Spinnaker3

Orbital Debris Assessment Report

(ODAR)

V4.0

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Record of Revisions

Revision	Date	Affected Pages	Description of Changes	Authors
Draft	1/6/2020	All	Initial Document	Brigitte Petersen
1.0	2/20/2020	All	Battery Material check	Brigitte Petersen
2.0	2/26/2020	7, 14, 15	General updates	Brigitte Petersen
3.0	4/9/2020	4, 5	Update Schedule	Alicia Johnstone
4.0	6/10/2020	4, 11,13,14	Update “spacecraft” language and clarify analysis configuration	Alicia Johnstone

Self-Assessment of the ODAR

A self-assessment of the ODAR is provided below.

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	Minimal risk to orbital environment, mitigated by orbital lifetime.
4.4-2	Compliant	Minimal risk to orbital environment, mitigated by orbital lifetime.
4.4-3	Not applicable	No planned breakups
4.4-4	Not applicable	No planned breakups
4.5-1	Compliant	Minimal risk, mitigated by orbital lifetime.
4.5-2	Not applicable	Minimal risk, mitigated by orbital lifetime.
4.6-1(a)	Compliant	Worst case lifetime 85 days
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

Section 1: Program Management and Mission Overview

The Spinnaker3 mission, a project in conjunction with Purdue University and the Cal Poly CubeSat Lab, will demonstrate deployment of a dragsail deorbit device and induce a decrease in the predicted deorbit time of the Firefly Alpha launch vehicle second stage. Following spacecraft health checkouts, Spinnaker3 will deploy an 18m^2 dragsail via four SHEAR-less booms designed by NASA Langley.

NOTE: All mentions of Spinnaker3 or "spacecraft" refer to the Spinnaker3 payload, which is attached to the spent Firefly Alpha upper stage throughout the orbital lifetime.

Spinnaker3: Anthony Cofer & David Spencer, Payload Managers; Brigitte Petersen, Avionics Manager

Launch Vehicle and launch site: Firefly Alpha from Vandenberg Air Force Base, CA.

Proposed launch date: July 2020

Mission duration: Between 2 and 150 days (most conservative analysis)

Launch and deployment profile, including all operational orbits with apogee, perigee, and inclination:

The Spinnaker3 orbital elements are defined as follows:

Apogee: 300 km

Perigee: 300 km

Inclination: 97 degrees

Foreign government or space agency participation:

- No foreign agency is participating in this mission. All personnel are United States citizens.

Summary of NASA's responsibility under the governing agreement(s):

- Not applicable

Table 2: Program Milestone Schedule

Program Milestone Schedule	
Task	Date
CubeSat Build, Test, and Integration	Q3 2019 – Q2-2020
Flight Unit Integration and Testing	Q2-2020
Environmental Testing	Q2-2020
Mission Readiness Review	Q2-2020
Launch Vehicle Integration	Q2-2020
Launch	Q3-2020 (approx. July 2020)
Deployment and Operations	Q3-2020 (2-150 day mission duration)

Section 2: Spacecraft Description

Physical description of the spacecraft:

Spinnaker3 is approximately a 9U CubeSat on 4 stilts (Pedestal Assembly) to raise the CubeSats height on the primary payload interface 30cm. Spinnaker3 has a total mass of 15.9 kg.

Table 3: Spinnaker3 Summary

CubeSat Quantity	CubeSat	CubeSat Name	CubeSat Mass (kg)
1	9U and Pedestal (200mm x 200mm x 640mm)	Spinnaker3	15.9

