ELVL-2022-0046469
Revision A
December 17, 2023

Orbital Debris Assessment for the M3 CubeSat per NASA-STD 8719.14C

Signature Page

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ELVL-2022-0046469
December 17, 2023

TO: Norman Phelps, LSP Mission Manager, NASA/KSC/VA-C

FROM: Caley Burke, NASA/KSC/VA-H1

SUBJECT: Orbital Debris Assessment Report (ODAR) for the M3 CubeSat

REFERENCES:

A. NASA Procedural Requirements for Limiting Orbital Debris Generation, NPR 8715.6B, 6 February 2017
B. *Process for Limiting Orbital Debris*, NASA-STD-8719.14C, 5 November 2021
C. McKissock, Barbara, Patricia Loyselle, and Elisa Vogel. *Guidelines on Lithium-ion Battery Use in Space Applications*. Tech. no. RP-08-75. NASA Glenn Research Center Cleveland, Ohio
D. *UL Standard for Safety for Lithium Batteries, UL 1642*. UL Standard. 5th ed. Northbrook, IL, Underwriters Laboratories, 2012
E. Kwas, Robert. Thermal Analysis of ELaNa-4 CubeSat Batteries, ELVL-2012-0043254, November 2012
F. Range Safety User Requirements Manual Volume 3- Launch Vehicles, Payloads, and Ground Support Systems Requirements, AFSCM 91-710 V3, 15 May 2019
G. NASA HQ Office of Safety and Mission Assurance (OSMA) Policy Memo/Email to 8719.14: *CubeSat Battery Non-Passivation*, Suzanne Aleman to Justin Treptow, 10 March 2014
H. NASA Orbital Debris Program Office (ODPO) Guidance Email: *Fasteners and Screws*, John Opiela to Yusef Johnson, 12 February 2020
I. *Debris Assessment Software User's Guide: Version 3.2*, NASA/TP-20210025946, December 2021

This report shows compliance with the orbital debris requirements listed in Reference A for the Multi-Mode Mission (M3) CubeSat launching on the SpaceX Transporter-10 mission. It serves as the final submittal in support of the spacecraft Safety and Mission Success Review (SMSR). Sections 1 through 8 of Appendix A.1.6 in Reference B are addressed in this document; sections 9 through 14 fall under the requirements levied on the primary mission and are not presented here.

This CubeSat will passively reenter, and therefore this ODAR will also serve as the End of Mission Plan (EOMP) for this CubeSat.

RECORD OF REVISIONS		
REV	DESCRIPTION	DATE
0	Original submission	May 2023
A	• Update launch orbit and date • Clarify passivation of stored energy sources on the CubeSat	December 2023

Section 1: Program Management and Mission Overview

M3 is sponsored by the Space Operations Mission Directorate at NASA Headquarters. The Program Executive is Jeanie Hall. Responsible program/project manager and senior scientific and management personnel are as follows:

Dr. Hank Pernicka, PM, Missouri Science & Technology University
Joshua Burch, Chief Engineer

The following table summarizes the compliance status of CubeSat, which will be flown on the SpaceX Transporter-10 mission. The current launch date is planned for no earlier than March 1, 2024 (2024.164 for DAS input). DAS version 3.2.5 was used to generate the data provided in this document. The CubeSat 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(s) incapable of debris-producing failure
4.4-2	Compliant	
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	No postmission disposal maneuvers
4.6-1a-c	Compliant	Maximum lifetime: 6.4 years
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 releases

Section 2: Spacecraft Description

Table 2 outlines the CubeSat's generic attributes.

Table 2: M3 Attributes

CubeSat Name	CubeSat Quantity	CubeSat size (mm)	CubeSat Mass (kg)
M3	1	344 x 108 x 102	4.0

The following pages describe the CubeSat.

M3 – Missouri University of Science and Technology– 3U

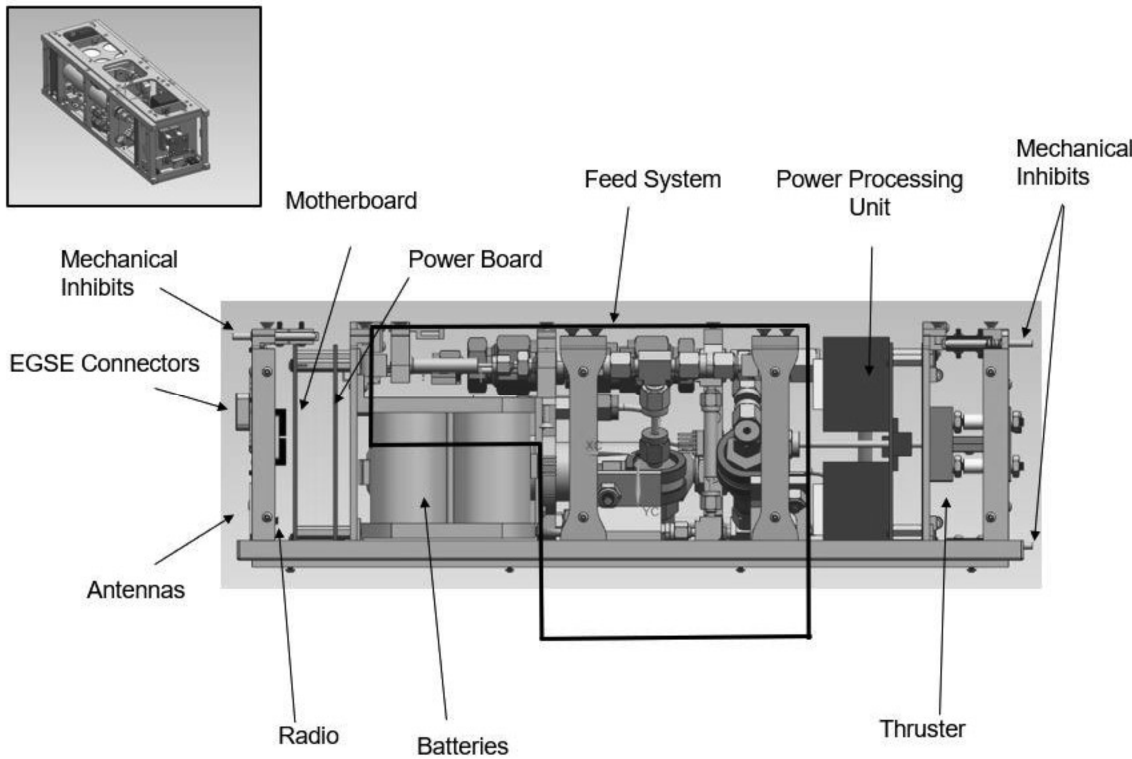

Figure 1: Spacecraft with side panels removed

Overview

The overall goal of the M3 mission is to demonstrate in the space environment a multi-mode-capable thruster operating in electric mode with a student-developed power processing unit (PPU), utilizing an ionic propellant.

