Phase Four ROSE-1 Orbital Debris Assessment Report (ODAR)

ROSE-1-ODAR-1.10

This report is presented as compliance with NASA-STD-8719.14, APPENDIX A. Report Version: 1.1, 2/21/2017

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DAS Software Version Used In Analysis: v2.1.1

Phase Four ROSE-1 Orbital Debris Assessment Report, ROSE-1-ODAR-1.10

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Revision Record				
Revision:	Date:	Affected Pages:	Changes:	Author(s):
1.0	31 Jan 2017	All –Initial	DAS Software Results Orbit Lifetime Analysis	B. Cooper
1.1	21 Feb 2017	4, 5, 6, 7	Schedule Propellant storage Tank pressure	J. Behmer
1.2	27 Feb 2017	7, 9, 12, 13	Leak before burst Passivation	J. Behmer
1.3	1 Mar 2017	1, 3, 5, 7	High res P4 logo Table of Contents Mission duration RFT description	J. Behmer
1.4	16 Mar 2017	18, 20	Modified reentry casualty analysis for 2 propellant tanks	B. Cooper
1.5	16 Mar 2017	8	Modified "target tracking mode" to exclude cameras	J. Behmer
1.6	12 Apr 2017	16 – 20	Casualty assessment	B. Cooper
1.7	17 Apr 2017	5	Launch date	J. Behmer
1.8	20 Mar 2018	4, 5	Company relationship and launch date	J. Behmer
1.9	23 Mar 2018	5	Mission duration	J. Behmer
1.10	18 Apr 2018	6, 14, 17	Launch date Ground station loc. Reentry config Mission profile DAS output	J. Behmer

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Self-assessment of the ODAR using the format in Appendix A.2 of NASA-STD-8719.14:

A self assessment is provided below in accordance with the assessment format provided in Appendix A.2 of NASA-STD-8719.14.

Comments:

Requirement #	Launch Vehicle				Spacecraft			Comments
	Compliant	Not Compliant	Incomplete	Standard Non Compliant	Compliant	Not Compliant	Incomplete	
4.3-1.a	☐	☐	☒	☐	☒	☐	☐	No Debris Released in LEO. See note 1.
4.3-1.b	☐	☐	☒	☐	☒	☐	☐	No Debris Released in LEO. See note 1.
4.3-2	☐	☐	☒	☐	☒	☐	☐	No Debris Released in GEO. See note 1.
4.4-1	☐	☐	☒	☐	☒	☐	☐	See note 1.
4.4-2	☐	☐	☒	☐	☒	☐	☐	See note 1.
4.4-3	☐	☐	☒	☐	☒	☐	☐	No planned breakups. See note 1.
4.4-4	☐	☐	☒	☐	☒	☐	☐	No planned breakups. See note 1.
4.5-1	☐	☐	☒	☐	☒	☐	☐	See note 1.
4.5-2					☒	☐	☐	No critical subsystems needed for EOM disposal
4.6-1(a)	☐	☐	☒	☐	☒	☐	☐	See note 1.
4.6-1(b)	☐	☐	☒	☐	☒	☐	☐	See note 1.
4.6-1(c)	☐	☐	☒	☐	☒	☐	☐	See note 1.
4.6-2	☐	☐	☒	☐	☒	☐	☐	See note 1.
4.6-3	☐	☐	☒	☐	☒	☐	☐	See note 1.
4.6-4	☐	☐	☒	☐	☒	☐	☐	See note 1.
4.6-5	☐	☐	☒	☐	☒	☐	☐	See note 1.
4.7-1	☐	☐	☒	☐	☒	☐	☐	See note 1.
4.8-1					☒	☐	☐	No tethers used.

Note 1: The primary payloads for this mission belong to other organizations. This is not a primary mission of Phase Four or Astro Digital. All other portions of the launch composite are not the responsibility of Phase Four or Astro Digital and the ROSE-1 program is not the lead launch organization.

Assessment Report Format:

ODAR Technical Sections Format Requirements:

Phase Four, Inc. and Astro Digital US, Inc. are both US companies. This ODAR follows the format in NASA-STD-8719.14, Appendix A.1 and includes the content indicated as a minimum, in each of sections 2 through 8 below for the ROSE-1 satellite. Sections 9 through 14 apply to the launch vehicle ODAR and are not covered here.

ROSE-1 Space Mission Program:

ODAR Section 1: Program Management and Mission Overview

Relationship between Phase Four and Astro Digital: Phase Four owns the ROSE-1 mission and provides the propulsion system. Phase Four has purchased a satellite bus along with integration and operation services from Astro Digital.

