April 6, 2013

Orbital Debris Assessment for the Ho`oponopono-2 CubeSat on the ORS 3 / ELaNa-4 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. *ORS-3 LV to IPS ICDORS-3 LV to IPS ICD* (Orbital Information), Orbital Document, #1047-0111 Rev Draft
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. *ORS-3 LV to IPS ICD*, Orbit Description, Orbital Document, #1047-0111 Rev Draft.
I. *UL Standard for Safety for Household and Commercial Batteries, UL 2054*. UL Standard. 2nd ed. Northbrook, IL, Underwriters Laboratories, 2005.
J. *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 Ho`oponopono-2 CubeSat. 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 Ho`oponopono-2 CubeSat. The Ho`oponopono-2 CubeSat in the ELaNa-4 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 3.3 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 Ho`oponopono-2 mission

Section 1: Program Management and Mission Overview

The ELaNa-4 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 for the Ho`oponopono-2 CubeSat is follows:

Principal Investigator: Wayne Shiroma
Project Manager: Larry Martin

Program Milestone Schedule

Task	Date
CubeSat Build, Test, and Integration	1/1/12 through 3/31/13
MRR	3/1/13
CubeSat Delivery to KAFB	4/1/13
CubeSat Integration into P-PODs	4/2/13 through 4/9/13
Launch	9/30/13

Figure 1: Program Milestone Schedule

The Ho`oponopono-2 CubeSat will be deployed with 11 other pico-satellites (or CubeSats) as a secondary payload on the ORS3 mission. The Ho`oponopono-2 CubeSat slotted position is identified in Table 2: Ho`oponopono-2 CubeSat Description. The ELaNa 4 manifest includes: Ho`oponopono-2, KySat-2, DragonSat-1, Trailblazer, ChargerSat, PhoneSat, Vermont Lunar Orbiter/Lander, COPPER, SwampSat, CAPE-2, and TJ3Sat.

The Ho`oponopono-2 CubeSat is a 10 cm x 10 cm x 30 cm picosatellite with a mass of 4 kg. The CubeSat was designed and built by the University of Hawaii.

The ELaNa-4 mission will be launched as an auxiliary payload on the ORS3 mission on a Minotaur launch vehicle from Wallops Flight Facility, Virginia. The current launch date is 30 September, 2013. The Ho`oponopono-2 CubeSat will be ejected from a P-POD carrier attached to the launch vehicle, placing the CubeSat in an orbit approximately 500 X 500 km at inclination of 40.5 deg (ref. (h)).

Section 2: Spacecraft Description

There are eleven CubeSats flying on the ELaNa-4 Mission. The Ho`oponopono-2 CubeSat will be deployed out of one of five P-PODs. The Ho`oponopono-2 CubeSat P-POD Slot is shown in Table 2 below.

Table 2: Ho`oponopono-2 CubeSat Description

PPOD Slot	CubeSat Quantity	CubeSat size	CubeSat Names	CubeSat Masses (kg)
2.2	1	3U (10 cm X 10 cm X 30 cm)	Ho`oponopono-2	4

The following subsections contain descriptions of the Ho`oponopono-2 CubeSat.