Concept of Operations (ConOps)

The CubeSat will begin transmitting 7 days after ejection from the deployer and cease after complete battery discharge.

Once the propellant reaches the desired temperatures, the flight computer will command the propellant feed system solenoid valves to open and the PPU to supply power to the payload, beginning an electrospray burn. The flight computer will then initiate a burn timer and continue the burn until the burn timer expires or the satellite batteries deplete to 30% charge.

The CubeSat will perform five electric burns for 30 seconds each while in this mode. During the burns, voltage from the payload's extractor will be measured by voltage dividers located on the flight computer and recorded at a rate of 1 Hz for insertion into a multi-mode thruster performance model.

Once the burn timer has expired, the CubeSat will close its solenoid valves, cease measuring the voltage from the voltage dividers, and cease supplying power to the payload. A full system checkout will be performed by the flight computer to ensure the health of the CubeSat. During this time, the CubeSat will also downlink temperature and pressure measurements from the burn and continue regular system health checks.

Upon completion of all five burns in Electric Burn Mode, the CubeSat will enter into its Downlink Mode. If, at any point during Electric Burn Mode, the satellite fails a health check, the CubeSat will enter the Primary Safe Mode. No deployables are used. An Eyestar-S4 simplex transmitter is utilized for downlinking thruster test data. An S band receiver on board the satellite can receive a “kill” command to immediately cease all transmissions.

The mission ends once the batteries can no longer provide enough power for the CubeSat to transmit.

The total delta-V for the mission duration will be 0.05 m/s. This has a negligible effect on the orbit (~0.17 km altitude maximum).

Materials

The CubeSat structure is composed of aluminum 6061. It contains standard commercial off-the-shelf (COTS) materials, electrical components, and printed circuit boards (PCBs) with the exception of the in-house developed thruster/propellant feed system (which largely consists of stainless-steel components).

Hazards

The propulsion system uses an ionic propellant (1-Ethyl-3-methylimidazolium ethyl sulfate ($C_8H_{16}N_2O_4S$)) classified as “not a hazardous substance or mixture” by its Material Safety Data Sheet (MSDS). There are 7 grams of propellant in the system. The propellant is fed into the thruster by gaseous nitrogen (N_2) gas loaded at 30 psia. Inhibits are used to prevent premature pressurant and propellent flow prior to orbit deployment.

The electric thruster releases small propellent droplets as part of its nominal operation; at the low orbital altitude and ballistic coefficient of each droplet they are expected to harmlessly disperse very quickly with no chance of presenting a debris hazard.

The CubeSat will complete five electric thruster burns lasting 30 seconds. The CubeSat will undergo environmental testing with propellant loaded and verify that there are no leaks. The Propellant System Hazards and Operability Study is in Appendix B.

The ionic propellant will be mostly exhausted by the five burns of the nominal mission; only a residual amount will remain.