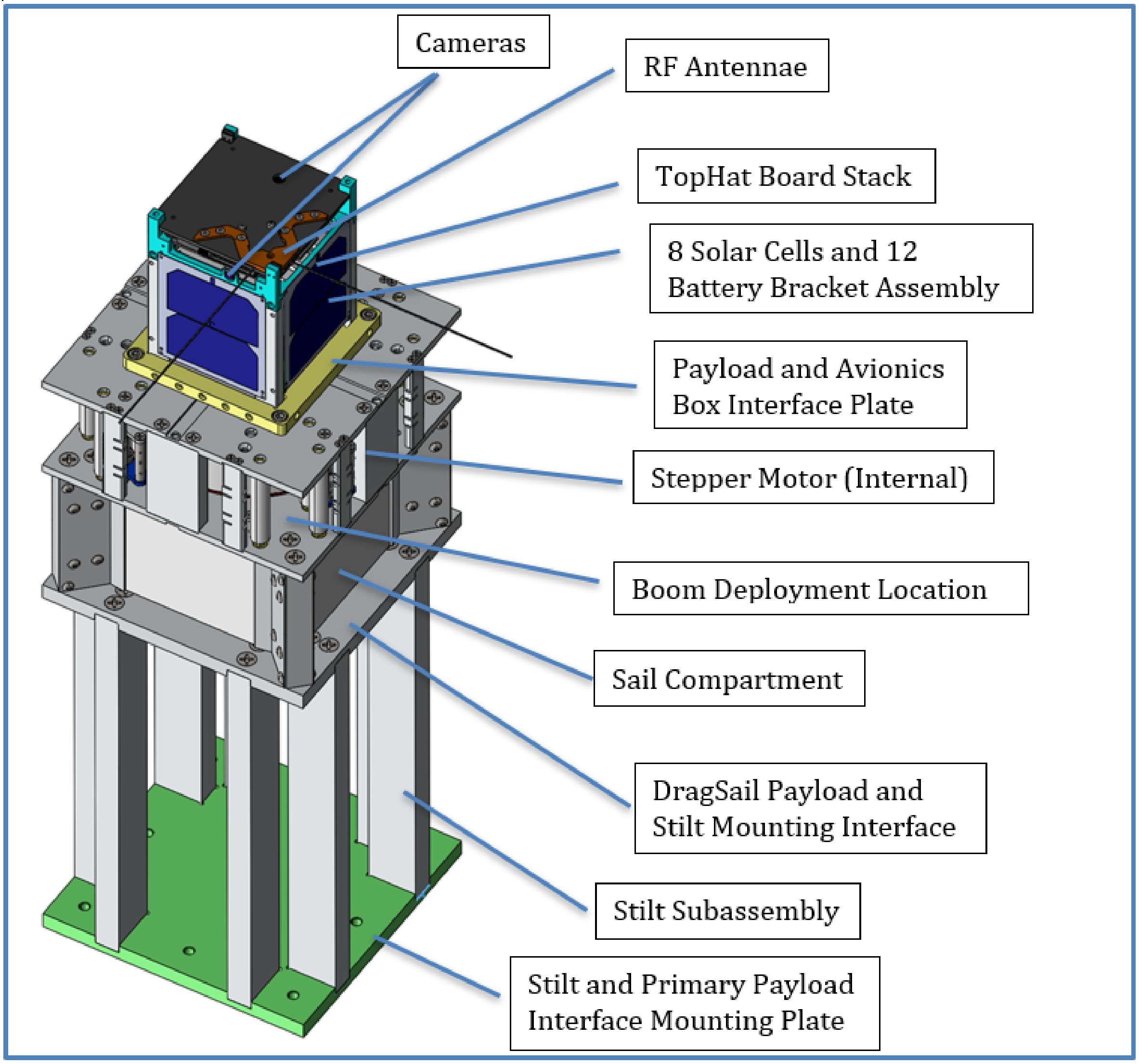

Figure 1: Spacecraft Physical Layout, An Expanded View

The Spinnaker3 payload is an 18 m^2 dragsail, sized to provide deorbit capability for the Firefly upper stage from altitudes of up to 650 km. The 8U 20 x 20 x 20 cm dragsail assembly and 1U 10 x 10 x 10 cm avionics box Spinnaker3 payload will be mounted on a set of stilts that connect to an interface plate, secured to the upper stage using the 15-inch Lightband standard interface. The stilt subassembly is only included to prevent physical interference with a neighboring payload.

Payload system startup will be initiated via a signal from the launch system of 3 – 5 amps for 150 – 500 ms. The Spinnaker3 avionics are based on the PolySat standard spacecraft bus avionics, adapted from the Aerodynamic Deorbit Experiment CubeSat. The PolySat flight software architecture is built around the Linux operating system, and operates on the flight-proven PolySat flight computer. A half-duplex, UHF band radio and a dipole antenna provides uplink and downlink capability at a frequency of approximately 437.15

MHz. A communications beacon will be transmitted at regular intervals, and file and image downlinks can be initiated via ground commands. An OmniVision OV3642 camera will be used to capture an image sequence of sail deployment. The camera will be configured to capture the dragsail and the Firefly upper stage in the field of view. The payload is powered by 12 Tenergy 18650 batteries (9V, 2200 mAh), sufficient to provide an operating lifetime of 35.28 hours with an average power utilization of 0.62 W while beaconing.

Dragsail deployment is initiated autonomously following system startup. A single stepper motor is used to control the deployment of four 3m SHEAth-based Rollable LEnticular Shaped and low-Stiction (SHEERLESS) carbon fiber booms developed by NASA Langley Research Center. Four triangular sail segments will unfurl as the booms are deployed. The sail material is aluminized Mylar with a thickness of 5 microns. Deployment of the sail takes approximately four minutes.