Ho`oponopono-2 CubeSat Description

University of Hawaii – 3U

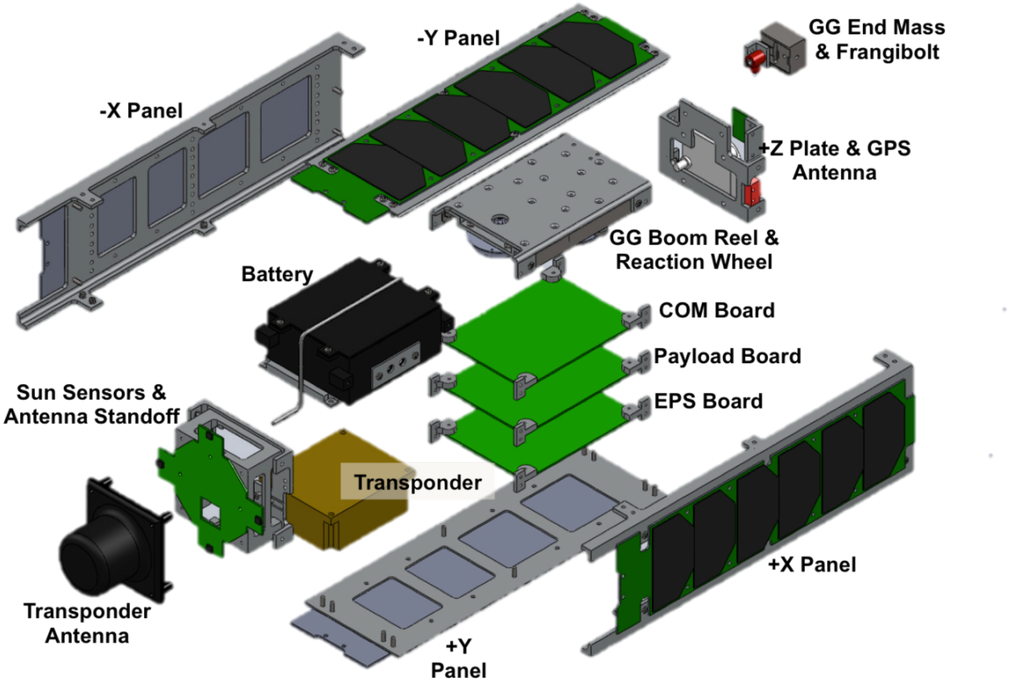


Figure 2: Ho`oponopono-2 Expanded View

Ho`oponopono-2 (H-2) will demonstrate the feasibility of a 3U CubeSat to support orbital radar calibration capabilities to the US Air Force by providing a source for radar interrogations, as well as collecting, disseminating, and forwarding ephemeris data for processing.

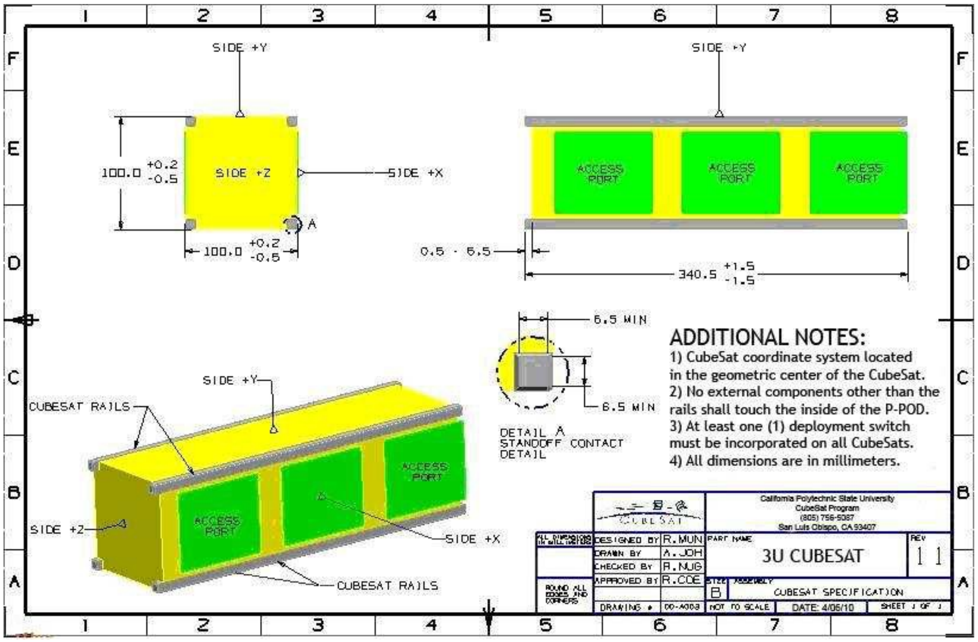
Once a positive PPOD deployment is confirmed, a 45-minute timer is started before beginning CubeSat operations. Additionally the battery capacity is required to increase by 2% before any RF related operations.

After 45 minutes H-2 will deploy its UHF dipole antenna, activate UHF beaconing, activate GPS data collection, and detumbling operations. Once successfully detumbled, Ho`oponopono-2 will be commanded by the ground station to deploy its gravity gradient boom and then enter the experimental phase of the operations.

The primary CubeSat structure is made of Aluminum 6016 T-6. 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 from Tenergy. See Table 3: ELaNa-4 CubeSat Cells for UL Listing.



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
ROUND ALL EDGES AND CORNERS
DESIGNED BY R. MUN
DRAWN BY A. JOH
CHECKED BY R. NUG
APPROVED BY R. COE
DRAWING # 00-A003
PART NAME 3U CUBESAT
REV 11
SIZE B
ASSEMBLY CUBESAT SPECIFICATION
NOT TO SCALE
DATE: 4/06/10
SHEET 1 OF 1

Figure 3: 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.

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 Ho`oponopono-2 CubeSat mission therefore this section is not applicable.

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

Note: This entire section applies to all eleven of the CubeSats on the ORS3/ELaNa-4 mission.