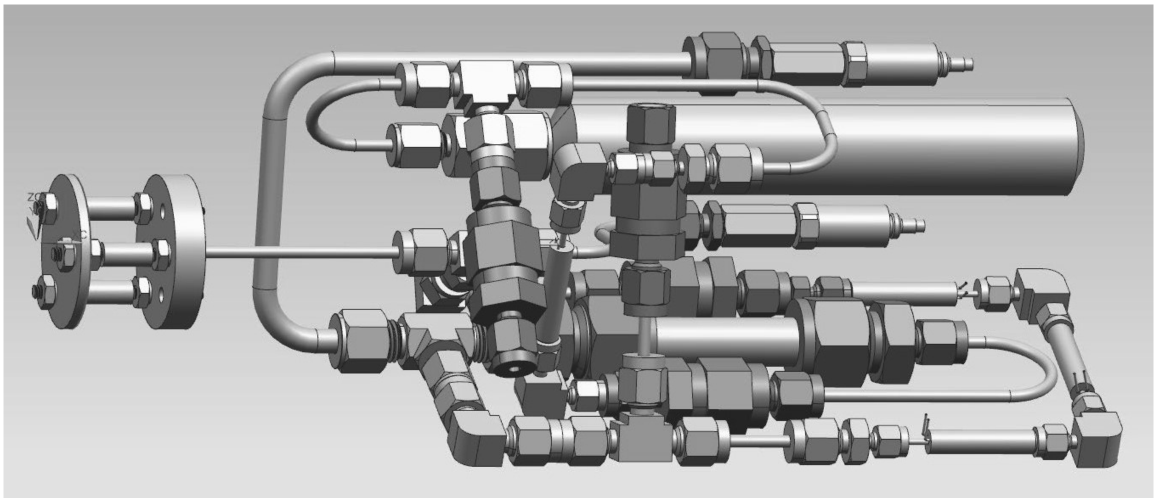

Figure 2: Spacecraft propulsion system CAD

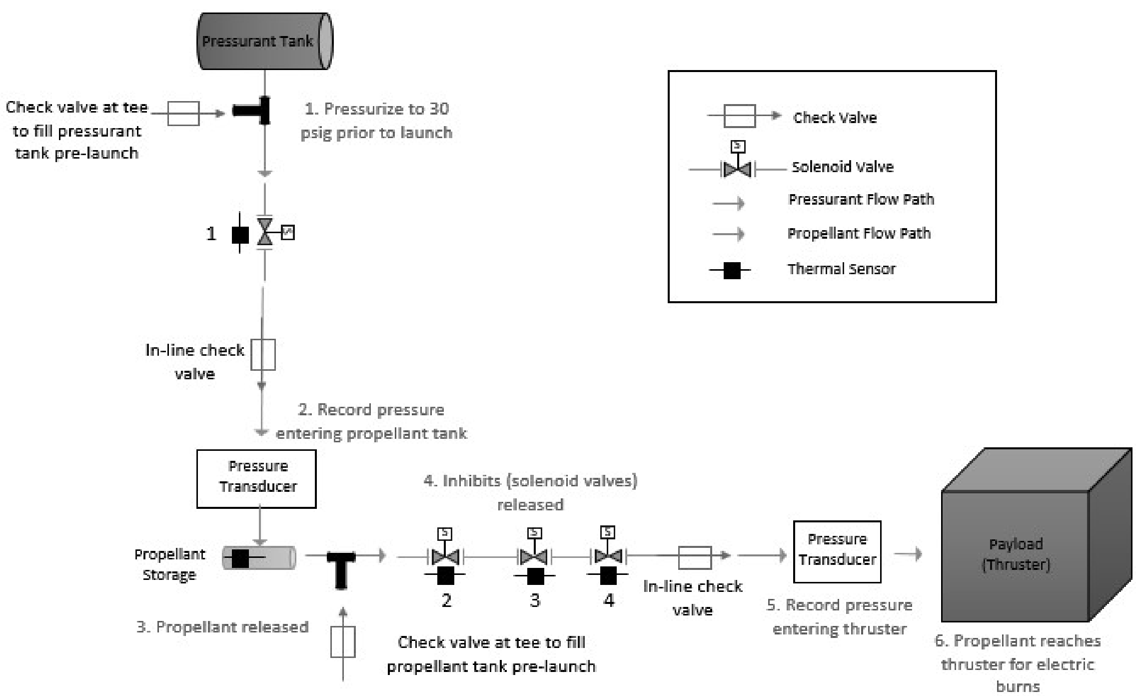

Figure 3: Spacecraft propulsion system schematic

Batteries

The electrical power storage system consists of four common EaglePicher LCF-133 3.0V Primary D Cell (non-rechargeable) lithium metal batteries with current protection circuitry. The nominal voltage and capacity for each battery is 2.6V and 16 Ah, respectively. The batteries have a fully welded hermetically sealed design, pressure relief vent, and shutdown separator.

A custom battery pack was developed in conjunction with EaglePicher and is assembled in a 4S1P (4 series/1 parallel) configuration and is protected from reverse current by two active blocking diodes. Each cell is in series with a polymeric positive temperature coefficient (PTC) device.

The PTC is thermally coupled to the cell providing both resettable overload and over-temperature protection. A separate Power Processing Unit (PPU) PCB operates as a transformer, converting the 12-volt supply into 3400 volts to energize the thruster.

The spacecraft does not have any solar cells. The electrical power system is not capable of charging the batteries after launch.

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.

As no releases are planned on the CubeSat mission, Requirements 4.3-1a, 4.3-1b, and 4.3-2 are not applicable.

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

As discussed in Reference G, with respect to 3U and smaller CubeSats, 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.

All stored energy sources on the spacecraft will be passivated by the nominal mission.

The battery system is not connected to solar arrays or any other power source and has no ability to charge the batteries. The batteries will only ever have the charge they start with at launch; this initial charge will be mostly depleted by the time the mission has completed the five burns. The mission will continue as long as there is sufficient charge for the transmitter to operate; the batteries will continue to discharge until they are depleted.

After the burns, the pressure of the gaseous nitrogen (N2) will be less than the 5 psia. The ionic propellant on board is an inert material and is not a source of stored energy.

There are no plans for designed spacecraft breakups, explosions, or intentional collisions for the CubeSat.

Assessment of the power system and hazards in Section 2 shows that the CubeSat is compliant with Requirement 4.4-1.

Assessment shows that with a maximum lifetime of 6.4 years (see Table 3 in Section 5), the CubeSat is compliant with Requirement 4.4-2.

As no breakups are planned on the CubeSat mission, Requirements 4.4-3 and 4.4-4 are not applicable.

Section 5: Assessment of Spacecraft Potential for On-Orbit Collisions

The 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 (CSA) and orbital lifetime.

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

Equation 1: Mean Cross Sectional Area for Convex Objects

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

Equation 2: Mean Cross Sectional Area for Complex Objects

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

The CubeSat's nominal orbit at deployment has a 510 km apogee and a 510 km perigee at a 97.44° inclination. The error on the apogee is +/-20 km and on the perigee is +/-20 km. The maximum apogee is 530 km and 530 km perigee. The maximum altitude values along with the inclination and current launch date (see Section 1) are input into DAS to result in the maximum orbital lifetime for each area-to-mass ratio.

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

$$\frac{0.0416\ m^2}{4.0\ kg} = 0.010\frac{m^2}{kg}$$

DAS yields the orbit lifetime and corresponding probability of collision for the CubeSat configuration in Table 3.

Table 3: CubeSat Orbital Lifetime & Collision Probability

	CubeSat	Value
	Mass (kg)	4.0
As-Ejected	Mean C/S Area (m^2)	0.0416
	Area-to Mass (m^2/kg)	0.010
	Orbital Lifetime (yrs)	6.4
	Probability of collision (10^{-6})	1.54

Solar Flux Table Dated: September 27, 2023

The probability of the CubeSat colliding with debris or meteoroids greater than 10 cm in diameter that can prevent post-mission disposal is less than 1.54×10^{-6}. This satisfies the 0.001 maximum probability requirement 4.5-1.

Assessment of the CubeSat mission shows it to be compliant with Requirement 4.5-1.

As the CubeSat will be disposed of passively and has no post mission disposal maneuvers, Requirement 4.5-2 is not applicable.

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

The CubeSat will naturally reenter from its orbit within 25 years after end of the mission, complying with Requirement 4.6-1a.

Planning for spacecraft maneuvers to accomplish post-mission disposal is not applicable. Disposal will be achieved via passive atmospheric reentry.