Spacecraft tracking and mission operations will be conducted at Purdue University and Cal Poly San Luis Obispo, while conops will be controlled at Cal Poly.

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.

There are no pressure vessels, hazardous or exotic materials.

The electrical power storage system consists of common lithium-polymer batteries with over-charge/current protection circuitry.

The spacecraft is not required to fit the CubeSat standard for a 9U as per Firefly aerospace standards for the Alpha launch vehicle. The maximum height due to fairing limitations is 2.5m which the spacecraft does not exceed.

Section 3: Assessment of Spacecraft Debris Released during Normal Operations

No releases are planned on the Spinnaker3 CubeSat mission therefore this section is not applicable.

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.

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

There are no plans for designed spacecraft breakups, explosions, or intentional collisions on the Spinnaker3 mission. No passivation of components is planned at the End of Mission for the Spinnaker3 CubeSat.

The probability of battery explosion is very low, and, due to the very small mass of the satellites and their short orbital lifetimes the effect of an explosion on the far-term LEO environment is negligible (ref (i)).

The CubeSats batteries still meet Req. 56450 (4.4-2) by virtue of the HQ OSMA policy regarding CubeSat battery disconnect stating;

"CubeSats as a satellite class need not disconnect their batteries if flown in LEO with orbital lifetimes less than 25 years." (ref. (i))

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.

Analysis in this section soley pertains to the Spinnaker3, and not the attached Alpha upper stage. For upper stage information, please refer to the Firefly ODAR, “FIREFLY ODAR V002”.

The largest mean cross sectional area (CSA) of Spinnaker3 is when it is fully deployed with antennas and solar sail deployed (424.26cm x 424.26cm):

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

Equation 1: Mean Cross Sectional Area for Convex Objects

The Spinnaker3 CubeSat evaluated for this ODAR is stowed in a convex configuration, indicating there are no elements of the CubeSat obscuring another element of the same CubeSat from view. Thus, mean CSA for Spinnaker3 was calculated using Equation 1. This configuration renders the longest orbital lifetime.

Spinnaker3 will be in the stowed configuration immediately after second stage fairing separation. After a TBD amount of time on the order of hours, the SHEAR-less™ booms will deploy the four panels of the dragsail. Once attitude determination has been established, the cross sectional area is now determined by what surface area is exposed normal to the velocity vector.

In determining the cross sectional area used in the DAS (Debris Assessment Software) analysis only the deployed configuration was considered. In the best case orbit lifetime scenario the full drag sail is presented to the velocity vector. The dragsail obscures all additional CubeSat geometry in a best case scenario, and the second stage obscures all additional CubeSat at most other angles. The second stage is not considered a part of the system in this report, and was not included in DAS analysis completed on Spinnaker3. Firefly aerospace has proven that the second stage individually follows all applicable ODAR requirements (ref Firefly Alpha ODAR Ver002, 1 NOV 2019), and this analysis will not be included in this report.

The Spinnaker3 orbit at deployment is 300 km apogee altitude by 300 km perigee altitude, with an inclination of 97 degrees. Using NASA’s DAS 2.1.1 (Debris Assessment Software), the orbital lifetime in a best case scenario is approximately 2 days. In the case that the sail is unable to deploy, the orbital lifetime will be no more than 150 days.

Table 4: CubeSat Orbital Lifetime & Collision Probability

	Sail Deployed	**Sail Stowed**
Orbital Lifetime	2 Days	150 Days
Mass (kg)	15.9	15.9
C/S Area (m^2)	18	0.087
Area-to-Mass (m^2/kg)	1.13208	0.005472
Probability of Collision	0.000000	0.000000

Post-mission disposal shall be accomplished passively should the dragsail not successfully deploy, therefore post-mission disposal is guaranteed to occur even without mission success.

The probability of a Spinnaker3 collision with debris and meteoroids greater than 10 cm in diameter was calculated with DAS to be 1x10^-4 in a worst case situation. This satisfies the 0.001 maximum probability requirement 4.5-1.

Requirement 4.5-2 is not applicable due to short mission lifetime and passive post-mission disposal.

Section 6: Assessment of Spacecraft Postmission Disposal Plans and Procedures

Analysis in this section was performed on the most conservative confiruation and soley pertains to the Spinnaker3, not the attached Alpha upper stage. For upper stage information, please refer to the Firefly ODAR, "FIREFLY ODAR V002".

Spinnaker3 will naturally decay from orbit within 150 days after the start of the mission, satisfying requirement 4.6-1a detailing the spacecraft disposal option.

