED	Li-Ion 18650	MH13806

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. (d)) 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).

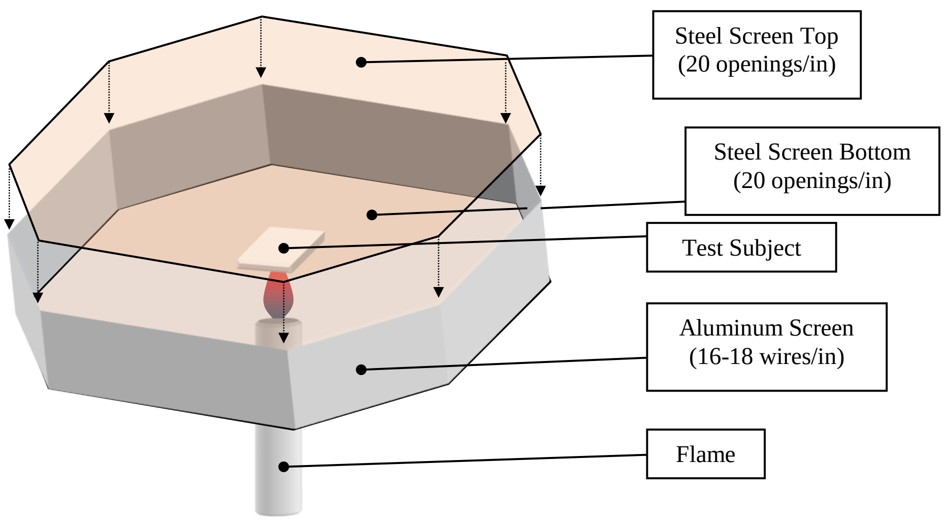

Figure 3: Underwriters Laboratory Explosion Test Apparatus

The batteries being launched via CubeSat will experience conditions on orbit that are generally much less severe that those seen during the UL test. 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. (c)) 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. (c), 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.

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

Equation 1: Mean Cross Sectional Area for Convex Objects

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

Equation 2: Mean Cross Sectional Area for Complex Objects

SGSat evaluated for this ODAR is 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 SGSat . Once a CubeSat has been ejected from the P-POD and deployables have been extended Equation 2 is utilized to determine the mean CSA. Amax is identified as the view that yields the maximum cross-sectional area. A1 and A2 are the two cross-sectional areas orthogonal to Amax. Refer to Appendix A for dimensions used in these calculations The SGSat orbit at deployment is 403 km apogee altitude by 404 km perigee altitude, with an inclination of 51.6 degrees. With an area to mass (1.2 kg) ratio of 0.013 m^2 /kg, DAS yields 1.22 years for orbit lifetime for its stowed state, which in turn is used to obtain the collision probability.

SGSat sees a $10^{-8.1}$ probability of collision. Table 4 below provides complete results.

Table 4: CubeSat Orbital Lifetime & Collision Probability

	CubeSat	SGSat
	Mass (kg)	1.2
Stowed	Mean C/S Area (m^2)	0.015
Stowed	Area-to Mass (m^2/kg)	0.013
Stowed	Orbital Lifetime (yrs)	1.22
Stowed	Probability of collision (10^X)	-8.4
Deployed	Mean C/S Area (m^2)	0.025
Deployed	Area-to Mass (m^2/kg)	0.021
Deployed	Orbital Lifetime (yrs)	0.68
Deployed	Probability of collision (10^X)	-8.1

The probability of the SGSat spacecraft colliding with debris and meteoroids greater than 10 cm in diameter and capable of preventing post-mission disposal is less than $10^{-8.0}$, for any configuration. This satisfies the 0.001 maximum probability requirement 4.5-1.

Since the SGSat CubeSat has 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 SGSat to be compliant. Requirement 4.5-2 is not applicable to this mission.

Section 6: Assessment of Spacecraft Post-mission Disposal Plans and Procedures

SGSat 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 post-mission disposal is not applicable. Disposal is achieved via passive atmospheric reentry.

The worst-case (smallest Area-to-Mass) post-mission disposal is SGSat in stowed configuration. The area-to-mass is calculated 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

$$\frac{0.015\ m^2}{1.2\ kg} = 0.013\,\frac{m^2}{kg}$$

The assessment of the spacecraft illustrates it is compliant with Requirements 4.6-1 through 4.6-5.

<u>DAS 2.0.2 Orbital Lifetime Calculations:</u>

DAS inputs are: 404 km maximum perigee X 403 km maximum apogee altitudes with an inclination of 51.6 degrees at deployment in the year 2016. An area to mass ratio of 0.013 m^2/kg for the SGSat CubeSat was imputed. DAS 2.0.2 yields a 1.22 years orbit lifetime for SGSat in its stowed state. This meets requirement 4.6-1. Assessment results show compliance.

Section 7: Assessment of Spacecraft Reentry Hazards

A detailed assessment of the components to be flown on SGSat was performed. The assessment used DAS 2.0 to provide bounding analysis to characterize component's risk. DAS 2.0 is a conservative tool used by the NASA Orbital Debris Office to verify Requirement 4.7-1.

DAS employs a conservative analysis methodology to determine if a component will survive reentry. Since DAS does not explicitly model the oxidative or ablative heating that a given component will experience during reentry, it generally over-predicts component survivability. This is an especially relevant consideration for small components that are on the edge of survivability, particularly those that are predicted to survive with very low residual kinetic energy.

The following steps are used to identify and evaluate a component's potential reentry risk.

1. Low melting temperature (less than 1000 °C) components are identified as materials that will never survive reentry and pose no risk to human casualty. This is confirmed through DAS analysis that shows that 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.