Program/project management: James Behmer (Phase Four), Brian Cooper (Astro Digital)
Senior Management: Simon Halpern (Phase Four), Chris Biddy (Astro Digital)

Foreign government or space agency participation: None.
Summary of NASA's responsibility under the governing agreement(s): N/A

Schedule of upcoming mission milestones:

- Shipment of one spacecraft to Spaceflight Industries in Seattle, WA: 16 July 2018
- Launch: 30 September 2018

Mission Overview: ROSE-1 (RFT Orbital Satellite Experiment) is a 6U experimental spacecraft designed to provide an orbital test-bed for the Phase Four Radio Frequency Thruster (RFT). It will be launched into a sun-synchronous, Low Earth Orbit (LEO) inside a 6U Cubesat deployer as a part of a QUADPACK device developed by Innovative Solutions in Launch (ISL). The deployer is to be included on-board a Falcon 9 launch vehicle, planned for launch on 30 September 2018. The spacecraft carries a single RFT to provide propulsion for experimental orbital course corrections. All experimental data is downlinked over one of two command and telemetry radios transceivers. A Lithium-1 radio allows for UHF data downlink and commanding with a ground station located in Santa Clara, California. An additional experimental Globalstar radio provides S-band and L-band connectivity to the Globalstar satellite constellation. A GPS receiver provides precise orbital ephemeris for tracking and propulsion maneuver assessment. The satellite bus uses reaction wheels, magnetic torque coils, a star tracker, magnetometers, sun sensors, and gyroscopes to enable precision 3-axis pointing.

Launch Vehicle and Launch Site: Falcon 9, Vandenberg AFB

Proposed Launch Date: 30 September 2018

Mission Duration: ROSE-1 mission operations will last for 1 year, and the ROSE-1 spacecraft is expected to remain in LEO for an additional 6.5 years before reentry.

Launch and deployment profile, including all parking, transfer, and operational orbits with apogee, perigee, and inclination: The Falcon 9 launch vehicle will transport multiple mission payloads to orbit. ROSE-1 will be deployed into an approximately sun synchronous near-circular low Earth orbit. ROSE-1 will wait 30 minutes after ejection from the ISL deployer and then deploy a UHF antenna and two solar panels. The spacecraft is guaranteed to decay naturally from an orbit with the following parameters, although Phase Four may choose to bring the spacecraft down faster through the use of a propulsive deorbit maneuver.

Apogee: 575 ± 10 km

Perigee: 575 ± 10 km

Inclination: 97.7° ± .1° (Sun synchronous)

ROSE-1 will not substantially change its orbit from the following parameters from the perspective of orbital lifetime. There is no parking or transfer orbit.

<u>ODAR Section 2</u>: Spacecraft Description:

Physical description of the spacecraft: ROSE-1 is based on the 6U Cubesat form factor. Basic physical dimensions are 265.9 mm x 242.65 mm x 115.7 mm with a mass of approximately 10.0 kg. The superstructure is comprised of five rectangular plates forming the sides of the structure with interior stiffening members. There are L rails along each of the 265.9 mm corner edges. These accommodate the deployment of the satellite from the deployer. Additional stiffness is provided by various major module components mounted within the spacecraft structure. These include the Engine Control Module, the Attitude Control Module, and the Data and Power Module. The design includes a spring-loaded UHF antenna and two solar panels that are deployed after jettison from the deployer by two independent burn wires controlled by software timers via the flight computer. Power is locked away from all spacecraft bus and payload components by means of redundant series separation switches. These switches cannot be activated until the spacecraft separates from the deployer structure. The spacecraft is depicted in Figure 1.

Figure 1: ROSE-1 Spacecraft

Total satellite mass at launch, including all propellants and fluids: 10.2 kg.

Dry mass of satellites at launch: 10.0 kg.

Description of all propulsion systems (cold gas, mono-propellant, bi-propellant, electric, nuclear): The Radio Frequency Thruster (RFT) uses radio waves to excite xenon inside of a specially designed chamber. The xenon is then accelerated out of the thruster using a magnetic nozzle. The RFT can also operate as a cold gas thruster by ejecting gaseous xenon with no radio waves applied. Up to 192 grams of xenon propellant are included on-board ROSE-1.

Identification, including mass and pressure, of all fluids (liquids and gases) planned to be on board and a description of the fluid loading plan or strategies, excluding fluids in sealed heat pipes: ROSE-1 will include a pressure system with two 55 cubic centimeter pressure vessels containing up to 192 grams of xenon propellant with a system Maximum Expected Operating Pressure (MEOP) of 3,000 psia. The xenon propellant will be loaded through a fill/drain valve located on the +Z face of the spacecraft. Propellant loading will occur prior to integration into the ISL deployer and will maintain pressurization throughout the installation process onto the Falcon 9 launch vehicle. Spaceflight Industries has developed procedures to ensure personnel and equipment safety around pressurized Cubesats. The spacecraft bus structure and ISL deployer will provide additional protection barriers between launch vehicle systems and the ROSE-1 pressurized system. All pressurized components will be acceptance tested, including pressurized proof testing, to expected flight environment in accordance with MIL-STD-1522A.

Fluids in Pressurized Batteries: None

The ROSE-1 satellite uses four unpressurized standard COTS Lithium-Ion battery cells in each spacecraft. The energy capacity of each cell is 12 W-Hrs. The total capacity energy capacity per spacecraft is 48 W-Hrs.

