March 20, 2013

Orbital Debris Assessment for FIREBIRD on the NROL-39 / ELaNa-2 Mission per NASA-STD 8719.14A

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. *GEMSat to ATLAS V / AFT BULKHEAD CARRIER INTERFACE CONTROL DOCUMENT*, Reference Orbit Requirements Baseline Draft, October 2012.
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. Myers, Gary. NROL-39_GEMSat_Gate#1_Mission_Design_final.ppt, 8.4 (U) Mission Design, Dec 13, 2012
I. *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 FIREBIRD auxiliary mission launching in conjunction with the NROL-39 primary payload. It serves as the final submittal in support of the spacecraft Safety and Mission Success Review (SMSR). 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 FIREBIRD auxiliary payload mission flown on NROL-39. FIREBIRD as part of the ELaNa-2 mission 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 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 under FIREBIRD mission

Section 1: Program Management and Mission Overview

The ELaNa-2 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:

FIREBIRD: Prof. David M. Klumpar, Principle Investigator
<klump@physics.montana.edu>;
Ehson Mosleh, Project Manager <ehson@ssel.montana.edu>

Program Milestone Schedule	
Task	**Date**
CubeSat Selection	5/16/12
CubeSat Build, Test, and Integration	1/1/12 through 3/31/13
MRR	4/27/13
CubeSat Delivery to Cal Poly	5/21/13
CubeSat Integration into P-PODs	5/21/13 through 5/31/13
Launch	12/1/13

Figure 1: Program Milestone Schedule

The ELaNa-2 mission will deploy 5 pico-satellites (or CubeSats) as a secondary payload on the NROL-39 mission. The CubeSat slotted position is identified in Table 2: ELaNa-2 CubeSats. The ELaNa-2 manifest includes: CUNYSAT-1, FIREBIRD (2 cubes), IPEX, MCubed-2.

Each CubeSat ranges in sizes from a 10 cm cube to 10 cm x 10cm x 15 cm, with masses from about 1 kg to 2 kg total. The CubeSats have been designed and built by universities and government agencies and each have their own mission goals.

The ELaNa-2 mission will be launched as an auxiliary payload on the NROL-39 mission on an Atlas V 501 launch vehicle from Vandenberg Air Force Base. The current launch date is in 2013. The four CubeSats will be ejected from P-POD carriers attached to the launch vehicle, placing the CubeSats in an orbit approximately 464 X 898 km at inclination of 120 deg (ref. (h)).

Section 2: Spacecraft Description

There are four CubeSats flying on the ELaNa-2 Mission. They will be deployed out of two P-PODs, as shown in Table 2: ELaNa-2 CubeSats below.

Table 2: ELaNa-2 CubeSats

PPOD Slot	CubeSat Quantity	CubeSat size	CubeSat Names	CubeSat Masses (kg)
PPOD 1	3	1U (10 cm X 10 cm X 10 cm) 1U (10 cm X 10 cm X 10 cm) 1U (10 cm X 10 cm X 10 cm)	CUNYSAT-1 IPEX MCubed-2	1.21 1.28 1.1
PPOD 2	2	1.5U (10 cm X 10 cm X 15 cm) 1.5U (10 cm X 10 cm X 15 cm)	FIREBIRD-1 FIREBIRD-2	1.9 1.9

The following subsections contain description of FIREBIRD.

FIREBIRD
Montana State University – 1.5U CubeSat (Qty 2)

