May 28, 2013

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

Prepared by:

Nicole Ela, Project Manager Nicole.Ela@Colorado.edu
Gabrielle Massone Systems Engineer Gabrielle.Massone@Colorado.edu
With inputs from CalPoly ELaNa-5 Mission Integration

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

The intent of this report is to satisfy the orbital debris requirements listed in ref. (a) for the ALL-STAR.THEIA 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 ALL-STAR/THEIA CubeSat as part of the ELaNa-5 auxiliary payload mission flown on SpX-3. The 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 under ELaNa-5 mission

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:

All-STAR/THEIA: Christopher Koehler, Principle Investigator;
Jesse Ellison, Nicole Ela, Gabrielle Massone, Project Managers

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: ALL-STAR/THEIA CubeSat
University of Colorado at Boulder – 3U

Table 3: ALL-STAR/THEIA CubeSat

CubeSat Quantity	**CubeSat size**	**CubeSat Names**	**CubeSat Mass (kg)**
1	3U (10 cm X 10 cm X 30 cm)	ALL-STAR/THEIA	3.97

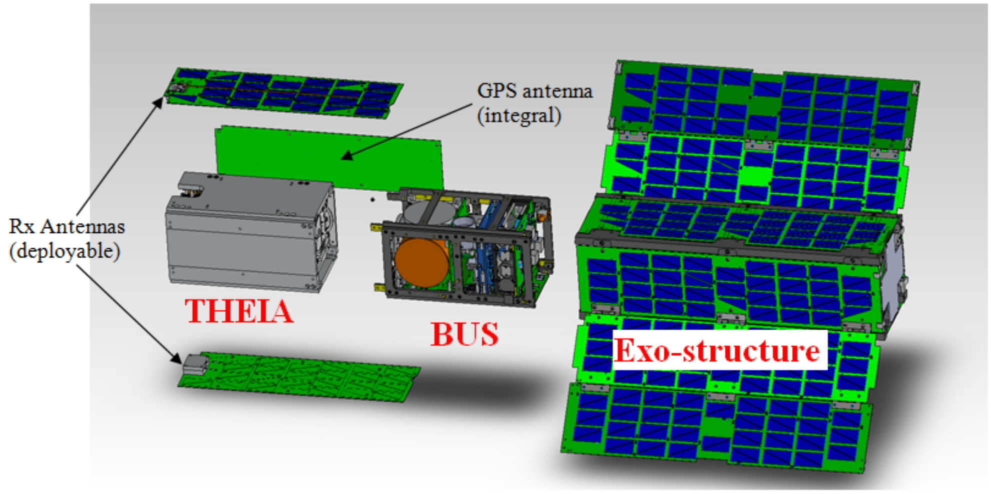

Figure 1: ALL-STAR/THEIA Expanded View

ALL-STAR/THEIA will demonstrate the performance of the student-designed All-Star 3U Bus, including custom-built high-speed radio, reaction wheels, torque rods, and star tracker. The THEIA Earth imaging payload (also custom student design) will facilitate demonstration.

Upon deployment from the P-POD, The ALL-STAR/THEIA EPS system will power up, turn on CDH and flight command software, which will begin counters. At 30 minutes, the exo-structure and Rx antennas will be deployed. After battery charging and autonomous system check-out, including GPS location and time fix, and star tracker attitude fix, the S-Band transmit antenna will begin broadcasting a beacon signal. For the first many passes the ground station operators will attempt communications to perform checkouts of the spacecraft. Approximately 14 days from launch, payload tests will begin and continue for at least 14 days.

The CubeSat structure is made of Aluminum 6061-T6. It contains all standard commercial off-the-shelf (COTS) materials, electrical components, PCBs and solar cells. The THEIA imager uses an Invar 36 structure to ensure the lens-to-sensor distance remains at the focal length across a large temperature range without active or passive temperature regulation. Both THEIA and the star tracker have glass optics.

There are no pressure vessels, hazardous or exotic materials.

The electrical power storage system consists of standard 18650 lithium-ion batteries with over-charge/current protection circuitry. The lithium batteries carry the UL-listing number MH48285.