Description of attitude control system and indication of the normal attitude of the spacecraft with respect to the velocity vector: The ROSE-1 spacecraft attitude will be controlled initially by the three reaction wheels. Once an attitude and rate solution is determined by the attitude determination sensors, these wheels will be used to slow the spacecraft and enter one of the following attitude modes.

- A *sun pointing mode* that is optimized for solar power generation from the satellite. The spacecraft's large fixed panel and deployable panel will be oriented towards the sun. This mode will make use of magnetometers, sun sensors, star trackers, reaction wheels, and magnetic torquers to orient the spacecraft correctly. This mode results in all faces of the spacecraft being oriented towards the velocity vector.

- A *target tracking mode*, which will allow the antenna to be directed at any location on the Earth's surface. This mode will make use of reaction wheels and star trackers to orient the spacecraft. The narrow +/- X faces of the spacecraft will be oriented along the velocity vector.

Description of any range safety or other pyrotechnic devices: None. The spacecraft deploys its antenna and panels using a melt-wire system. System power is locked off during launch by two series and two parallel deployment switches, but the 6U deployer container prevents any form of premature deployment in any case. The antenna and panel spring constants are very low.

Description of the electrical generation and storage system: Standard COTS Lithium-Ion battery cells are charged before payload integration and provide electrical energy during the eclipse portion of the satellite's orbit. A series of Triple Junction Solar Cells generate a maximum on-orbit power of approximately 35 watts at the end-of-life of the mission (5 years for calculation purposes). Typical operational mode for the satellite consumes 14 watts of power on average. The charge/discharge cycle is managed by a power management system overseen by the Flight Computer. During thruster firings, the spacecraft can momentarily consume up to 100 watts for short periods of time.

Identification of any other sources of stored energy not noted above: None

Identification of any radioactive materials on board: None

<u>ODAR Section 3</u>: Assessment of Spacecraft Debris Released during Normal Operations:

Identification of any object (>1 mm) expected to be released from the spacecraft any time after launch, including object dimensions, mass, and material: None.

Rationale/necessity for release of each object: N/A.

Time of release of each object, relative to launch time: N/A.

Release velocity of each object with respect to spacecraft: N/A.
Expected orbital parameters (apogee, perigee, and inclination) of each object after release: N/A.

Calculated orbital lifetime of each object, including time spent in Low Earth Orbit (LEO): N/A.

Assessment of spacecraft compliance with Requirements 4.3-1 and 4.3-2 (per DAS v2.1.1)

4.3-1, Mission Related Debris Passing Through LEO: COMPLIANT
4.3-2, Mission Related Debris Passing Near GEO: COMPLIANT

<u>ODAR Section 4</u>: Assessment of Spacecraft Intentional Breakups and Potential for Explosions.

Potential causes of spacecraft breakup during deployment and mission operations: The failure of the propellant pressure vessel or the explosive failure of a battery cell are the only credible potential causes for an unintended breakup. There are no planned breakups.

Summary of failure modes and effects analyses of all credible failure modes which may lead to an accidental explosion:
1) The structural failure of the xenon propellant pressure vessel could conceivably result in a release of debris on-orbit. The FMEA (see requirement 4.4-1 below) describes the chain of events necessary to cause such a failure.
2) The in-orbit failure of a battery cell protection circuit could lead to a short circuit resulting in overheating and a very remote possibility of battery cell explosion. The battery safety systems discussed in the FMEA (see requirement 4.4-1 below) describe the combined faults that must occur for any of seven (7) independent, mutually exclusive failure modes to lead to such an explosion.

Detailed plan for any designed spacecraft breakup, including explosions and intentional collisions: There are no planned breakups.

List of components which shall be passivated at End of Mission (EOM) including method of passivation and amount which cannot be passivated:
Four (4) Lithium Ion Battery Cells – Disabling of input photovoltaic converters. This will result in a gradual discharge and full shutdown of all battery cells.
Xenon Propellant Pressure Vessel – Full draining of the pressure tank. The tank can vent all xenon by firing the thruster in "cold gas" mode.

Rationale for all items which are required to be passivated, but cannot be due to their design: None

Assessment of spacecraft compliance with Requirements 4.4-1 through 4.4-4:

Requirement 4.4-1: Limiting the risk to other space systems from accidental explosions during deployment and mission operations while in orbit about Earth or the Moon: *"For each spacecraft and launch vehicle orbital stage employed for a mission, the program or project shall demonstrate, via failure mode and effects analyses or equivalent analyses, that the integrated probability of explosion for all credible failure modes of each spacecraft and launch vehicle is less than 0.001 (excluding small particle impacts) (Requirement 56449)."*

Compliance statement:

Required Probability: 0.001.
Expected probability: 0.000.

Supporting Rationale and FMEA details:

Battery explosion:

Effect: All failure modes below might result in battery explosion with the possibility of orbital debris generation. However, in the unlikely event that a battery cell does explosively rupture, the small size, mass, and potential energy, of these small batteries is such that while the spacecraft could be expected to vent gases, most debris from the battery rupture should be contained within the spacecraft due to the lack of penetration energy to the multiple enclosures surrounding the batteries.