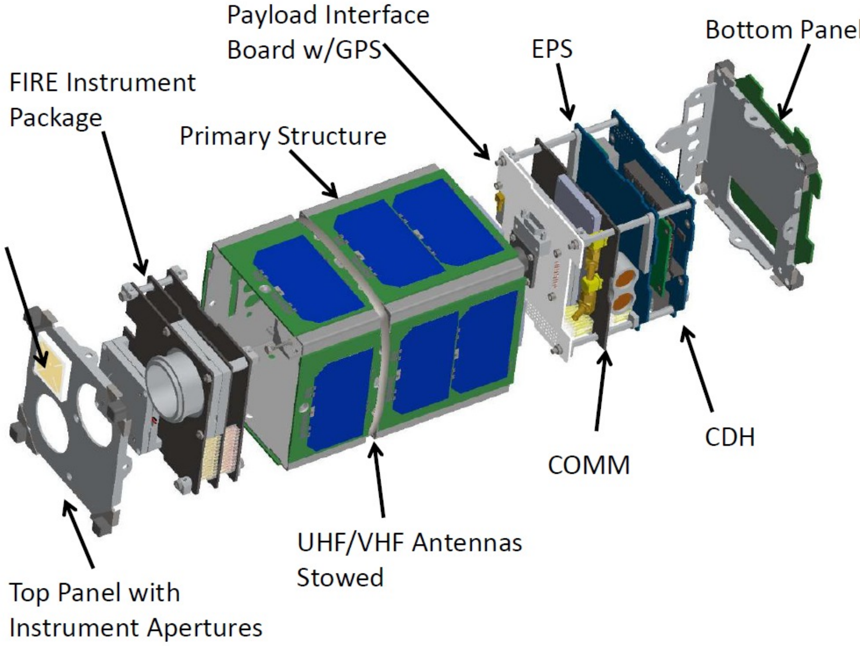

Figure 2: FIREBIRD Expanded View

FIREBIRD, which stands for **F**ocused **I**nvestigations of **R**elativistic **E**lectron **B**urst, **I**ntensity, **R**ange, and **D**ynamics, is funded by the National Science Foundation.

The mission is a targeted, goal-directed, space weather Cubesat mission to resolve the spatial scale size and energy dependence of electron microbursts in the Van Allen radiation belts. FIREBIRD's unique two-point, focused observations at low altitudes fully exploit the capabilities of the Cubesat platform.

The CubeSats will deploy out of the P-POD and when the system turns on thereafter a 1 hour timer begins to tick. When that 1 hour is complete, the flight computer will engage the antenna deployment sequence and the system will begin to start UHF beacon transmissions at a 20 seconds cadence. This mission is set to last 3 months nominally with an extended period of 6 months pending vehicle performance and operations funding.

The CubeSat structure is made of Aluminum 5052H32 and Aluminum 6061-T6. It contains all standard commercial off the shelf (COTS) materials, electrical components, PCBs and solar cells. The GPS patch antenna radio uses a ceramic patch antenna and the UHF/VHF antennas are made of spring steel 410.

There are no pressure vessels, hazardous or exotic materials.

The electrical power storage system consists of common lithium-ion batteries with overcharge/undercurrent circuitry protection. There are no modifications to the cell cases as tested by UL and they are considered safe for travel. See Table 3 for UL Listing information.