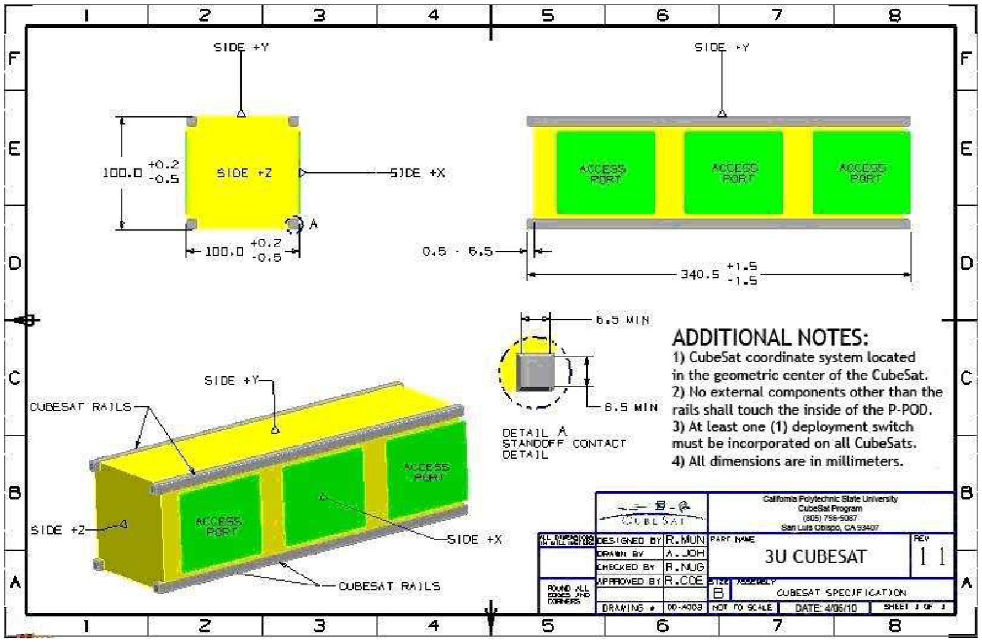

Figure 2: 3U CubeSat Specification

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 the 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 ALL-STAR/THEIA 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 in the ALL-STAR/THEIA 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 ALL-STAR/THEIA.

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 4.4-2 shows that ALL-STAR/THEIA 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 CubeSats 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: ALL-STAR/THEIA Cells

CubeSat	Technology	Manufacturer	Model	UL Listing Number
ALL-STAR/THEIA	Lithium Ion	Tenergy	ICR 18650-2600	MH48285

The batteries are all consumer-oriented devices. All battery cells have been recognized as Underwriters Laboratories (UL) tested and approved, and are compliant with UL Standard 2054. 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).

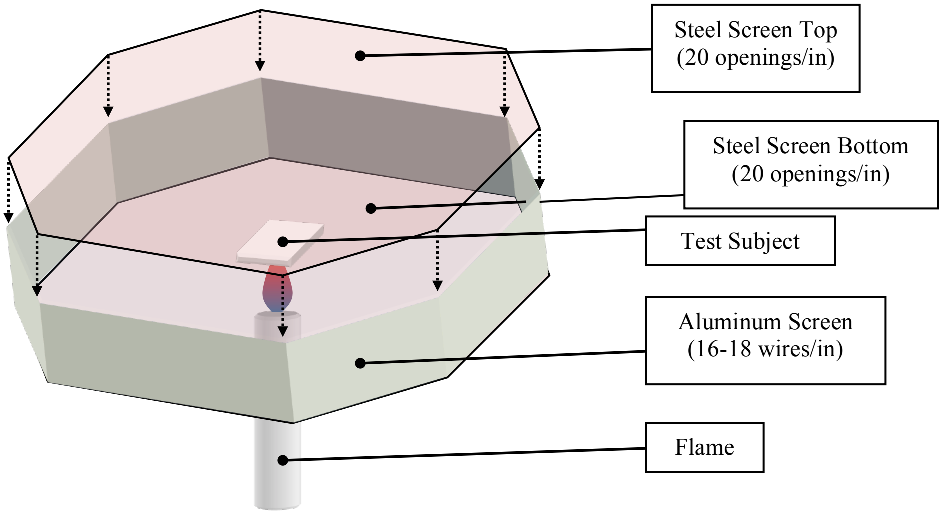

Figure 3: Underwriters Laboratory Explosion Test Apparatus

The batteries being launched via CubeSat will experience conditions on orbit that are generally much less severe than 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 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 of the ALL-STAR/THEIA CubeSat is the exo-bus with deployed solar panels (maximum wingspan of 31.9 cm in the X and Y axis with a total length of 59.4 cm):