The as-ejected area-to-mass ratio with the DAS inputs in Section 5 finds the maximum orbital lifetime for the launch date for post-mission disposal; see the as-ejected configuration's orbital lifetime in Table 3.

Assessment of the CubeSat mission shows it to be compliant with Requirement 4.6-1.

As the CubeSat mission's orbit will not exceed a LEO, Requirements 4.6-2 and 4.6-3 are not applicable.

As the CubeSat mission will be disposed of passively and has no post mission disposal maneuvers, Requirement 4.6-4 is not applicable.

Section 7: Assessment of Spacecraft Reentry Hazards

A detailed assessment of the components to be flown on the CubeSat was performed. The assessment used DAS, 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 they 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 1:10,000 probability of a human casualty in the event it survives reentry.

1. Low melting temperature (less than 1000 °C) components are identified as materials that would never survive reentry and pose no risk of 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 of human casualty through a bounding DAS analysis of the highest temperature components, stainless steel (1500°C). If a component has a melting temperature between 1000 °C and 1500°C, it can be expected to possess the same negligible risk as a stainless steel component of similar dimensions.

3. Fasteners and similar materials that are composed of stainless steel or a lower melting point material will not be input into DAS, as suggested by guidance from the Orbital Debris Project Office (Reference I)

Table 4: M3 High Melting Temperature Material Analysis

Name	Material	Total Mass (kg)	Demise Alt (km)	Kinetic Energy (J)
Pressurant Tank	AISI 316 Stainless Steel	0.1450	74.8	-
Battery D-Cell	Stainless Steel/Lithium	0.3415	73.3	-
1/2" to 1/8" Union Reducer	Stainless Steel	0.0780	72.3	-
1/8" Check Valve	Stainless Steel 316	0.2978	73.6	-
1/2" to 1/4" Stem Reducer	AISI 316 Stainless Steel	0.0659	74.0	-
1/4", 1/8" Tee Fitting	AISI 316 Stainless Steel	0.0599	76.9	-
3/8" to 1/8" Union Reducer	AISI 316 Stainless Steel	0.0419	74.6	-

Name	Material	Total Mass (kg)	Demise Alt (km)	Kinetic Energy (J)
1/8" Tee Fitting	Stainless Steel 316	0.1254	75.6	-
Pressure Transducer	Stainless Steel 316	0.0720	74	-
Thruster Heatsink	AISI 316 Stainless Steel	0.0300	75.7	-
1/8" Elbow	Stainless Steel 316	0.0596	75.5	-
1/4" Tube	AISI 316 Stainless Steel	0.0270	75.8	-
1/2" diam Propellant Tank	Stainless Steel 316	0.0215	76.6	-
1/4" 10-32 Male SAE	AISI 316 Stainless Steel	0.0206	75.5	-
Extractor Grid	AISI 316 Stainless Steel	0.0199	76	-
Union 1/8" to 1/16"	Stainless Steel 316	0.0177	75.4	-
1/8" to 1/16" Union Reducer	Stainless Steel 316	0.0177	75.4	-
1/16" Elbow	Stainless Steel 316	0.0163	75.9	-
1/8" 10-32 Male SAE	AISI 316 Stainless Steel	0.0134	75.9	-
10-32 Female Adapter	AISI 316 Stainless Steel	0.0194	75.6	-
Hysteresis Rod	Nickel	0.0246	76.6	-
1/16" to 1/8" Stem Adapter	AISI 316 Stainless Steel	0.0059	76.8	-
Solenoid Valve	316 Stainless Steel Chrome Core 18	0.0227	77.1	-
1/8" 90deg Connector	AISI 316 Stainless Steel	0.0045	77.1	-
1/8" 180 deg Tube	AISI 316 Stainless Steel	0.0084	77.2	-
1/8" Prop to Thruster Pipe	AISI 316 Stainless Steel	0.0035	77.3	-
1/8" Tube	AISI 316 Stainless Steel	0.0022	77.3	-
1/8" Connector Tube	Stainless Steel 316	0.0019	77.4	-
1/8" Tube	AISI 316 Stainless Steel	0.0018	77.3	-
1/8" Connector Tube	AISI 316 Stainless Steel	0.0015	77.3	-
1/8" Connector Tube	Stainless Steel 316	0.0036	77.3	-
1/8" to 1/16" Port Connector	AISI 316 Stainless Steel	0.0012	77.5	-
1/8" to 1/16" Port Reducing	AISI 316 Stainless Steel	0.0012	77.5	-

All high melting point components demise upon reentry and M3 complies with the 1:10,000 probability of Human Casualty Requirement 4.7-1. A breakdown of the determined probabilities follows:

Table 5: Requirement 4.7-1 Compliance by CubeSat

Name	Status	Risk of Human Casualty
M3	Compliant	0

*Requirement 4.7-1 Probability of Human Casualty ≤ 1:10,000

If a component survives to the ground but has less than 15 Joules of kinetic energy, it is not included in the Debris Casualty Area that inputs into the Probability of Human Casualty calculation. This is why the CubeSat has a zero probability, as none of its components have more than 15J of energy.

Assessment of the CubeSat mission shows it to be compliant with Requirement 4.7-1.

Section 8: Assessment for Special Classes of Space Missions

As the CubeSat mission will not be deploying any tethers or is in any of the special classes of space missions, Requirement 4.8-1 is not applicable.

Section 9-14

ODAR sections 9 through 14 pertain to the launch vehicle and are not covered here. Launch vehicle sections of the ODAR are the responsibility of the launch provider.

If you have any questions, please contact the undersigned at 321-867-5543.