Probability: Extremely Low. It is believed to be less than 0.01% given that multiple independent (not common mode) faults must occur for each failure mode to cause the ultimate effect (explosion).

Failure mode 1: Internal short circuit.

Mitigation 1: Protoflight level sine and random vibration in three axes of the full spacecraft, thermal vacuum cycling, and extensive functional testing followed by maximum system rate-limited charge and discharge cycles were performed to prove that no internal short circuit sensitivity exists. Additional environmental and functional testing of the batteries at the power subsystem vendor facilities were also conducted on the batteries at the component level.

Combined faults required for realized failure: Environmental testing **AND** functional charge/discharge tests must both be ineffective in discovery of the failure mode.

***Failure Mode 2*:** Internal thermal rise due to high load discharge rate.

Mitigation 2: Battery cells were tested in lab for high load discharge rates in a variety of flight-like configurations to determine if the feasibility of an out-of-control thermal rise in the cell. Cells were also tested in a hot, thermal vacuum environment (5 cycles at 50° C, then to -20°C) in order to test the upper limit of the cells capability. No failures were observed or identified via satellite telemetry or via external monitoring circuitry.

Combined faults required for realized failure: Spacecraft thermal design must be incorrect **AND** external over-current detection and disconnect function must fail to enable this failure mode.

Failure Mode 3**:** Excessive discharge rate or short-circuit due to external device failure or terminal contact with conductors not at battery voltage levels (due to abrasion or inadequate proximity separation).

Mitigation 3: This failure mode is negated by:

a) qualification tested short circuit protection on each external circuit,

b) design of battery packs and insulators such that no contact with nearby board traces is possible without being caused by some other mechanical failure,

c) observation of such other mechanical failures by protoflight level environmental tests (random vibration, thermal cycling, and thermal-vacuum tests).

Combined faults required for realized failure: An external load must fail/short-circuit AND external over-current detection and disconnect function must all occur to enable this failure mode.

Failure Mode 4: Inoperable vents.

Mitigation 4: Battery venting is not inhibited by the battery holder design or the spacecraft design. The battery can vent gases to the external environment.

Combined effects required for realized failure: The cell manufacturer OR the satellite integrator fails to install proper venting.

Failure Mode 5: Crushing

Mitigation 5: This mode is negated by spacecraft design. There are no moving parts in the proximity of the batteries.

Combined faults required for realized failure: A catastrophic failure must occur in an external system **AND** the failure must cause a collision sufficient to crush the batteries leading to an internal short circuit **AND** the satellite must be in a naturally sustained orbit at the time the crushing occurs.

Failure Mode 6: Low level current leakage or short-circuit through battery pack case or due to moisture-based degradation of insulators.

Mitigation 6: These modes are negated by:

a) battery holder/case design made of non-conductive plastic, and

b) operation in vacuum such that no moisture can affect insulators.

Combined faults required for realized failure: Abrasion or piercing failure of circuit board coating or wire insulators **AND** dislocation of battery packs **AND** failure of battery terminal insulators **AND** failure to detect such failures in environmental tests must occur to result in this failure mode.

Failure Mode 7: Excess temperatures due to orbital environment and high discharge combined.

Mitigation 7: The spacecraft thermal design will negate this possibility. Thermal rise has been analyzed in combination with space environment temperatures showing that batteries do not exceed normal allowable operating temperatures under a variety of modeled cases, including worst case orbital scenarios. Analysis shows these temperatures to be well below temperatures of concern for explosions.

Combined faults required for realized failure: Thermal analysis **AND** thermal design **AND** mission simulations in thermal-vacuum chamber testing **AND** over-current monitoring and control must all fail for this failure mode to occur.

Pressure Vessel Explosion:

In order for the xenon propellant pressure vessel to explosively fail and release debris on-orbit, the tank must first:

1) Survive the extremely harsh environment of launch inside the 6U deployer while still harboring a defect that will result in a failure in the much more benign environment on-orbit.
2) Spontaneously fail in such a way as to cause an explosive decompression.
3) Release enough energy during the explosion to puncture the solid aluminum side walls of the spacecraft.

This chain of events will be mitigated through both analysis and a rigorous qualification testing campaign involving vibration, thermal cycling, and over-pressurization. The system design is compliant with a leak before burst (LBB) failure mode pursuant with MIL-STD-1522A, which renders likelihood of catastrophic structural failure in the launch environment negligible. The propellant tank will be thermally insulated to reduce the temperature swings it experiences on-orbit below the already very moderate 25°C delta temperature expected inside the spacecraft. The spacecraft structure itself is also designed very robustly, and will provide an extra layer of protection in the event of an explosion to contain any released particles. The final consideration is the low orbit of this mission. In the worst case, any released particles will reenter fairly quickly due to their characteristically low ballistic coefficient.

Requirement 4.4-2: **Design for passivation after completion of mission operations while in orbit about Earth or the Moon:**

'Design of all spacecraft and launch vehicle orbital stages shall include the ability to deplete all onboard sources of stored energy and disconnect all energy generation sources when they are no longer required for mission operations or post-mission disposal or control to a level which cannot cause an explosion or deflagration large enough to release orbital debris or break up the spacecraft (Requirement 56450)."