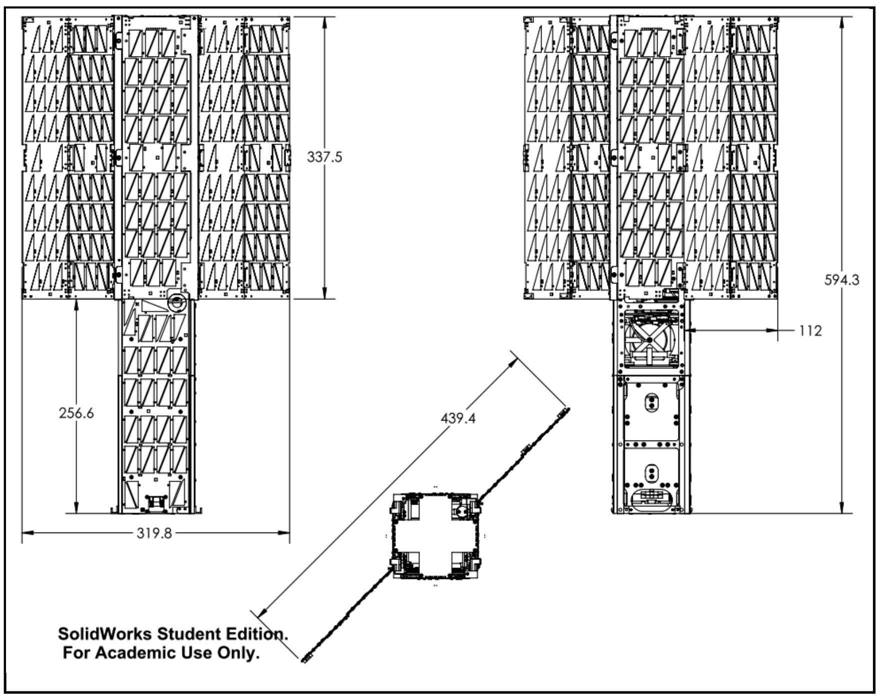

Figure 4: ALL-STAR/THEIA deployed configuration

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

Equation 1: Mean Cross Sectional Area for Convex Objects

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

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 Appendix A for dimensions used in these calculations

The ALL-STAR/THEIA 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 (3.97 kg) ratio of 0.0346 m^2/kg, DAS yields 0.1 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. ALL-STAR/THEIA in the deployed configuration sees the highest probability of collision of $10^{-8.4}$. Table 4 below provides complete results.

Table 5: ALL-STAR/THEIA Orbital Lifetime & Collision Probability

	CubeSat	**ALL-STAR/THEIA**
	Mass (kg)	3.97
Stowed	**Mean C/S Area (m^2)**	0.0310
	Area-to Mass (m^2/kg)	0.0078
	Orbital Lifetime (yrs)	0.2
	Probability of collision (10^X)	-9.1
Deployed	**Mean C/S Area (m^2)**	0.1372
	Area-to Mass (m^2/kg)	0.0346
	Orbital Lifetime (yrs)	0.1
	Probability of collision (10^X)	-8.4