/original signed by/

Caley Burke
Flight Design Analyst
NASA/KSC/VA-H1

cc : VA-C/Liam J. Cheney
VA-C/Norman L. Phelps
AIS2/ Maria Diaz
SA-D2/Homero Hidalgo

Appendix Index:

Appendix A. M3 Component List

Item Number	Name	Qty	Material	Body Type	Mass (g) (total)	Diameter / Width (mm)	Length (mm)	Height (mm)	High Temp	Melting Temp (F°)	Survivability
1	M3		Aluminum 6061	Box	3335.65	108.000	344.310	102.000	No	-	Demise
2	NSL RX Board	1	PCB	Plate	29.459	25.500	1.6000	55.000	No	-	Demise
3	Eyestar-S4 Board	1	PCB	Plate	17.230	25.500	14.207	55.000	No	-	Demise
4	Simplex Antenna	2	PCB	Plate	29.400	35.154	1.6764	35.154	No	-	Demise
5	Flight Computer	1	PCB	Plate	29.400	95.884	1.5748	90.168	No	-	Demise
17	EPS Board	1	PCB	Plate	60.000	95.885	1.5748	90.170	No	-	Demise
6	#4-48 x 1/4" Panhead Screw	5	AISI 316 Stainless Steel	Cylinder	2.1540	5.4102	5.4102	7.8586	No	-	Demise
7	Battery Pack Brace	1	Aluminum 6061	Plate	6.5170	15.000	3.0000	54.363	No	-	Demise
8	TC74 Temperature Sensor	2	PTFE/ETFE plastic	Plate	8.3224	10.541	4.6990	30.632	No	-	Demise
9	Battery Top Cap	1	Aluminum 6061	Plate	25.037	73.243	26.500	77.208	No	-	Demise
10	Battery Bottom Cap	1	Aluminum 6061	Plate	32.365	73.243	16.500	77.208	No	-	Demise
11	Battery Bottom insulator	1	PTFE (Teflon)	Plate	11.566	69.600	2.3620	69.600	No	-	Demise
12	Battery D-Cell	4	Stainless Steel/Lithium	Cylinder	341.49	33.300	33.300	55.120	Yes	2550°	Demise (73.3 km)
13	Battery Insulator	1	PEEK	Box	46.757	49.300	54.880	49.300	No	-	Demise
14	Battery Top Insulator	1	PTFE (Teflon)	Plate	3.7406	69.600	0.3810	69.600	No	-	Demise
15	Magnet Body Cover	1	Aluminum 6061	Plate	0.1462	6.0000	1.0000	11.000	No	-	Demise
16	Magnet Body	1	Neodymium	Cylinder	0.5660	3.1750	3.1750	9.5250	No	-	Demise
18	Switch Screw	6	AISI 316 Stainless Steel	Cylinder	1.8366	4.1656	4.1656	10.698	No	-	Demise
19	Pin	3	Aluminum 6061	Cylinder	2.2500	3.1750	3.1750	36.000	No	-	Demise
20	Retaining Ring	3	Steel 1060	Ring	0.0450	4.1910	0.3810	0.4000	No	-	Demise
21	Switch	3	PTFE Plastic	Box	5.3910	6.4000	14.601	19.812	No	-	Demise
22	Spring	2	Steel 1060	Cylinder	0.1674	0.4581	6.3010	4.5601	No	-	Demise

Item Number	Name	Qty	Material	Body Type	Mass (g) (total)	Diameter / Width (mm)	Length (mm)	Height (mm)	High Temp	Melting Temp (F°)	Survivability
23	PPU Board	1	PCB	Plate	217.80	90.200	42.650	95.800	No	-	Demise
24	Screw Standoffs	6	AISI 316 Stainless Steel	Cylinder	2.9244	5.5626	5.5626	7.6561	No	-	Demise
25	PPU Insulator	1	PTFE (Teflon)	Plate	6.8673	95.799	0.3810	90.198	No	-	Demise
26	Threaded Hex Standoff	4	AISI 316 Stainless Steel	Cylinder	3.6000	5.4993	5.4993	17.521	No	-	Demise
27	#2-64 x 1/4" Screw	63	AISI 316 Stainless Steel	Cylinder	14.276	4.1656	4.1656	7.5243	No	-	Demise
28	Flat Washer	6	AISI 316 Stainless Steel	Plate	2.4000	6.3500	0.4572	6.3500	No	-	Demise
29	Hole Mounted Clamp	4	AISI 316 Stainless Steel	Plate	7.6000	12.700	3.9688	17.502	No	-	Demise
30	SideBar 1A	1	Aluminum 6061	Plate	13.841	20.000	12.000	94.000	No	-	Demise
31	SideBar 2A	1	Aluminum 6061	Plate	12.795	20.000	12.000	94.000	No	-	Demise
32	Side Shield 3A	1	Aluminum 6061	Plate	58.850	83.000	1.0000	330.50	No	-	Demise
33	Side Shield 4A	1	Aluminum 6061	Plate	56.950	83.000	1.0000	330.50	No	-	Demise
34	1/16" Collar	2	Aluminum 6061	Plate	1.3000	16.611	3.0000	17.682	No	-	Demise
35	1/4" Flathead Screw	39	AISI 316 Stainless Steel	Cylinder	13.650	6.4770	6.4770	6.3500	No	-	Demise
36	1/2" Gasket PB2 1A	1	PTFE (Teflon)	Cylinder	2.0473	16.000	3.0000	16.000	No	-	Demise
37	1/8" Collar PB2 1A	2	Aluminum 6061	Plate	4.8730	27.994	3.0000	16.000	No	-	Demise
38	1/8" Collar PB2 2A	1	Aluminum 6061	Plate	2.4375	23.363	3.0000	20.101	No	-	Demise
39	1/8" Gasket PB2 1A	5	PTFE (Teflon)	Cylinder	3.2500	16.000	3.0000	16.000	No	-	Demise
40	Tank Collar	1	Aluminum 6061	Plate	2.3843	12.700	12.700	85.000	No	-	Demise
41	Tank Gasket	1	PTFE (Teflon)	Cylinder	0.5350	27.400	3.0000	27.400	No	-	Demise
42	10-32 Collar PB3 1A	2	Aluminum 6061	Plate	1.3508	17.400	3.0000	23.638	No	-	Demise
43	10-32 Gasket PB3 1A	2	PTFE (Teflon)	Cylinder	0.9722	14.000	3.0000	14.000	No	-	Demise
44	1/8" Collar PB3 1A	1	Aluminum 6061	Plate	2.1012	19.432	3.0000	24.769	No	-	Demise
45	#4-48 x 3/8" FlatScrew	41	AISI 316 Stainless Steel	Cylinder	20.500	6.5000	6.5000	9.5250	No	-	Demise
46	Hysteresis Rod	4	Nickel	Cylinder	24.600	3.3020	3.3020	80.000	Yes	2550˚	Demise (76.6 km)