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

Calculating the area-to-mass ratio for the worst-case (smallest Area-to-Mass) postmission disposal among the CubeSats finds Spinnaker3 in its stowed configuration as the worst case. The area-to-mass is calculated for is as follows:

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

Equation 2: Area to Mass

A stowed Spinnaker3 has the smallest Area-to-Mass ratio and as a result will have the longest orbital lifetime. DAS calculated the final Area-to-Mass ratio with a stowed sail to be 0.005 m^2/kg. The assessment of the spacecraft illustrates it is compliant with requirement 4.6-1. Requirements 4.6-2 through 4.6-5 are not applicable as the max orbital lifetime is less than 150 days and the spacecraft remains within LEO throughout the duration of the mission; risk to on-orbit collision is therefore minimal.

<u>DAS 2.1.1 Orbital Lifetime Calculations:</u>

DAS inputs are: 300 km maximum perigee 300 km maximum apogee altitudes with an inclination of 97 degrees at deployment in the year 2020. An area to mass ratio of 0.005 m^2/kg for the Spinnaker3 CubeSat was inputed. DAS yields a 150 day maximum orbit lifetime for Spinnaker3 in its stowed state.

This meets requirement 4.6-1. Assessment results show compliance.

Section 7: Assessment of Spacecraft Reentry Hazards

Analysis in this section soley pertains to the Spinnaker3, and not the attached Alpha upper stage. For upper stage information, please refer to the Firefly ODAR, "FIREFLY ODAR V002".

A material assessment of the components to be flown on Spinnaker3 was performed using DAS 2.1.1, 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 considering 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 component's potential reentry risk relative to the 4.7-1 requirement of having less than 15 J of kinetic energy and a 1:10000 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: Spinnaker3 High Melting Temperature Materials DAS Analysis

Stainless Steel Components	Material	Mass (g)	Demise Alt (km)	KE (J)
Antenna	Nickel Titanium (NiTi)	3	0	0
Motor	Stainless Steel	661	64.2	0
Door Hinge	Stianless Steel	52	76.8	0
Tensioner Post	Stainless Steel	50	77.4	0
Tensioner Spring	Stainless Steel	26	75.6	0
Fasteners	Stainless Steel	130	75.4	0

The majority of components demise upon reentry. The component that DAS conservatively identifies as reaching the ground has 0 joules of kinetic energy, far below the requirement of 15 joules. No 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: Spinnaker3 High Melting Temperature Materials DAS Analysis, and the full component list in the Appendix Spinnaker3 has been conservatively shown to be in compliance with Requirement 4.7-1 of NASA-STD-8719.14A.

Section 8: Assessment for Tether Missions

Spinnaker3 will not be deploying any tethers.

Spinnaker3 satisfy Section 8’s requirement 4.8-1.