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 Ho`oponopono-2 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 Ho`oponopono-2 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 Ho`oponopono-2 CubeSat, 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 Ho`oponopono-2 CubeSat is compliant. Requirements 4.4-3 and 4.4-4 are not applicable.

The following addresses requirement 4.4-2. The Ho`oponopono-2 CubeSat has not been designed to disconnect its onboard storage energy devices (lithium ion). However, the Ho`oponopono-2 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 batteries used in the Ho`oponopono-2 CubeSat utilizes lithium ion technology and is compliant with Underwriters Laboratory (UL) Standard 1642.

Table 3: ELaNa-4 CubeSat Cells

CubeSat	Technology	Manufacturer	Model	UL Listing Number
Ho`oponopono-2	Li-Ion	Tenergy	ICR18650-2600	MH4285

The Ho`oponopono-2 batteries are consumer-oriented and have been recognized as Underwriters Laboratories (UL) as 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).

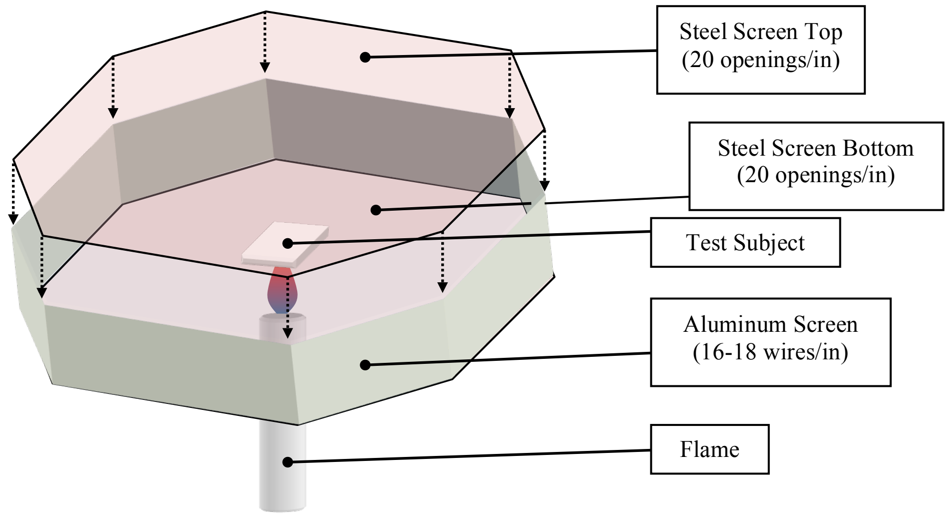

Figure 4: Underwriters Laboratory Explosion Test Apparatus

The batteries being launched on the Ho`oponopono-2 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 (<=41.44 W-hr, maximum for PhoneSat) 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 on the Ho`oponopono-2 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.

For the Ho`oponopono-2 CubeSat with antennas deployed (10 X 10 X 30 cm with one deployable antenna 2.3 X 500 cm):

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

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

The Ho`oponopono-2 CubeSat evaluated for this ODAR will be stowed in a convex configuration, indicating there are no elements of the CubeSats obscuring another element of the same CubeSats from view. Thus, the mean CSA was calculated using Equation 1. This configuration renders the longest orbital life time.

Once the Ho`oponopono-2 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 Ho`oponopono-2 orbit at deployment is 500 km apogee altitude by 500 km perigee altitude, with an inclination of 40.5 degrees. With an area to mass (4.0 kg) ratio of 0.011 m^2/kg, DAS yields 3.3 years for orbit lifetime for its stowed state, which in turn is used to obtain the collision probability. Ho`oponopono-2 sees the a probability of collision of $10^{-7.1}$. Table 4 below provides complete results.

Table 4: CubeSat Orbital Lifetime & Collision Probability

	CubeSat	**Ho`oponopono-2**
	Mass (kg)	4.0
Stowed	**Mean C/S Area (m^2)**	0.045
	Area-to Mass (m^2/kg)	0.011
	Orbital Lifetime (yrs)	3.3
	Probability of collision (10^X)	-7.1
Deployed	**Mean C/S Area (m^2)**	0.114
	Area-to Mass (m^2/kg)	0.029
	Orbital Lifetime (yrs)	1.0
	Probability of collision (10^X)	-7.0