Item Number	Name	Qty	Material	Body Type	Mass (g) (total)	Diameter / Width (mm)	Length (mm)	Height (mm)	High Temp	Melting Temp (F°)	Survivability
47	15mm Standoff	3	Aluminum 6061	Cylinder	0.8838	5.4993	5.4993	10.369	No	-	Demise
48	17mm Standoff	4	Aluminum 6061	Cylinder	3.0976	5.4993	5.4993	20.638	No	-	Demise
49	Wire Shield	1	Aluminum 6061	Plate	0.6271	12.000	1.0000	20.000	No	-	Demise
50	Prop Bracket Component	1	Aluminum_6060	Plate	25.184				No	-	Demise
51	1/8" Hex 1/4" Tube Collar	1	Aluminum 6061	Plate	1.6231	20.702	3.0000	34.493	No	-	Demise
52	1/8" Hex 1/4" Tube Gasket	1	PTFE (Teflon)	Cylinder	1.0289	16.000	3.0000	27.243	No	-	Demise
53	1/4" Collar PB1 1A	1	Aluminum 6061	Plate	0.6951	21.662	3.0000	27.912	No	-	Demise
54	1/4" Gasket PB1 1A	1	PTFE (Teflon)	Cylinder	0.6885	19.000	3.0000	19.000	No	-	Demise
55	1/8" Collar PB 1A	1	Aluminum 6061	Plate	0.7409	16.875	3.0000	26.411	No	-	Demise
56	1/8" Collar PB1 2A	1	Aluminum 6061	Plate	0.6557	18.763	3.0000	21.776	No	-	Demise
57	3/8" Gasket PB1 1A	1	PTFE (Teflon)	Cylinder	1.4628	25.000	3.0000	25.000	No	-	Demise
58	3/8" Collar PB1 1A	1	Aluminum 6061	Plate	1.5226	26.784	3.0000	29.821	No	-	Demise
59	Gasket 4	1	PTFE (Teflon)	Cylinder	0.3222				No	-	Demise
60	Gasket 3	1	PTFE (Teflon)	Cylinder	1.0606				No	-	Demise
61	Gasket 2	3	PTFE (Teflon)	Cylinder	2.8074				No	-	Demise
62	Gasket 1	1	PTFE (Teflon)	Cylinder	2.0669				No	-	Demise
63	Prop Bracket 1-2A	1	Aluminum 6061	Plate	22.405	27.474	8.0000	100.00	No	-	Demise
64	Prop Bracket 1-1A	1	Aluminum 6061	Plate	26.357	32.505	8.0000	100.00	No	-	Demise
65	Thruster Bracket 1A	1	Aluminum 6061	Plate	105.45	34.491	8.0000	91.497	No	-	Demise
66	#10-32 Locknut	2	AISI 316 Stainless Steel	Cylinder	4.3000	11.800	5.9531	11.800	No	-	Demise
67	#10-32 x 5/8" Screw	2	AISI 316 Stainless Steel	Cylinder	4.9000	9.1694	9.1694	18.440	No	-	Demise
68	Prop Bracket 2-2A	1	Aluminum_6060	Plate	32.069 9	13.130	8.0000	71.010	No	-	Demise
69	Prop Bracket 2-1A	1	Aluminum 6061	Plate	14.106 3	25.503	8.0000	100.00	No	-	Demise
70	Prop Bracket 3-2A	1	Aluminum 6061	Plate	19.162 5	17.816	8.0000	71.095	No	-	Demise

Item Number	Name	Qty	Material	Body Type	Mass (g) (total)	Diameter / Width (mm)	Length (mm)	Height (mm)	High Temp	Melting Temp (F°)	Survivability
71	Prop Bracket 3-1A	1	Aluminum 6061	Plate	15.627 5	19.500	8.0000	97.000	No	-	Demise
72	Prop Bracket 4-2A	1	Aluminum 6061	Plate	7.9214	7.5000	8.0000	94.473	No	-	Demise
73	Prop Bracket 4-1A	1	Aluminum 6061	Plate	24.655				No	-	Demise
74	3/4" P-Clamps	2	AISI 316 Stainless Steel	Cylinder	29.200	25.654	15.240	42.954	No	-	Demise
75	Check Valve Bracket 2A	1	Aluminum 6061	Plate	10.883	25.000	4.0000	36.385	No	-	Demise
76	Check Valve Bracket 1A	1	Aluminum 6061	Plate	13.949	30.000	4.0000	40.419	No	-	Demise
77	Side Shield 1A	1	Aluminum 6061	Plate	69.150	83.000	1.0000	330.50	No	-	Demise
78	Side Sheild 2A	1	Aluminum 6061	Plate	70.250	83.000	1.0000	330.50	No	-	Demise
79	Battery Bracket	1	Aluminum 6061	Plate	88.881	98.000	14.000	106.00	No	-	Demise
80	Structural Rib 1A	1	Aluminum 6061	Plate	40.650	100.00	21.000	100.00	No	-	Demise
81	Structural Rib 2A	1	Aluminum 6061	Plate	73.789	100.00	10.000	100.00	No	-	Demise
82	HV -9D D-sub Connector	2	Aluminum 6061	Box	12.700	15.138	15.240	30.988	No	-	Demise
83	Side Panel 1A	1	Aluminum-7075	Plate	180.65	100.00	7.5000	340.50	No	-	Demise
84	Side Panel 2A	1	Aluminum-7075	Plate	186.60	100.00	11.500	340.50	No	-	Demise
85	1/8" Prop to Thruster Pipe	1	AISI 316 Stainless Steel	Cylinder	3.5392	3.1750	3.1750	69.293	Yes	2550°	Demise (77.3 km)
86	TC74 Temperature Sensor	7	PTFE/ETFE plastic	Plate	29.233	10.541	11.049	23.698	No	-	Demise
87	Swagelock Nut	1	AISI 316 Stainless Steel	Cylinder	8.7074	15.424	15.424	12.405	No	-	Demise
88	#18-8 Screw	4	AISI 316 Stainless Steel	Cylinder	6.7360	7.7978	7.7978	22.225	No	-	Demise
89	Ring Connector	1	AISI 316 Stainless Steel	Plate	0.4098	7.8740	0.9000	12.810	No	-	Demise
90	Copper Tape	1	Copper	Cylinder	0.0023	0.2000	0.2000	12.502	No	-	Demise
91	Needle Lock	1	AISI 316 Stainless Steel	Plate	5.8364	14.500	3.2404	16.450	No	-	Demise
92	Needle	1	AISI 316 Stainless Steel	Cylinder	0.0010	0.1000	0.1000	31.944	No	-	Demise
93	Threaded Rod	4	AISI 316 Stainless Steel	Cylinder	4.7256	3.1552	3.1165	19.194	No	-	Demise