The remaining higher temperature materials are shown to pose negligible risk to human casualty through a bounding analysis of the highest temperature components. For SGSat the material with the highest melting temperature is stainless steel (1500°C). If a component is of similar dimensions and has a melting temperature between 1000 °C and 1500°C, it can be expected to posses the same negligible risk as stainless steel components. (see

2. Table 5)

Table 5: SGSat Stainless Steel DAS Analysis

CubeSat	Stainless Steel Components	Mass (g)	Length / Diameter (cm)	Width (cm)	Height (cm)		Demise Alt (km)	KE (J)
SGSat	Sep Switches	10	1.5	1	0.6		0	<1
	VHF Dipole Blades	20	26	1.2	0.02		0	<1
	UHF Dipole Blades	16	18	1.2	0.02		0	<1

The majority of stainless steel components demise upon reentry. For SGSat, the components that DAS conservatively identifies as reaching the ground have one joule of kinetic energy or less, far below fifteen joule threshold. Since any injury incurred or inflicted by an object with such low energy would be negligible and would not require the individual to seek medical attention, these objects pose no risk of human casualty as defined by the Range Commander's Counsel ref (h).

Through the method described above, Table 5, and the full component list in the Appendix, the SGSat CubeSat is conservatively shown to be in compliance with Requirement 4.7-1 of NASA-STD-8719.14A.

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

Section 8: Assessment for Tether Missions

SGSat will not be deploying any tethers.

SGSat satisfies Section 8’s requirement 4.8-1.

Appendix Index:

Appendix A. SGSat Component List

Row Number	Name	External/Internal (Major/Minor Components)	Qty	Material	Body Type	Mass (g)	Diameter/ Width (mm)	Length (mm)	Height (mm)	Low Melting Temp	Melting Temp	Comment
	Solar Panel Hinges	Rectangular Mount and Flat Hinges	4	Aluminum 6061	16	64	100	16.5 (max)	15.4 (max)	y		Demises
6	Sep Switches	Foot Switch/Box	2	Stainless Steel, Plastic Case	5	10	10	15	6	High Melt	1500	Negligible Risk: KE ~ 0 J See Table 5.
7	C&DH Board	PCB Board	1	PCB (FR-4) plus electronics	60	60	80	80	1.6	y		Demises
8	Power Management Board	PCB Board	1	PCB (FR-4), surface mount electronics	20	20	80	80	1.6	y		Demises
9	Batteries	Cylindrical	4	Lithium Ion	50	200	19 (diameter)	-	65	y		Demises
10	ADCS Components	PCB Boards		Details Below	-	-	-	-	-	y		Demises
	Passive Alnico Magnets	PCB Board	1	PCB (FR-4) plus electronics	10	10	25	25	25	y		Demises
11	Communications Systems	PCB Boards		Details Below	-	-	-	-	-	y		Demises
	UHF / VHF Radio	PCB Board	1	PCB (FR-4) plus electronics, AL housing	90	90	50	40	6	y		Demises
12	Antenna Matching/Phasing Circuits	PCB Board	2	PCB (FR-4) plus electronics	12	24	30.1	30	4.3	y		Demises
1	CubeSat Structure	Rectangular Box	1	Aluminum 6061	90	90	100 (X axis)	100 (Y axis)	113.5 (Z axis)	y		Demises
13	Fasteners	Nuts, Bolts, Standoffs	TBD	Stainless Steel 316,303		25	Various	Various	Various	High Melt	1500	Negligible Risk, bounded by larger SS components. See Table 5.
14	Cabling, Connectors, RF Connectors	Insulated Wire, Various Connectors	TBD	Copper, FTFE Insulator, SMAs (Cu/Gold)		25	Various	Various	Various	Verify Temp	1000	Demises
15	Staking and Thermal Compound	Conformal	N/A	Stycast 2850 FT, Dow Corning		8	N/A	N/A	N/A	y		Demises

				3145 RTV								
16	Payload System	PCB Boards		Details Below	-	-	-	-	-	y		Demises
	Camera Board	PCB Board w/ Camera Lens	1	PCB (RF4), Plastic Lens Cylinder, Glass Lens	20.6	20.6	43.7	38.1	24	y		Demises
	Image Processing Board	PCB Board	1	PCB (FR-4) plus electronics	66.4*	66.4	85.1	85.6	1.6	y		Demises
2	CubeSat Structure-Rails (Corners)	CubeSat Box Structure Corners	4	Aluminum 6061 hard anodized	30	120	8.5	8.5	113.5	y		Demises
3	Antennas	Blades and Patch		Details Below	-	-	-	-	-	y		Demises
	VHF Dipole Blades	Blades	2	Spring Steel with gold alloy electroplating	10	20	12	260	0.2	High Melt	1000/1400	Negligible Risk: KE ~ 0 J See Table 5.
	UHF Dipole Blades	Blades	2	Spring Steel with gold alloy electroplating	8	16	12	180	0.2	High Melt	1000/1400	Negligible Risk: KE ~ 0 J See Table 5.
4	Solar Panels	Rectangular Panels	9	Cover Glass, Si, PCB (FR-4)	40	360	84	84	1.6	y		Demises
	Solar Cells	Rectangular Cells	16	GaInP/GaAs/Ge on Ge substrate triple junction	2.7	incl in #4	40	80	1	High Melt	1238	Negligible Risk, bounded by larger SS components. See Table 5.
5	Solar Panel and Antenna Deployer	Wrapped Nylon w/ Cutter	1	Nylon, Al 6061, PCB (FR4), Nichrome	8	8	100	100		y		Demises