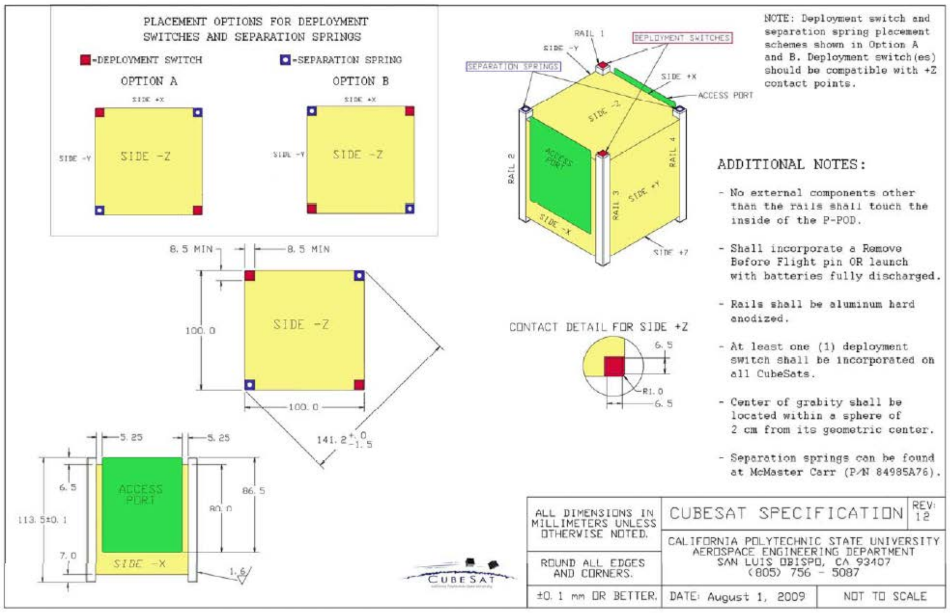

Figure 3: 1U CubeSat Specification

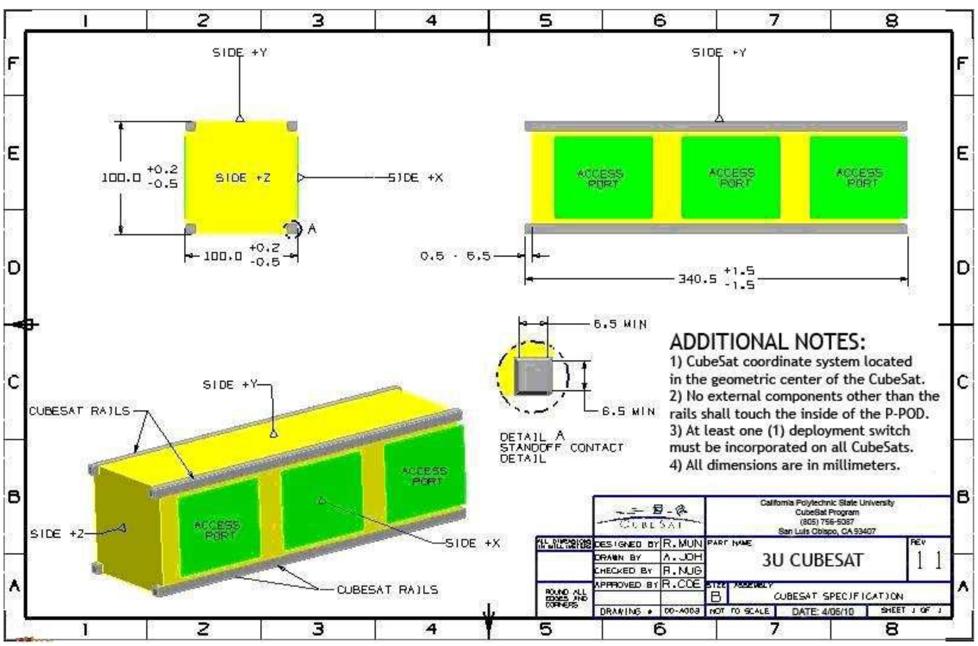

Figure 4: 3U CubeSat Specification

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 FIREBIRD 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 13.2 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 FIREBIRD 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 FIREBIRD 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 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 4.4-4 shows that the FIREBIRD CubeSat is compliant. Requirements 4.4-3 and 4.4-4 are not applicable.

The following addresses requirement 4.4-2. FIREBIRD has not been designed to disconnect onboard storage energy devices (lithium ion and lithium polymer batteries). However, the CubeSat 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 cells utilize lithium ion technology and are compliant with Underwriters Laboratory (UL) Standard 1642.

Table 3: ELaNa-2 CubeSat Cells

CubeSat	Technology	Manufactor	Model	UL Listing Number
FIREBIRD*	Lithium-Ion	LG	ICR18650B2	MH19896

The batteries are 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).

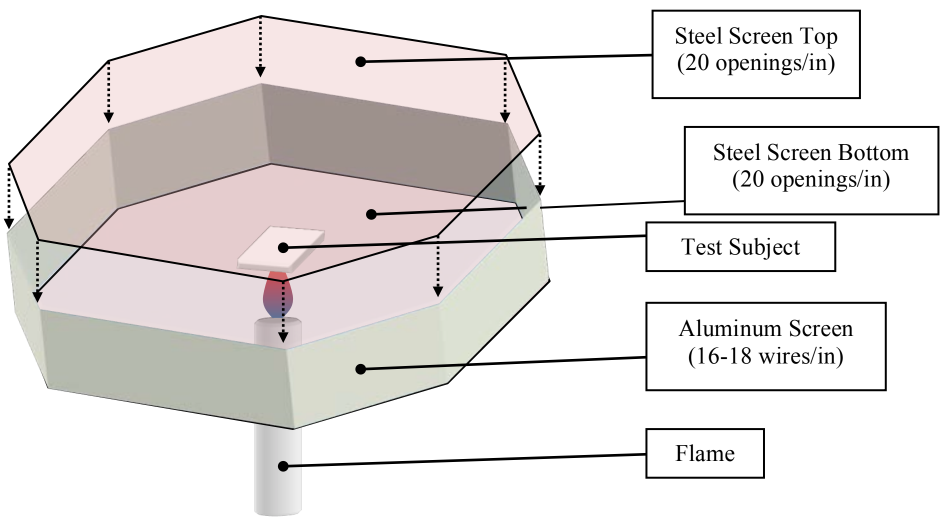

Figure 5: Underwriters Laboratory Explosion Test Apparatus

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 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.

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

Equation 1: Mean Cross Sectional Area for Convex Objects

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

Equation 2: Mean Cross Sectional Area for Complex Objects

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

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 FIREBIRD orbit at deployment is 898 km apogee altitude by 464 km perigee altitude, with an inclination of 120 degrees. With an area to mass ratio of 0.0117 m^2/kg, DAS yields 13.2 years for orbit lifetime for its stowed state, which in turn is used to obtain the collision probability. Table 4 below provides complete results.