Item Number	Name	Qty	Material	Body Type	Mass (g) (total)	Diameter / Width (mm)	Length (mm)	Height (mm)	High Temp	Melting Temp (F°)	Survivability
94	Thruster Insulator	4	Ceramic	Cylinder	10.345	6.3000	6.3000	12.900	No	-	Demise
95	Thrust Hex Nut	12	AISI 316 Stainless Steel	Cylinder	12.524	9.3961	9.3961	2.7781	No	-	Demise
96	Thrust Washer	12	AISI 316 Stainless Steel	Cylinder	1.6164	6.1000	6.1000	0.8600	No	-	Demise
97	Extractor Grid	1	AISI 316 Stainless Steel	Plate	19.900	31.876	2.5400	31.876	Yes	2550°	Demise (76.0 km)
98	Thruster Heatsink	1	AISI 316 Stainless Steel	Plate	29.950	31.876	9.9060	31.876	Yes	2550°	Demise (75.7 km)
100	1/8" Connector Tube	1	AISI 316 Stainless Steel	Cylinder	1.4976	3.1750	3.1750	29.322	Yes	2550°	Demise (77.4 km)
101	1/8" 90deg Connector	1	AISI 316 Stainless Steel	Cylinder	4.5199	3.1750	3.1750	59.082	Yes	2550°	Demise (77.1 km)
102	Solenoid Valve	4	316 Stainless Steel Chrome Core 18	Cylinder	22.707	6.3500	6.3500	51.950	Yes	2550°	Demise (77.1 km)
103	1/8" 10-32 Male SAE	1	AISI 316 Stainless Steel	Cylinder	13.409	15.127	15.127	24.892	Yes	2550°	Demise (75.9 km)
104	1/4" 10-32 Male SAE	1	AISI 316 Stainless Steel	Cylinder	20.567	18.440	18.440	27.432	Yes	2550°	Demise (75.5 km)
105	1/8" to 1/16" Port Connector	1	AISI 316 Stainless Steel	Cylinder	1.1970	6.0960	6.0960	18.288	Yes	2550°	Demise (77.5 km)
106	10-32 Female Adapter	2	AISI 316 Stainless Steel	Cylinder	19.372	10.999	10.999	19.050	Yes	2550°	Demise (75.6 km)
107	Union 1/8" to 1/16"	1	Stainless Steel 316	Cylinder	17.719	12.905	12.905	30.988	Yes	2550°	Demise (75.4 km)
108	1/8" Connector Tube	1	Stainless Steel 316	Cylinder	1.8791	3.1750	3.1750	39.528	Yes	2550°	Demise (77.4 km)
109	1/8" Connector Tube	3	Stainless Steel 316	Cylinder	3.6342	3.1750	3.1750	25.400	Yes	2550°	Demise (77.3 km)
110	1/8" to 1/16" Port Reducing	1	AISI 316 Stainless Steel	Cylinder	1.1970	6.0960	6.0960	18.288	Yes	2550°	Demise (77.5 km)
111	1/4" Tube	1	AISI 316 Stainless Steel	Cylinder	26.964	6.3500	6.3500	76.750	Yes	2550°	Demise (75.8 km)
112	1/4", 1/8" Tee Fitting	1	AISI 316 Stainless Steel	Box	59.918	53.340	14.288	111.87	Yes	2550°	Demise (76.9 km)
113	1/2" to 1/4" Stem Reducer	1	AISI 316 Stainless Steel	Cylinder	65.852	25.810	25.810	44.958	Yes	2550°	Demise (74.0 km)
114	1/8" Tube	1	AISI 316 Stainless Steel	Cylinder	1.8387	3.1750	3.1750	36.000	Yes	2550°	Demise (77.3 km)
115	1/8" to 1/16" Union Reducer	1	Stainless Steel 316	Cylinder	17.719	12.905	12.905	30.988	Yes	2550°	Demise (75.4 km)
116	1/8" Tube	1	AISI 316 Stainless Steel	Cylinder	2.1707	3.1750	3.1750	42.500	Yes	2550°	Demise (77.3 km)

Item Number	Name	Qty	Material	Body Type	Mass (g) (total)	Diameter / Width (mm)	Length (mm)	Height (mm)	High Temp	Melting Temp (F°)	Survivability
117	1/8" 180 deg Tube	2	AISI 316 Stainless Steel	Cylinder	8.3648	3.1750	3.1750	31.750	Yes	2550°	Demise (77.2 km)
118	1/8" Tee Fitting	3	Stainless Steel 316	Box	125.43	44.704	11.176	27.115	Yes	2550°	Demise (75.6 km)
119	Pressure Transducer	2	Stainless Steel 316	Cylinder	72.007	11.902	11.902	43.810	Yes	2550°	Demise (74.0 km)
120	3/8" to 1/8" Union Reducer	1	AISI 316 Stainless Steel	Cylinder	41.858	20.164	20.164	40.894	Yes	2550°	Demise (74.6 km)
121	1/8" Elbow	2	Stainless Steel 316	Box	59.574	28.805	11.176	28.805	Yes	2550°	Demise (75.5 km)
122	1/16" Elbow	1	Stainless Steel 316	Box	16.336	22.326	22.326	9.5250	Yes	2550°	Demise (75.9 km)
123	1/16" to 1/8" Stem Adapter	1	AISI 316 Stainless Steel	Cylinder	5.9246	9.1654	9.1654	29.210	Yes	2550°	Demise (76.8 km)
124	1/8" Check Valve	4	Stainless Steel 316	Cylinder	297.78	20.164	20.164	57.658	Yes	2550°	Demise (73.6 km)
125	1/2" diam Propellant Tank	1	Stainless Steel 316	Cylinder	21.491	12.700	12.700	85.000	Yes	2550°	Demise (76.6 km)
126	1/2" to 1/8" Union Reducer	1	Stainless Steel	Cylinder	78.004	25.810	25.810	45.212	Yes	2550°	Demise (72.3 km)
127	Pressurant Tank	1	AISI 316 Stainless Steel	Cylinder	145.00	25.400	25.400	159.03	Yes	2550°	Demise (74.8 km)
132	Cable Harness	1	PTFE Cable		23.700				No	-	Demise