Compliance statement: ROSE-1 includes the ability to fully disconnect the Lithium Ion cells from the charging current of the solar arrays. At End-Of-Life, this feature can be used to completely passivate the batteries by removing all energy from them. In the unlikely event that a battery cell does explosively rupture, the small size, mass, and potential energy, of these small batteries is such that while the spacecraft could be expected to vent gases, most debris from the battery rupture should be contained within the spacecraft due to the lack of penetration energy to the multiple enclosures surrounding the batteries.
The ROSE-1 mission intends to operate the propulsion system until propellant tank depletion. As a back-up method, ROSE-1 also includes the ability to fully vent the propellant tank at the End-of-Life prior to electrical passivation. The thruster valve will be fully opened, allowing all contents of the tank to flow out of the engine nozzle at a maximum of 100 seconds per gram of propellant onboard. If the thruster unexpectedly loses power, ROSE-1's valves fail closed and the spacecraft loses the ability to vent its tanks. Even if an electrical failure prevents ROSE-1 from venting the tanks, the spacecraft retains at most (i.e., at system MEOP) 1,678 ft-lbs of energy, 88% lower than the hazardous energy level specified in MIL-STD-1522A.

Requirement 4.4-3. Limiting the long-term risk to other space systems from planned breakups: Compliance statement: This requirement is not applicable. There are no planned breakups.

Requirement 4.4-4: Limiting the short-term risk to other space systems from planned breakups: Compliance statement: This requirement is not applicable. There are no planned breakups.

<u>ODAR Section 5</u>: Assessment of Spacecraft Potential for On-Orbit Collisions

The flight profile for the satellite begins with initial checkouts of the satellite subsystems after orbit insertion at 575±10 km. Once checkouts are complete, ground operators will command the spacecraft to perform a 5 km orbit decrease. The transfer will consist of up to 90 thirty-second propulsive maneuvers in the satellite anti-velocity direction, one at perigee and one at apogee during each orbit. Ground operators will control the satellite and monitor the health of the satellite and propulsion subsystem throughout the transfer. Once the initial orbit decrease transfer is complete and satellite health is verified, ground operators will command the satellite to perform a series of 5 km altitude increases and decreases until propellant is depleted.

Orbit transfers are designed to control semi-major axis and eccentricity, which keeps the satellite within 1 km of desired altitude and maintains a circular orbit. Ground operators will use the onboard GPS receiver for precise tracking and propulsion maneuver assessment. Ground operators will also use Two-Line Elements (TLEs) from the JSpOC for back up orbit determination.

Ground operators will interface closely with the Joint Space Operations Center (JSpOC) to assess the collision risk of trajectories resulting from propulsive maneuvers and to share data on maneuver plans with other operators, following the processes outlined in the JSpOC's Spaceflight Safety Handbook for Satellite Operators. Specifically, operators will submit an early orbit maneuver plan to the JSpOC and request an Early Orbit Conjunction Assessment (CA) before launch. Ground operators will then provide ephemeris to the JSpOC after launch. During operation, ground operators will share maneuver plans with the JSpOC before executing each maneuver. Operators will also request CA screenings from the JSpOC before ceasing operations. This will allow the JSpOC to coordinate with NASA to ensure the deorbiting spacecraft will safely descend through the International Space Station's orbit.

Assessment of spacecraft compliance with Requirements 4.5-1 and 4.5-2 (per DAS v2.1.1, and calculation methods provided in NASA-STD-8719.14, section 4.5.4):

Requirement 4.5-1. Limiting debris generated by collisions with large objects when operating in Earth orbit:

"For each spacecraft and launch vehicle orbital stage in or passing through LEO, the program or project shall demonstrate that, during the orbital lifetime of each spacecraft and orbital stage, the probability of accidental collision with space objects larger than 10 cm in diameter is less than 0.001 (Requirement 56506)."

Large Object Impact and Debris Generation Probability: 0.000003; COMPLIANT.

Requirement 4.5-2. Limiting debris generated by collisions with small objects when operating in Earth or lunar orbit:

"For each spacecraft, the program or project shall demonstrate that, during the mission of the spacecraft, the probability of accidental collision with orbital debris and meteoroids sufficient to prevent compliance with the applicable postmission disposal requirements is less than 0.01 (Requirement 56507)."

Small Object Impact and Debris Generation Probability: 0.001978; COMPLIANT

Identification of all systems or components required to accomplish any post-mission disposal operation, including passivation and maneuvering: None

<u>ODAR Section 6</u>: Assessment of Spacecraft Post-mission Disposal Plans and Procedures

6.1 Description of spacecraft disposal option selected: The satellite will de-orbit naturally by atmospheric re-entry. If propellant is available at the end of the mission, a de-orbit maneuver may be attempted to accelerate the re-entry.