Appendix

Payload Section Component List

Row Number	Name	Qty	Material	Body Type	Mass (g)	Diameter/ Width (mm)	Length (mm)	Height (mm)	Low Melting	Melting Temp C	Survivability
1	Bottom Plate	1	6061 T6	Box	1274	200	200	12	yes	--	Demise
2	Bottom Post	4	6061 T6	Box	698	36	18	105	yes	--	Demise
3	Sail Caddy	4	6061 T6	Box	168	105	240	1	yes	--	Demise
4	Motor Mount	1	6061 T6	Box	73	45	45	10	yes	--	Demise
5	Motor	1	Stainless Steel	Box	661	42	42	108	no	1400	Demise
6	Sail Door	4	6061 T6	Box	288	102	6	102	yes	--	Demise
7	Door Magnet	4	Nd, Fe, Ni	Box	13.6	10	10	10	yes	--	Demise
8	Door Hinge	8	Stainless Steel	Box	52	10	20	5	no	1400	Demise
9	Sail Quadrant	4	Polycarbonate	Box	132.8	100	20	100	yes	--	Demise
10	Sail to Body Linkage	8	304 SS	Box	22.4	20	20	10	yes	--	Demise
11	Sail to Boom Linkage	8	304 SS	Box	12.8	20	20	6	yes	--	Demise
12	Top Plate	1	6061 T6	Box	613.2	200	200	6	yes	--	Demise
13	Center Plate	1	6061 T6	Box	605.7	200	200	6	yes	--	Demise
14	Post	4	6061 T6	Box	327.2	40	13	72	yes	--	Demise
15	Spring Block	8	6061 T6	Box	135.2	16	6	72	yes	--	Demise
16	Roller Post	12	6061 T6	Cylinder	162.8	5	77	--	yes	--	Demise
17	Tensioner Roller Post	4	6061 T6	Cylinder	12	6	41	--	yes	--	Demise
18	Tensioner Roller	4	PTFE	Cylinder	28.8	13	34	--	yes	--	Demise
19	Tensioner Post	4	Stainless Steel	Cylinder	50	5	71	--	no	1400	Demise
20	Tensioner Post Sleeve	4	PTFE	Cylinder	7.2	6	36	--	yes	--	Demise
21	Tensioner Top	4	6061 T6	Box	14.4	46	24	3	yes	--	Demise
22	Tensioner Bottom	4	6061 T6	Box	14.4	46	24	3	yes	--	Demise
23	Tensioner Spring	16	Stainless Steel	Cylinder	25.6	11	6	--	no	1400	Demise
24	Bottom Rotor	1	6061 T6	Cylinder	66.7	76	23	--	yes	--	Demise
25	Bottom Flange	1	6061 T6	Cylinder	214.5	150	7	--	yes	--	Demise
26	Boom	4	Carbon Fiber	Cylinder	404	32	2997	--	yes	--	Demise
27	Boom Mount	4	Carbon Fiber	Box	181.2	46	47	42	yes	--	Demise
28	Boom Mount Peg	8	6061 T6	Cylinder	20.8	5	33	--	yes	--	Demise
29	Center chunk	1	6061 T6	Box	82.5	31	31	46	yes	--	Demise
30	Lineup Pin	2	6061 T6	Cylinder	3.6	6	76	--	yes	--	Demise
31	Top Flange	1	6061 T6	Cylinder	192.2	150	7	--	yes	--	Demise
32	Top Rotor	1	6061 T6	Cylinder	57.6	76	11	--	yes	--	Demise
33	Boom Cap	4	6061 T6	Cylinder	30.8	32	3	--	yes	--	Demise
34	Boom Cap Cover	4	6061 T6	Cylinder	6.8	32	3	--	yes	--	Demise
35	Boom Cover	4	6061 T6	Cylinder	139.6	32	2997	--	yes	--	Demise
36	Ceramic Bearings	2	Zr02	Cylinder	49.6	52	7	--	yes	--	Demise
37	Fasteners	255	Stainless Steel	Cylinder	68	2.2	7.62		no	1400	Demise

Avionics Section Components List

Row Number	Name	Qty	Material	Body Type	Mass (g)	Diameter/ Width (mm)	Length (mm)	Height (mm)	Low Melting	Melting Temp C	Survivability
1	1U Structure	1	Al 6061	Box	155	100	100	100	yes	--	Demise
2	Antenna	2	Nitinol Wire	Cylinder	3	0.3	160		no	1400	Demise
3	Antenna Route	1	Delrin	Rect Prism	4	2.64	81.8	25.88	yes	--	Demise
4	Solar Cell	16	Germanium	Sheet	36	40	69	0.45	yes	--	Demise
5	SidePanels	5	Fiberglass	Box	67	82.7	109.5	1.55	yes	--	Demise
6	Batteries	12	Li Cobalt Ox	Cylinder	132	37	66		yes	--	Demise
7	Battery Mount	1	Al 6061	Box	28	82	82	52	yes	--	Demise
8	Fasteners	88	Stainless Steel	Cylinder	40	2.2	7.62		no	1400	Demise
9	Cabling	many	Copper	Wire	1025	2.2	7.6		yes	--	Demise
10	System Board	1	Fiberglass	Box	60	83	100	13.8	yes	--	Demise
11	ayload Interface Boar	1	Fiberglass	Box	50	83	83	3	yes	--	Demise
12	Comm Board	1	Fiberglass	Box	20	36	82	5	yes	--	Demise
13	Battery Board	1	Fiberglass	Box	20	20	30	1.6	yes	--	Demise

Pedestal Components List

Row Number	Name	Qty	Material	Body Type	Mass (g)	Diameter/ Width (mm)	Length (mm)	Height (mm)	Low Melting	Melting Temp C	Survivability
1	Base Plate	1	Aluminum 6061	Flat Plate	1340	200	200	12	yes	--	Demise
2	Base Post	8	Aluminum 6061	Box	3276	34	16	287	yes	--	Demise
3	Adapter Plate	1	Aluminum 6061	Flat Plate	660	200	200	6	yes	--	Demise
5	Leg Magnets	4	Nd, Fe, Ni	Cylinder	5	10	15	n/a	yes	--	Demise
6	Connector	1	Aluminum 6061	Cylinder	4	25	13	n/a	yes	--	Demise
7	Connector Mount	1	Aluminum 6061	Cylinder	11	38	15	n/a	yes	--	Demise
8	Fasteners	48	Stainless Steel	Cylinder	22	2.2	7.62		no	1400	Demise