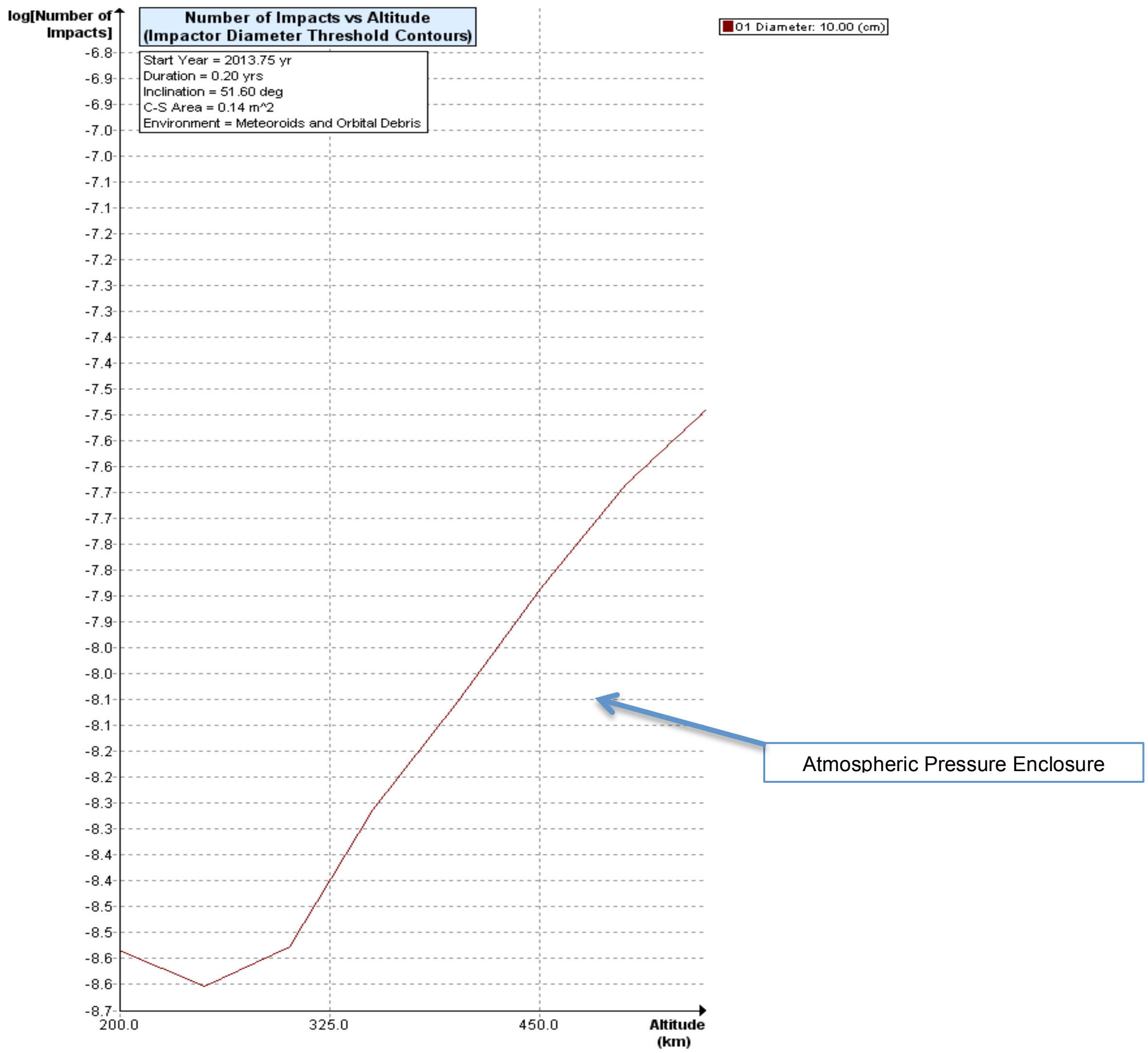

Figure 5: Highest Risk of Orbit Collision vs. Altitude (ALL-STAR/THEIA Deployed)

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 an ALL-STAR/THEIA collision with debris and meteoroids greater than 10 cm in diameter and capable of preventing post-mission disposal is less than $10^{-8.4}$, 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 ALL-STAR/THEIA to be compliant. Requirement 4.5-2 is not applicable to this mission.

Section 6: Assessment of Spacecraft Postmission Disposal Plans and Procedures

ALL-STAR/THEIA 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.

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

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

Equation 3: Area to Mass

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

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

Assessment results show compliance of ALL-STAR/THEIA. This meets requirements 4.6-1. For orbital lifetime of ALL-STAR/THEIA reference Table 5.

Section 7: Assessment of Spacecraft Reentry Hazards

A detailed assessment of the components to be flown on ALL-STAR/THEIA 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 ALL-STAR/THEIA's components 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 they reenter the atmosphere, further reducing the risk they pose.

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 ALL-STAR/THEIA mission all complies with Requirement 4.7-1, to have less than 1:10,000 risk of human casualty.