6.2 Plan for any spacecraft maneuvers required to accomplish post-mission disposal: None

6.3 Calculation of area-to-mass ratio after post-mission disposal, if the controlled reentry option is not selected:

Spacecraft Mass: 10.0 kg

Cross-sectional Area (with solar panels and antenna deployed): 0.124 m^2

(Calculated by DAS 2.1.1). Area to mass ratio: 0.124/10.0 = 0.0124 m^2/kg

6.4 Assessment of spacecraft compliance with Requirements 4.6-1 through 4.6-5 (per DAS v 2.1.1 and NASA-STD-8719.14 section): Requirement 4.6-1. Disposal for space structures passing through LEO:

"A spacecraft or orbital stage with a perigee altitude below 2000 km shall be disposed of by one of three methods: (Requirement 56557)

a. Atmospheric reentry option: Leave the space structure in an orbit in which natural forces will lead to atmospheric reentry within 25 years after the completion of mission but no more than 30 years after launch; or Maneuver the space structure into a controlled de-orbit trajectory as soon as practical after completion of mission.

b. Storage orbit option: Maneuver the space structure into an orbit with perigee altitude greater than 2000 km and apogee less than GEO - 500 km.

c. Direct retrieval: Retrieve the space structure and remove it from orbit within 10 years after completion of mission."

Analysis: The ROSE-1 satellite method of disposal is COMPLIANT using method "a." The spacecraft will be left in an orbit with a maximum altitude of 585 x 585 km, reentering in approximately 3222 days (8.8 years) after launch with orbit history as shown in Figure 2 (analysis assumes an approximate random tumbling behavior).

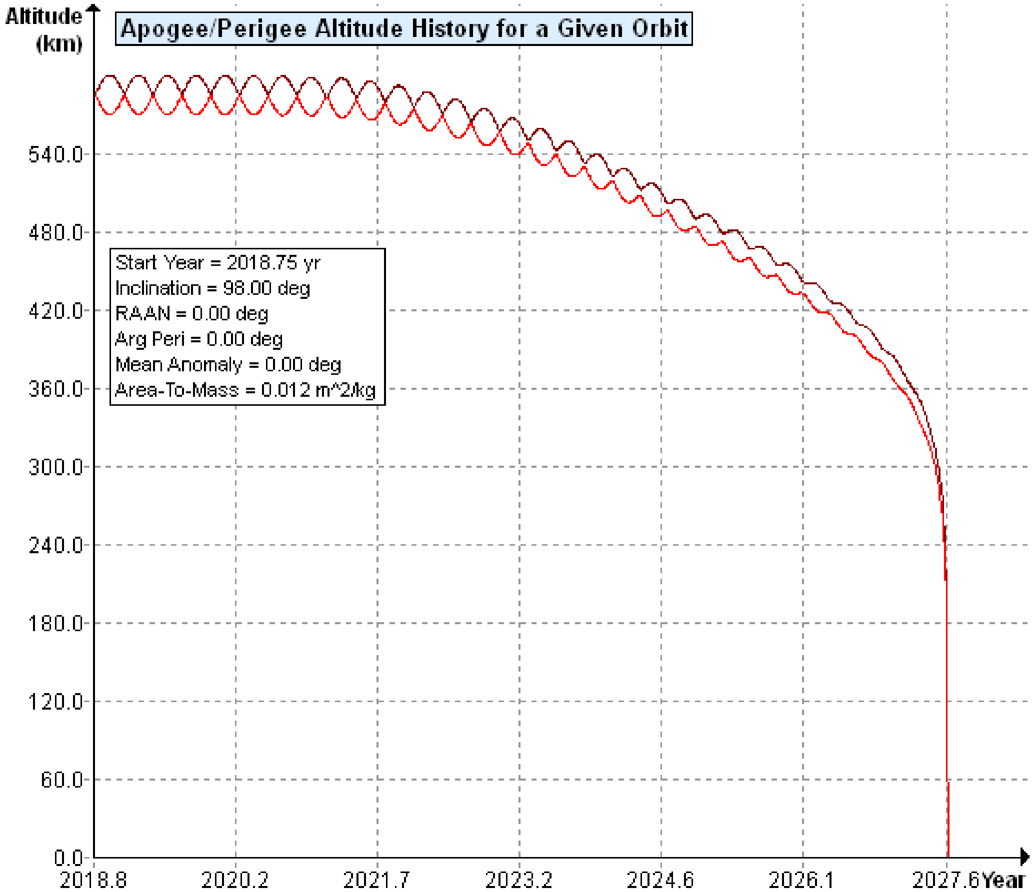

Figure 2: ROSE-1 Orbit History

Requirement 4.6-2. Disposal for space structures near GEO:
Analysis is not applicable.

Requirement 4.6-3. Disposal for space structures between LEO and GEO:
Analysis is not applicable.

Requirement 4.6-4. Reliability of Post-mission Disposal Operations:
The satellite will reenter passively without post mission disposal operations within the allowable timeframe.