Table 4: CubeSat Orbital Lifetime & Collision Probability

	CubeSat	FIREBIRD
	Mass (kg)	1.9
Stowed	Mean C/S Area (m^2)	0.0223
	Area-to Mass (m^2/kg)	0.0117
	Orbital Lifetime (yrs)	13.2
	Probability of collision (10^X)	-6.5
Deployed	Mean C/S Area (m^2)	0.0288
	Area-to Mass (m^2/kg)	0.0152
	Orbital Lifetime (yrs)	12.5
	Probability of collision (10^X)	-6.4

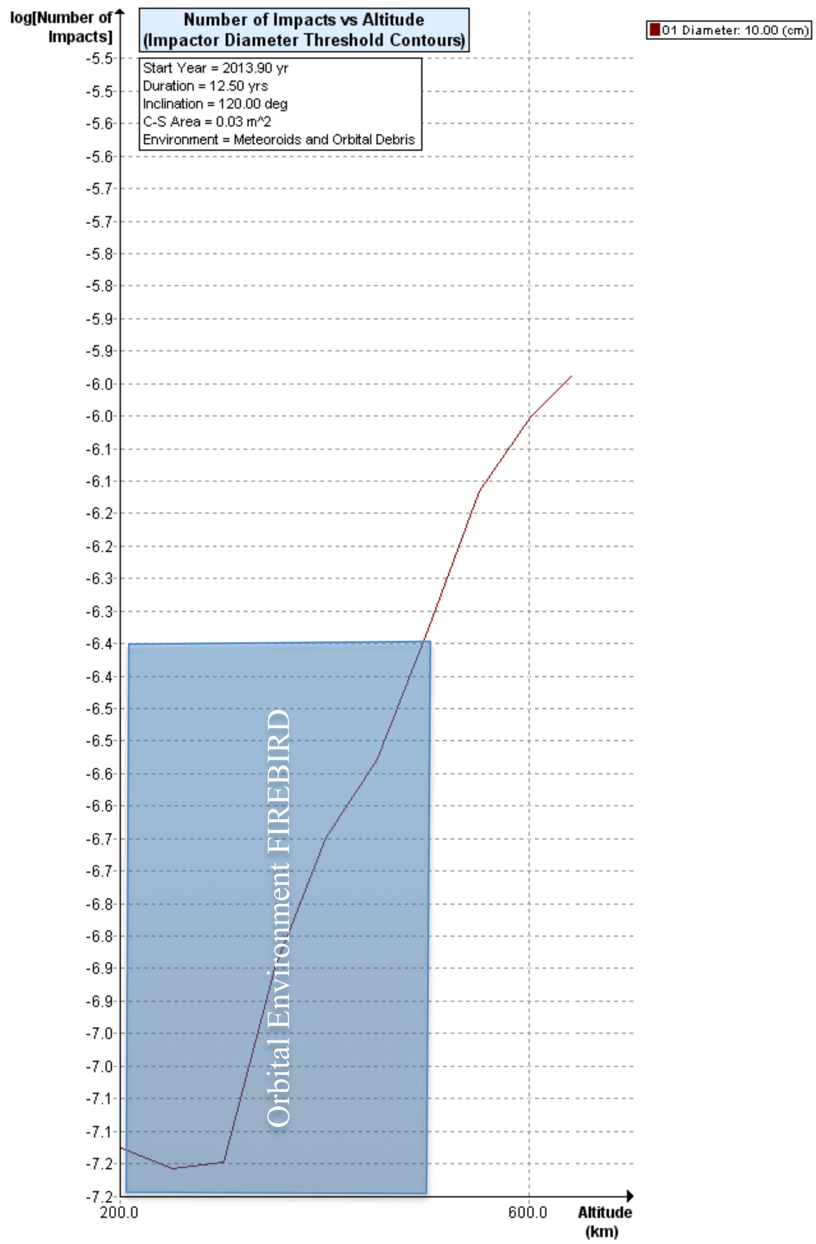

Figure 6: Highest Risk of Orbit Collision vs. Altitude (FIREBIRD Deployed)

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 any ELaNa-2 spacecraft collision with debris and meteoroids greater than 10 cm in diameter and capable of preventing post-mission disposal is less than $10^{-6.4}$, for any configuration. This satisfies the 0.001 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 FIREBIRD to be compliant. Requirement 4.5-2 is not applicable to this mission.

Section 6: Assessment of Spacecraft Postmission Disposal Plans and Procedures

FIREBIRD 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.