Appendix B. Propellant System Hazards and Operability Study

Introduction

A hazards and operability study (HAZOP) is a risk assessment methodology developed by the chemical industry to systematically identify the hazards in a planned or existing system. This technique is based around dividing the system into several simple subsystems called nodes. Once the nodes are identified the HAZOP team must then decide which parameters are applicable to each node. Guide words are then assigned to express how each parameter may deviate. The team then assesses potential causes and consequences of each deviation, existing safeguards, and further actions required. There are several generally accepted parameters (flow, temperature, pressure, etc.) and guide words (more, less, none, etc.), but each can be created in order to aptly assess a node.

For this HAZOP the thruster feed system was divided into five nodes: the pressurized tank housing nitrogen gas (henceforth referred to as the pressurant tank), the piping system from the pressurant tank to the propellant storage tube (pressurant transport line), the tube storing the propellant, including the o-ring and cylinder (propellant storage tube), the piping system from the propellant storage tube to the thruster feed (the propellant transport line), and the thruster feed. Terminology used to compose the HAZOP include the parameters flow, pressure, temperature, and containment along with the guide words more, less, no, reverse, small leak*, and large leak* to produce our HAZOP. Below is a summary of our findings, with the HAZOP spreadsheet in the appendix.

Pressurant Tank

A small leak may be caused by improper connection assembly and will result in a slow pressure drop in the pressurant tank. A large leak may be caused by launch vibrations either shaking the exit connection loose or shaking loose a component from elsewhere on the satellite, which could puncture the tank or shear off a connection. A large leak in the pressurant tank will result in a complete loss of pressure, rendering the feed system inoperable. A rise in temperature, caused by solar radiation, battery heat, thruster heat, or heater "runaway" will increase the pressure in the tank. Unless this increase is so great that it causes equipment failure, the pressure will not negatively impact the system as a whole. A drop in temperature might be caused by the heater failing while the satellite is in eclipse, which could result in a pressure drop in the pressurant tank. The risk of the nitrogen condensing is unlikely because the critical temperature of nitrogen is -146.9 °C and it is unlikely to reach that level.

Pressurant Transport Line

An increase or decrease in temperature will cause an increase or decrease in pressure respectively. The consequences of these deviations are negligible to the system as a whole and will only have an impact in performance, not structural integrity. A large leak in the pressurant transport line may result in reverse flow downstream. The check valves prevent reverse flow, and the solenoid valves prevent any flow unless specifically activated by the flight computer.

Propellant Storage Tube

A small leak in the propellant storage tube will cause a pressure drop and release a small amount of propellant into the satellite. This could cause corrosion of the satellite, or due to the propellant being ionic and circuit board wires being exposed could potentially cause a short. If reverse flow occurs it will be mitigated by the cylinder, which will be large enough that it will not travel backwards into the pressurant transport line. This means that the more propellant that remains in the storage tube, less reverse flow is possible. Regarding pressure, unless the deviation is an increase that is sufficiently large to cause structural failure of the tube, the only consequence is that the change will be present downstream. Changes in temperature may significantly affect the viscosity of the propellant, which would in turn affect flow rates. If the flow rate increases or decreases, it will result in a rise or drop in downstream pressure respectively.

Propellant Transport Line

Leaks, temperature changes, and pressure changes in the propellant transport line will show the same effects as in the fuel storage tube. Reverse flow (caused by a large upstream leak) will be mitigated by the check valve, the three solenoid valves, and by the cylinder if the reverse flow occurs upstream of the fuel storage tube.

Thruster Feed

At the thruster feed, if the pressure, temperature, or flow rate varies it will negatively affect thruster performance and efficiency. If pressure or flowrate is lost completely then the thruster will fail. If flow reverses, it will allow propellant to propagate back up the feed system. If this were to occur, the check valve would inhibit the reverse flow.

Conclusions

From this HAZOP analysis, it was determined that the most probable anomalies present the lowest consequence, while the most concerning outcomes are very unlikely to occur. There are three major tiers of failure. The first and most common of lowest consequences is deviations in pressure, temperature, or flowrate causing inefficient thruster performance. The second tier is a small leak causing complete pressure loss of the system resulting in flow stoppage and thruster failure. Also, in this tier is the possibility of leaked propellant causing exposed wire to short. Mitigating these issues will be using proper pipe assembly procedures, vibration testing to ensure the pipe connections are secure, and circuit board shielding. The third tier, the rarest but also the most dangerous, is a large leak causing rapid pressure drop, which could potentially lead to reverse flow in the system allowing propellant to propagate up the feed line into the propellant storage. This could be caused by a component failing during launch and puncturing a pipe. Mitigating this will be vibration testing of the entire satellite to ensure that every component is secure and specifying a minimum torque requirement for every pipe connection. Mitigation for the third tier includes the check valves, and the emergency closing of solenoid valves to contain the reverse flow to the propellant transport line.

* A small leak is defined by a slow trickle, most likely caused by improper assembly of pipe connections.

* A large leak is defined as a severe, rapid leak, most likely caused by structural failure of the pipe and/or assembly (if a connection shears off or a pipe is punctured).