ALL-STAR/THEIA has multiple components of high temperature Invar material. These survive reentry with more than 15 J of energy. However, the risk of human casualty for all pieces of ALL-STAR/THEIA does not exceed 1:10,000 probability (ALL-STAR/THEIA has 1:47,100 probability).

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: ALL-STAR/THEIA Survivability DAS Analysis, and the Appendix, the ALL-STAR 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 ALL-STAR/THEIA components.

Table 6: ALL-STAR/THEIA Survivability DAS Analysis

CubeSat	ELaNa-5 Stainless Steel Components	Mass (g)	Length / Diameter (cm)	Width (cm)	Height (cm)	Demise Alt (km)	KE (J)
ALL-STAR /THEIA	Bus solar panel hinge	3.4	0.781	3.18	0.30	75.1	0
ALL-STAR/ THEIA	Bus Rx Antenna Axle	3.4	0.50	2.20		76.3	0
ALL-STAR/ THEIA	Bus Magnetic Torque Rod	12.5	1.20	5.00		73.9	0
ALL-STAR/ THEIA	Bus Star Camera Lens & Frame	10.8	2.20	1.89		74.5	0
ALL-STAR/ THEIA	Bus Deployment Spring	3.5	1.29	0.82		76.1	0
ALL-STAR/ THEIA	Bus Standoffs	3.0	0.37	0.65		76.7	0
ALL-STAR/ THEIA	THEIA SS Fasteners	1.0	1.27	1.59		77.2	0
ALL-STAR/ THEIA	Bus SS Fasteners	1.0	1.27	0.79		77.2	0
ALL-STAR/ THEIA	Bus Spring Plunger	0.5	0.30	1.06		76.9	0
ALL-STAR/ THEIA	Pandaligner - Invar	5.8	4.45	0.70		0	< 1 J
ALL-STAR/ THEIA	Base Plate - Invar	320.3	6.60	16.51	0.64	0	198
ALL-STAR/ THEIA	Reinforcement Bracket - Invar	95.8	6.67	8.04	0.64	0	33
ALL-STAR/ THEIA	Electronics Bracket - Invar	73.1	7.11	7.43	1.09	0	18
ALL-STAR/ THEIA	Lens Bracket A -Invar	58.2	7.53	8.00	1.14	0	5
ALL-STAR/ THEIA	Adjustment Plate - Invar	48.7	6.88	7.38	0.51	0	4

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

Section 8: Assessment for Tether Missions

ALL-STAR/THEIA will not be deploying any tethers.

ALL-STAR/THEIA satisfies 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 authors on the title page of this document.

Appendix A

A ALL-STAR/THEIA 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	Melting Temp	Comment
1	AS-01 THEIA CubeSat		1		3U	4000	100	600	100	Yes		Demises
2	THEIA Payload		1		~1.5U					Yes		Demises
3	AS-01 Bus		1		~1.5U					Yes		Demises
4	THEIA Base Plate	External - Major	1	Invar (Alloy 36)	Plate	320.3	66.0	165.1	6.4	No	1400	Compliant (<1:10,000 probability of casualty) See **Error! Reference source not found.**
5	THEIA Side Plate	External - Major	2	Aluminum 6061	Plate	305.3	90.6	165.1	22.9	Yes		Demises
6	THEIA Top Plate	External - Major	1	Aluminum 6061	Plate	235.6	44.9	165.1	15.2	Yes		Demises
7	Bus Deployed Solar Panel	External - Major	4	FR-4, GaAs	Plate	65.0	84.0	340.0	2.0	Yes		Demises
8	Bus Exo-Frame (Rails)	External - Major	4	Aluminum 6061	Plate	55.9	98.5	340.5	8.5	Yes		Demises
9	Bus Exo-frame Solar Panel	External - Major	4	FR-4, GaAs	Plate	45.0	84.0	340.0	2.0	Yes		Demises
10	Bus PEZ Solar Panel	External - Major	3	FR-4, GaAs	Plate	40.0	65.9	244.2	1.0	Yes		Demises