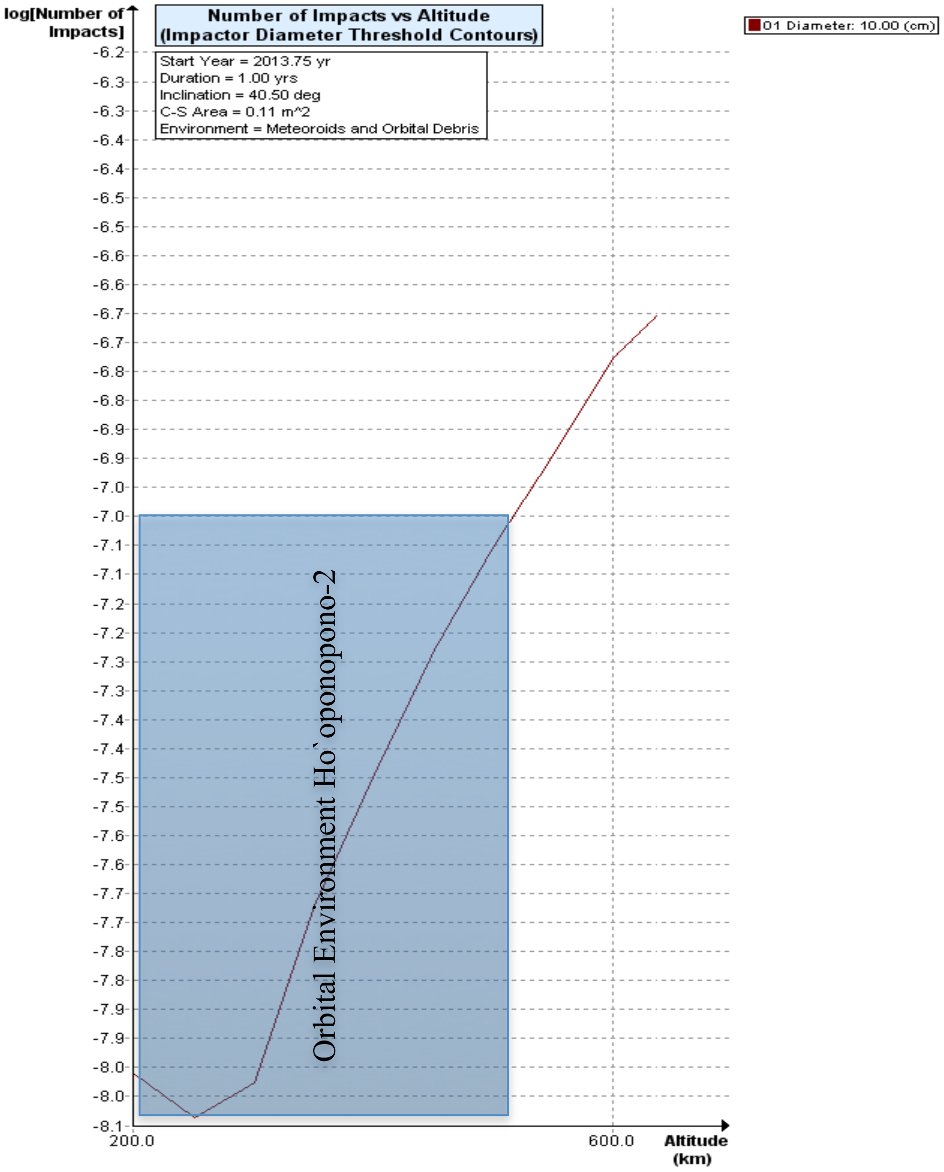

Figure 5: Highest Risk of Orbit Collision vs. Altitude (Ho`oponopono-2 Deployed)

There will be no post-mission disposal operation. As such the identification of the Ho`oponopono-2 components required to accomplish post-mission disposal operation, including passivation and maneuvering, is not applicable.

The probability of the Ho`oponopono-2 CubeSat colliding with debris and meteoroids greater than 10 cm in diameter and capable of preventing post-mission disposal is less than
$10^{-7.0}$, for any configuration. This satisfies the 0.001 maximum probability requirement 4.5-1.

Since the Ho`oponopono-2 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 the Ho`oponopono-2 CubeSat to be compliant. Requirement 4.5-2 is not applicable to this mission.

Section 6: Assessment of Spacecraft Postmission Disposal Plans and Procedures

The Ho`oponopono-2 spacecraft 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 Ho`oponopono-2 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 for the Ho`oponopono-2 CubeSat in its stowed configuration is calculated for is 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

$$\frac{0.045\, m^2}{4.0\, kg} = 0.011 \frac{m^2}{kg}$$

The assessment of the Ho`oponopono-2 spacecraft illustrates they are compliant with Requirements 4.6-1 through 4.6-5.

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

DAS inputs are: 500 km maximum perigee X 500 km maximum apogee altitudes with an inclination of 40.5 degrees at deployment in the year 2013. An area to mass ratio of 0.011 m^2/kg for the Ho`oponopono-2 CubeSat was imputed. DAS 2.0.2 yields a 3.3 years orbit lifetime for Ho`oponopono-2 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 the Ho`oponopono-2 CubeSat 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.