The satellite will reenter with solar panels and antenna deployed, increasing its cross-sectional area. This solar panel deployment system has been tested to GEVS qualification levels and has functioned perfectly in three separate satellite launches. The deployment system uses a very simple spectra braid to hold the panels closed with a Nickel-Chrome wire to melt the spectra braid. A similar mechanism has been used to deploy antennas for Astro Digital satellites and has deployed successfully 10 times on-orbit with zero failures.

The mission profile starts with a 5 km decrease in orbit altitude immediately after checkout, followed by a series of alternating 5 km altitude increases and 5 km altitude decreases until the system runs out of propellant. Even if the launch vehicle places the satellite 10 km higher than the intended 575 km orbit, at no time will a propulsive maneuver increase the satellite altitude above 585 km. Therefore, there is no operational scenario in which the satellite orbit will be raised beyond the 585 km altitude used in this analysis.

The DAS orbit lifetime analysis assumes a worst-case scenario where the satellite is deployed 10 km higher than intended, fails to perform the initial 5 km orbit decrease, and ends its mission at 585 km altitude. This worst-case scenario yields an expected mission lifetime of 9 years, which is 16 years lower than the 25-year requirement.

An unintentional orbit raise due to valve failure is negated by the RFT propellant management unit (PMU) design. The PMU is composed of a high-pressure system, which stores propellant for flight and interfaces with Ground Support Equipment (GSE) through a dry-break quick-disconnect fitting; a 3-stage diaphragm regulator; and the low-pressure thruster feed system, which is isolated from supply pressure and vented while the system is de-energized. To inadvertently offload propellant, the dry-break quick-disconnect must fail in addition to *either* the check valve or the Normally Closed solenoid valve. On the low-pressure side of the PMU, two Normally Closed solenoid valves must both fail OPEN to allow propellant to offload. In the extremely unlikely event that propellant is offloading through either the high pressure or low-pressure side of the PMU, the spacecraft will be oriented such that the thrust vector is opposite the spacecraft velocity vector, thus decreasing the satellite's altitude.

<u>ODAR Section 7</u>: Assessment of Spacecraft Reentry Hazards:

Assessment of spacecraft compliance with Requirement 4.7-1: Requirement 4.7-1. Limit the risk of human casualty:

"The potential for human casualty is assumed for any object with an impacting kinetic energy in excess of 15 joules:
a) For uncontrolled reentry, the risk of human casualty from surviving debris shall not exceed 0.0001 (1:10,000) (Requirement 56626)."
Summary Analysis Results: DAS v2.1.1 reports that ROSE-1 is COMPLIANT with the requirement. The critical values reported by the DAS software are:

- Demise Altitude = 63.5 km
- Debris Casualty Area = 0.0 m^2
- Impact Kinetic Energy = 0 J
- Risk of Human Casualty = 1:100000000

This is expected to represent the absolute maximum casualty risk, as calculated with DAS's limited modeling capability. The DAS Output Summary Follows:

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************************************

=====================
No Project Data Available
=====================

=============== End of Requirement 4.3-1 ===============
04 18 2018; 20:37:18PM     Processing Requirement 4.3-2: Return
Status : Passed

=====================
No Project Data Available
=====================

=============== End of Requirement 4.3-2 ===============
04 18 2018; 20:37:24PM     Requirement 4.4-3:  Compliant

=============== End of Requirement 4.4-3 ===============
04 19 2018; 14:19:52PM     Processing Requirement 4.5-1:
     Return Status :  Passed

==============
Run Data
==============

**INPUT**

     Space Structure Name = ROSE-1
     Space Structure Type = Payload
     Perigee Altitude = 585.000000 (km)
     Apogee Altitude = 585.000000 (km)
     Inclination = 98.000000 (deg)
     RAAN = 0.000000 (deg)
     Argument of Perigee = 0.000000 (deg)
     Mean Anomaly = 0.000000 (deg)
     Final Area-To-Mass Ratio = 0.012000 (m^2/kg)
     Start Year = 2018.750000 (yr)
     Initial Mass = 10.200000 (kg)
     Final Mass = 10.000000 (kg)
     Duration = 1.000000 (yr)
     Station-Kept = False
     Abandoned = True
     PMD Perigee Altitude = -1.000000 (km)
     PMD Apogee Altitude = -1.000000 (km)
     PMD Inclination = 0.000000 (deg)
     PMD RAAN = 0.000000 (deg)
     PMD Argument of Perigee = 0.000000 (deg)
```

```
      PMD Mean Anomaly = 0.000000 (deg)

**OUTPUT**

      Collision Probability = 0.000003
      Returned Error Message: Normal Processing
      Date Range Error Message: Normal Date Range
      Status = Pass

==============

=============== End of Requirement 4.5-1 ===============
04 18 2018; 20:41:59PM     Requirement 4.5-2:  Compliant
04 18 2018; 20:53:44PM     Processing Requirement 4.6  Return
Status :  Passed