11	Bus X PEZ Frame	External - Major	2	Aluminum 6061	Plate	35.4	82.5	165.1	6.1	Yes		Demises
12	Bus Y PEZ Frame	External - Major	2	Aluminum 6061	Plate	27.7	82.5	165.1	13. 3	Yes		Demises
13	Bus Tx Antenna	External - Minor	1	Brass, FR-4	Can	13.0	60.0	32.6	-	Yes		Demises
14	Bus Rx Antenna Bracket	External - Minor	2	Aluminum 6061	Block	7.4	22.0	26.0	10. 0	Yes		Demises
15	Bus solar panel hinge	External - Minor	12	Steel 304	Plate	3.4	7.8	31.8	3.0	No	1500	Demises see **Error! Reference source not found.**
16	Bus Rx Antenna Axle	External - Minor	2	Tool Steel	Rod	3.4	5.0	22.0	-	No	1500	Demises see **Error! Reference source not found.**
17	Bus Deployment Claws -Z	External - Minor	4	Aluminum 6061	Block	1.8	10.8	13.8	12. 3	Yes		Demises
18	Bus Rx Antenna	External - Minor	2	Copper	Rod	1.4	1.0	200.0	-	Yes		Demises
19	Bus Deployment Claws +Z	External - Minor	4	Aluminum 6061	Block	0.2	6.1	8.9	8.7	Yes		Demises
20	THEIA Reinforcement Bracket	Internal - Major	1	Invar (Alloy 36)	Box Frame	95.8	66.7	80.4	6.4	No	1400	Compliant (<1:10,000 probability of casualty) See **Error! Reference source not found.**
21	THEIA Light Baffle	Internal - Major	1	Aluminum 6061	Tube	75.0	61.4	142.0	-	Yes		Demises
22	THEIA Electronics Bracket	Internal - Major	1	Invar (Alloy 36)	Box Frame	73.1	71.1	74.3	10. 9	No	1400	Compliant (<1:10,000 probability of casualty) See **Error! Reference source not found.**

23	Bus CDH board	Internal - Major	1	FR-4, Copper	Plate	62.0	74.2	169.2	11.6	Yes		Demises
24	THEIA Lens Bracket A	Internal - Major	1	Invar (Alloy 36)	Tube	58.2	75.3	80.0	11.4	No	1400	Compliant (5J) See **Error! Reference source not found.**
25	Bus EPS Main board	Internal - Major	1	FR-4, Copper	Plate	56.0	78.3	82.5	12.4	Yes		Demises
26	THEIA Achromatic Double Lens	Internal - Major	1	BK7/SF5 Glass	Disk	55.3	55.9	8.0	-	Yes		Demises
27	Bus COM RF board	Internal - Major	1	FR-4, Copper	Plate	50.0	78.3	82.5	11.3	Yes		Demises
28	THEIA Adjustment Plate	Internal - Major	1	Invar (Alloy 36)	Disk	48.7	68.8	73.8	5.1		1400	Compliant (4J) See **Error! Reference source not found.**
29	Bus EPS Li-ion cell	Internal - Major	4	Li-Ion	Rod	46.0	18.4	66.5	-	Yes		Demises
30	Bus ACS Main board	Internal - Major	1	FR-4, Copper	Plate	45.0	78.3	82.5	5.1	Yes		Demises
31	Bus COM Digital board	Internal - Major	1	FR-4, Copper	Plate	44.0	78.3	82.5	8.7	Yes		Demises
32	THEIA Spider Bracket	Internal - Major	1	Aluminum 6061	Plate	36.9	79.4	115.6	10.3	Yes		Demises
33	THEIA Electronics	Internal - Major	1	FR-4, Copper	Plate	32.0	85.0	85.0	6.0	Yes		Demises
34	Bus Backplane board	Internal - Major	1	FR-4, Copper	Plate	23.0	100.0	100.0	2.0	Yes		Demises
35	Bus Reaction Wheel	Internal - Major	3	Aluminum 6061	Disk	21.2	57.2	5.1	-	Yes		Demises
36	Bus JTAG board	Internal - Major	1	FR-4, Copper	Plate	20.0	22.0	62.0	5.0	Yes		Demises
37	Bus ACS Star Camera board 2	Internal - Major	1	FR-4, Copper	Plate	18.3	44.5	82.6	6.3	Yes		Demises
38	Bus GPS board	Internal - Major	1	FR-4, Copper	Plate	18.0	46.0	71.0	13.0	Yes		Demises
39	Bus EPS battery bracket	Internal - Major	2	Aluminum 6061	Box Frame	18.0	26.5	80.7	12.0	Yes		Demises
40	Bus Star Camera Bracket	Internal - Major	1	Aluminum 6061	Plate	15.3	22.0	82.5	10.5	Yes		Demises
41	Bus ACS Motor Driver board	Internal - Major	1	FR-4, Copper	Plate	15.2	40.6	54.6	8.7	Yes		Demises