2. The remaining higher temperature materials are shown to pose negligible risk to human casualty through a bounding analysis of the highest temperature components. For the Ho`oponopono-2 CubeSat, 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 Table 5)

Table 5: Ho`oponopono-2 CubeSat Stainless Steel DAS Analysis

CubeSat	ELaNa-4 Stainless Steel Components	Mass (g)	Length / Diameter (cm)	Width (cm)	Height (cm)		Demise Alt (km)	KE (J)
Ho`oponopono-2	Sep Switch Plunger	9.6	5.84	0.7	0.76		75	0

The majority of stainless steel components demise upon reentry. For the Ho`oponopono-2 CubeSat, 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 (j).

Through the method described above, Table 5: Ho`oponopono-2 CubeSat Stainless Steel DAS Analysis, and the full component lists in the Appendix the Ho`oponopono-2 CubeSat launching under the ELaNa 4 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 the Ho`oponopono-2 CubeSat components.

Section 8: Assessment for Tether Missions

The Ho`oponopono-2 CubeSat will not be deploying any tethers.

The Ho`oponopono-2 CubeSat satisfies Section 8’s requirement 4.8-1.

Appendix Index:

Appendix A. Ho`oponopono-2 CubeSat 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
1	Ho'oponopono		1	Assorted	CubeSat	3517.4	110.5	376.5	110.5	y		Demises
2	CubeSat Structural Chassis	External - Major	1	Al 6061-T6	Box	745	100	340.5	100	y		Demises
3	Transponder Antenna	External - Major	1	Assorted	Helix w/ Radome	101.5	50.8	50.8	76.2	y		Demises
4	GPS Antenna	External - Major	1	Aluminum		76	50.8	50.8	13.5	y		Demises
5	COM Antenna Assy	External - Minor	1	Delrin/Brass/Steel	Deployable Monopoles	41.5	90.5	90.5	18.4	Mixed Melt	175 / 1000 / 1500	Component’s average density is calculated to 2.75g/cm^3 while stainless steel is 7.86g/cm^3 indicating only a small amount of stainless steel. In particular, Delrin melts at an extremely low temperature of approximately 175 deg. Therefore it provides negligible risk, bounded by larger SS components. See Table 5.
6	Long Solar Panel	External - Major	2	G10/Glass	Panel	87.2	81.3	288.3	1.7	y		Demises
7	Long Solar Panel C	External - Major	2	G10/Glass	Panel	87.2	81.3	288.3	1.7	y		Demises
8	Sep Switches	External - Minor	3	Assorted		3.5	6.4	19.8	11.5	y		Demises
9	Sep Switch Plunger	External - Minor	2	316L Stainless Steel	Plunger	9.6	7	58.4	7.6	High Melt		Demises See Table 5
10	Zenith Sun Sensor Assy	External - Minor	1	G10/Al 6061-T6	PCBA w/ Bracket	7.8	25.4	31.7	17.9	y		Demises
11	GG Endmass	External - Minor	1	316L Stainless Steel	Block	131.5	25.4	30.5	16.7	High Melt	1500	Demises See Table 5.
12	Frangibolt	Internal - Minor	1	Shape Memory Alloy	Actuator	6	10.2	12.7	15	y		Demises
13	Frangibolt Bracket	Internal - Minor	1	Al 6061-T6	Bracket	3.4	14	17.8	12.7	y		Demises

17	Transponder Box	Internal - Major	1	Assorted	Box	377	76.2	88.9	33	y		Demises
18	ADCS/GG Assembly	Internal - Major	1	Al 6061-T6	Bracket/Reel	589.2	93.7	141.7	33.7	y		Demises
19	Nadir Torque Coil	Internal - Minor	1	G10	PCBA	4.5				y		Demises
20	PLD Board	Internal - Major	1	G10	PCBA	79.3	90.2	120.7	1.6	y		Demises
21	GPS Unit	Internal - Major	1	G10	PCBA	22.1				y		Demises
22	COM Board	Internal - Major	1	G10	PCBA	91.2	90.2	120.7	1.6	y		Demises
23	EPS Board	Internal - Major	1	G10	PCBA	75.2	90.2	120.7	1.6	y		Demises
24	Board Mounts	Internal - Minor	12	Al 6061-T6	Bracket	2.5	11.9	20.3	16.5	y		Demises
25	Sun Sensor Board	Internal - Major	1	G10	PCBA	28.6	110.5	110.5	1.6	y		Demises