==============
Project Data
==============

**INPUT**

      Space Structure Name = ROSE-1
      Space Structure Type = Payload

      Perigee Altitude = 585.000000 (km)
      Apogee Altitude = 585.000000 (km)
      Inclination = 98.000000 (deg)
      RAAN = 0.000000 (deg)
      Argument of Perigee = 0.000000 (deg)
      Mean Anomaly = 0.000000 (deg)
      Area-To-Mass Ratio = 0.012000 (m^2/kg)
      Start Year = 2018.750000 (yr)
      Initial Mass = 10.200000 (kg)
      Final Mass = 10.000000 (kg)
      Duration = 1.000000 (yr)
      Station Kept = False
      Abandoned = True
      PMD Perigee Altitude = 573.982606 (km)
      PMD Apogee Altitude = 595.215216 (km)
      PMD Inclination = 97.993650 (deg)
      PMD RAAN = 11.004440 (deg)
      PMD Argument of Perigee = 131.246812 (deg)
      PMD Mean Anomaly = 0.000000 (deg)

**OUTPUT**

      Suggested Perigee Altitude = 573.982606 (km)
      Suggested Apogee Altitude = 595.215216 (km)
      Returned Error Message = Passes LEO reentry orbit criteria.

      Released Year = 2028 (yr)
```

```
      Requirement = 61
      Compliance Status = Pass

==============

=============== End of Requirement 4.6 ===============
04 18 2018; 20:53:59PM     *********Processing Requirement 4.7-1
      Return Status :  Passed

***********INPUT****
 Item Number = 1

name = ROSE-1
quantity = 1
parent = 0
materialID = 5
type = Box
Aero Mass = 10.000000
Thermal Mass = 10.000000
Diameter/Width = 0.200000
Length = 0.300000
Height = 0.100000

name = Thruster Head
quantity = 1
parent = 1
materialID = 56
type = Cylinder
Aero Mass = 0.800500
Thermal Mass = 0.800000
Diameter/Width = 0.090000
Length = 0.080000

name = Tungsten Probe
quantity = 2
parent = 2
materialID = 67
type = Cylinder
Aero Mass = 0.000250
Thermal Mass = 0.000250
Diameter/Width = 0.010160
Length = 0.152400

name = Prop Tank
quantity = 2
parent = 1
materialID = 59
type = Cylinder
Aero Mass = 0.500000
Thermal Mass = 0.500000
Diameter/Width = 0.050000
Length = 0.100000
```

```
*************OUTPUT****
Item Number = 1

name = ROSE-1
Demise Altitude = 77.998512
Debris Casualty Area = 0.000000
Impact Kinetic Energy = 0.000000

*************************************
name = Thruster Head
Demise Altitude = 63.516556
Debris Casualty Area = 0.000000
Impact Kinetic Energy = 0.000000

*************************************
name = Tungsten Probe
Demise Altitude = 63.516556
Debris Casualty Area = 0.000000
Impact Kinetic Energy = 0.000000

*************************************
name = Prop Tank
Demise Altitude = 67.247055
Debris Casualty Area = 0.000000
Impact Kinetic Energy = 0.000000

*************************************

=============== End of Requirement 4.7-1 ===============
04 18 2018; 20:54:06PM     Project Data Saved To File
************************************
```

Requirements 4.7-1b, and 4.7-1c:
ROSE-1 will utilize an uncontrolled reentry by default. Any deorbit burns will only serve to lower the mean altitude of ROSE-1 to reduce the orbital life prior to the uncontrolled reentry. As such, requirements 4.7-1b and 4.7-1c do not apply to ROSE-1.

4.7-1, b): *"For controlled reentry, the selected trajectory shall ensure that no surviving debris impact with a kinetic energy greater than 15 joules is closer than 370 km from foreign landmasses, or is within 50 km from the continental U.S., territories of the U.S., and the permanent ice pack of Antarctica (Requirement 56627)."*

4.7-1 c): *"For controlled reentries, the product of the probability of failure of the reentry burn (from Requirement 4.6-4.b) and the risk of human casualty assuming uncontrolled reentry shall not exceed 0.0001 (1:10,000) (Requirement 56628)."*

<u>ODAR Section 8</u>: Assessment for Tether Missions

Not applicable. There are no tethers used in the ROSE-1 mission.

END of ODAR for ROSE-1

Appendix A: Acronyms

Arg peri	Argument of Perigee
CDR	Critical Design Review
cm	centimeter
COTS	Commercial Off-The-Shelf (items)
DAS	Debris Assessment Software
EOM	End Of Mission
FRR	Flight Readiness Review
GEO	Geosynchronous Earth Orbit
ITAR	International Traffic In Arms Regulations
kg	kilogram
km	kilometer
LEO	Low Earth Orbit
Li-Ion	Lithium Ion
m^2	Meters squared
ml	milliliter
mm	millimeter
N/A	Not Applicable.
NET	Not Earlier Than
ODAR	Orbital Debris Assessment Report
OSMA	Office of Safety and Mission Assurance
PDR	Preliminary Design Review
PL	Payload
ISIPOD	ISIS CubeSat Deployer
PSIa	Pounds Per Square Inch, absolute
RAAN	Right Ascension of the Ascending Node
SMA	Safety and Mission Assurance
Yr	year