42	Bus Magnetic Torque Rod	Internal - Major	3	Steel, Copper	Rod	12.5	12.0	50.0	-	No	1500	Demises See **Error! Reference source not found.**
43	Bus ACS Star Camera board 1	Internal - Major	1	FR-4, Copper	Plate	12.0	22.0	82.5	5.0	Yes		Demises
44	Bus RWM Bracket	Internal - Major	3	Aluminum 6061	Plate	10.4	60.0	66.8	1.6	Yes		Demises
45	Bus frangibolt assembly	Internal - Minor	1	Aluminum 6061	Tube	11.7	21.0	25.0	22.8	Yes		Demises
46	Bus Star Camera Lens & Frame	Internal - Minor	1	Glass & Steel	Disk/Rod	10.8	22.0	18.9	-	No	1500	Demises See **Error! Reference source not found.**
47	Bus Star Camera Baffle	Internal - Minor	1	Aluminum 6061	Tube	10.1	25.2	27.2	-	Yes		Demises
48	THEIA Brass nuts	Internal - Minor	3	Brass	Tube	9.5	14.7	13.3	-	Yes		Demises
49	Bus GPS wire harness	Internal - Minor	1	Copper	Wires	8.5				Yes		Demises
50	THEIA Baffle Brackets	Internal - Minor	2	Aluminum 6061	Block	6.5	15.2	49.5	8.0	Yes		Demises
51	Bus EPS wire harness 1	Internal - Minor	1	Copper	Ribbon	6.0	25.0	350.0	2.0	Yes		Demises
52	THEIA Pandaligner	Internal - Minor	1	Invar (Alloy 36)	Disk	5.8	44.5	7.0	-	No	1400	Compliant (<1J) See **Error! Reference source not found.**
53	Bus Deployment Spring	Internal - Minor	2	Spring Steel	Coiled Sheet	3.5	12.9	8.2	-	No	1500	Demises See **Error! Reference source not found.**
54	Bus RF Cabling	Internal - Minor	3	Copper	Wire	3.0				Yes		Demises
55	Bus Standoffs	Internal - Minor	12	Steel (304, 316)	Rod	3.0	3.7	6.5	-	No	1500	Demises See **Error! Reference source not found.**
56	Bus Tx Antenna Bracket	Internal - Minor	2	Aluminum 6061	Plate	2.8	16.8	36.4	7.6	Yes		Demises
57	Bus Reaction Wheel Motor	Internal - Minor	3	Multiple (Steel)	Rod	2.5	6.0	20.0	-	Yes		Demises
58	THEIA Lens Bracket B	Internal - Minor	1	Aluminum 6061	Disk	1.9	57.8	2.0	-	Yes		Demises

59	Bus board clips 1	Internal - Minor	15	Aluminum 6061	Block	1.8	7.6	18.2	6.8	Yes		Demises
60	Bus EPS wire harness 2	Internal - Minor	2	Copper	Ribbon	1.5	20.0	50.0	4.0	Yes		Demises
61	Bus Dep Spring Spool	Internal - Minor	2	Aluminum 6061	Tube	1.5	9.0	8.2	-	Yes		Demises
62	THEIA SS Fasteners	Internal - Minor	76	Steel (304, 316)	Rod	1.0	#2, #4, 1/2"	.25 - 1.00"	-	No	1500	Demises See **Error! Reference source not found.**
63	Bus SS Fasteners	Internal - Minor	29 8	Steel (304, 316)	Rod	1.0	#0, #2, #4	.125 - .5"	-	No	1500	Demises See **Error! Reference source not found.**
64	Bus board clips 2	Internal - Minor	6	Aluminum 6062	Block	0.9	5.7	10.8	6.4	Yes		Demises
65	Bus Spring Plunger	Internal - Minor	2	Steel 316	Rod	0.5	3.0	10.6	-	No	1500	Demises See **Error! Reference source not found.**