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

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

Equation 3: Area to Mass

$$\frac{.0223\,m^2}{1.9\,kg} = \ 0.0117\frac{m^2}{kg}$$

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: 464 km maximum perigee X 898 km maximum apogee altitudes with an inclination of 120 degrees at deployment in the year 2013. An area to mass ratio of 0.0117 m^2/kg for the FIREBIRD CubeSat was input. DAS 2.0.2 yields a 13.2 year orbit lifetime for FIREBIRD 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 ELaNa-2 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 pose negligible risk to human casualty through a bounding DAS analysis of the highest temperature components, 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 Table 5.

Table 5: ELaNa-2 Stainless Steel DAS Analysis

CubeSat	ELaNa-4 Stainless Steel Components	Mass (g)	Length / Diameter (cm)	Width (cm)	Height (cm)		Demise Alt (km)	KE (J)
FIREBIRD								
	VHF Antenna	15	1	50	<0.1		0	1
	UHF Antenna	8	1	10	<0.1		77	0
	Sep Switch	1	0.2	0.5	0		77.3	0

*HuMy80 is a magnet and not a steel alloy, however the melting temperature is 1450°C which is similar to that of stainless steel. Representing the component as steel provides a conservative analysis of the material's demise characteristics.

The majority of stainless steel components demise upon reentry. The components that DAS conservatively identifies as reaching the ground have 1 or less joules of kinetic energy, far below the requirement of 15 joules. No stainless steel component will pose a risk to human casualty as defined by the Range Commander's Council. In fact, any injury incurred or inflicted by an object with such low energy would be negligible and wouldn't require the individual to seek medical attention.

Through the method described above, Table 5: ELaNa-2 Stainless Steel DAS Analysis, and the full component list in the Appendix, the FIREBIRD CubeSat launching under the ELaNa-2 mission 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

FIREBIRD will not be deploying any tethers.

FIREBIRD satisfies Section 8's 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 321-867-2958.

/original signed by/

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cc: VA-H/Mr. Carney
VA-H1/Mr. Beaver
VA-H1/Mr. Haddox
VA-G2/Mr. Atkinson
VA-G2/Mr. Fineberg
SA-D2/Mr. Frattin
SA-D2/Mr. Hale
SA-D2/Mr. Henry
Analex-3/Mr. Davis
Analex-22/Ms. Ramos

Appendix Index:

Appendix A. FIREBIRD Component List

Appendix A. FIREBIRD Component List

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	Comment
FIREBIRD	1	FIREBIRD		2	CubeSat	Box	2000	100	100	150			Demises
FIREBIRD	2	CubeSat Structure	External - Major	1	5052H32 aluminum	Box	308				Y		Demises
FIREBIRD	3	VHF Antenna	External - Major	1	Spring Steel 410	Rectangle	15	10	500	<1	N	1500	Negligible Risk, bounded by larger SS components. See Table 5.
FIREBIRD	4	UHF Antenna	External - Major	1	Spring Steel 410	Rectangle	8	10	100	<1	N	1500	Demises See Table 5.
FIREBIRD	5	Solar Panels	External - Major	4	FR4 PCB Fiberglass	Rectangle	52.5	85	130		Y		Demises
FIREBIRD	6	Sep Switches	External - Minor	1	Steel and Delrin	Rectangle	1	2	5		N	175 / 1500	Demises See Table 5.
FIREBIRD	7	GPS Antenna	External - Minor	1	FR4 PCB Fiberglass and Copper	Square	30	20	20		Y		Demises
FIREBIRD	8	Batteries	Internal - Major	2	Lithium Ion	Cylinder	48	18.29	N/A	65.05	Y		Demises
FIREBIRD	9	ADCS Magnets	Internal - Major	1	Nickel-plated Neodymium Grade N52	Cylinder	5.09	9.52	N/A	9.52	N	1000	Demises
FIREBIRD	10	Payload Board	Internal - Major	3	FR4 PCB Fiberglass	Square	120	95	95		Y		Demises
FIREBIRD	11	Comm Board	Internal - Major	1	FR4 PCB Fiberglass	Square	78	95	95		Y		Demises
FIREBIRD	12	Battery Board	Internal - Major	1	FR4 PCB Fiberglass	Square	158	95	95		Y		Demises
FIREBIRD	13	C&DH Board	Internal - Major	1	FR4 PCB Fiberglass	Square	92	95	95		Y		Demises
FIREBIRD	14	Fasteners	Internal - Minor	57	Stainless Steel	Rectangle	1				N	1500	Negligible Risk, bounded by larger SS components. See Table 5.
FIREBIRD	15	Cabling - Board Traces	Internal - Minor	1	Copper Alloy	N/A	N/A	N/A	N/A	N/A	Y		Demises
FIREBIRD	16	Cabling - Solar Array Harness	Internal - Minor	4	Teflon	Wire	5	3	40	N/A	Y	327	Demises