



Vigoride-1 Spacecraft Orbital Debris Assessment Report (ODAR)

v1

02/21/2020

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Document contains no ITAR or otherwise restricted data.

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Revision History

Revision Number	Updates	Page #	Author	Date
1	Initial Release	All	Sam Avery	02/18/19

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Orbital Debris Self-Assessment Evaluation

Requ't #	Launch Vehicle					Spacecraft				Comments <i>For all incompletes, include risk assessment (low, medium, or high risk) of non-compliance & Project Risk Tracking #</i>
	Compliant	N/A	Not Compliant	Std. Non-Compliant	Incomplete	Compliant	N/A	Not Compliant	Incomplete	
4.3-1.a <i>25 year limit</i>	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	See comment 1. No debris released.
4.3-1.b <i><100 object x year limit</i>	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	See comment 1. No debris released.
4.3-2 <i>GEO +/- 200km</i>	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	See comment 1. No debris released.
4.4-1 <i><0.001 Explosion Risk</i>	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	See comment 1.
4.4-2 <i>Passivate Energy Sources</i>	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	See comment 1.
4.4-3 <i>Limit BU Long term Risk</i>	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	See comment 1. No intentional breakups.
4.4-4 <i>Limit BU Short term Risk</i>	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	See comment 1. No intentional breakups.
4.5-1 <i><.001 10cm Impact Risk</i>	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	See comment 1.
4.5-2 <i>Postmission Disposal Risk</i>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	
4.6-1a-c <i>Disposal Method</i>	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	See comment 1.
4.6-2 <i>GEO Disposal</i>	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	See comment 1.
4.6-3 <i>MEO Disposal</i>	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	See comment 1.
4.6-4 <i>Disposal Reliability</i>	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	See comment 1.
4.7-1 <i>Ground Population Risk</i>	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	See comment 1.
4.8-1 <i>Tether Risk</i>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	No tethers used.

Comment 1. This ODAR analyzes only VR-1 and provides representative information regarding the customer payloads. The launch vehicle and other launch vehicle payloads are not considered in this ODAR.

Assessment Report Format

ODAR Technical Sections Format Requirements: This ODAR follows the format recommended in NASA-STD-8719.14, Appendix A.1 and includes the content indicated at a minimum in sections 2 through 8 for the Vigoride-1 (“VR-1”) satellite. Sections 9 through 14 of the NASA standard apply to the launch vehicle ODAR and are not covered here.

I. Program Management and Mission Overview

Project Manager:

- Aliko Loper-Leddy

Foreign Government or space agency participation:

- None.

Schedule of Upcoming Mission Milestones:

- Launch - August 2020

Mission Overview:

Momentum Inc. (“Momentum”) provides efficient and inexpensive in-space transportation services for small satellites. We deliver small satellites to exact orbits cheaper and faster by providing connecting flights in space. Our orbit transfer vehicles are built to carry customer payloads on either dedicated or rideshare rockets. Once a launch vehicle reaches initial orbit following launch, a Vigoride spacecraft is able to deliver customer satellites to one or multiple custom final orbits. Vigoride is designed around a Microwave Electrothermal Thruster (MET), which runs using non-toxic and low-pressurized water propellant to provide low-thrust orbit transfers. The Momentum-designed Vigoride service will provide operators a cost-effective means of achieving custom orbits for their spacecrafts. The ability to customize orbits within and adjacent to high density orbits empowers a greater user population to make more efficient and safer use of common orbits.

This ODAR evaluates the Momentum initial demonstration mission, Vigoride-1 (“VR-1”), which has a planned launch on a Soyuz-2 rocket in August 2020. For the initial mission, VR-1 will have the capacity to transport and deploy multiple payloads (individually, “Payload 1” and “Payload 2,” and together, the “Payloads”). Payload 1 is a 1.5U cubesat launched on behalf of Steamjet Space Systems. Payload 2 is a Spire Inc. 3U Lemur-class cubesat. The de-orbit analysis for customer satellite payloads will be addressed through the licensing process for the relevant payload.¹

Launch Vehicle:

- Soyuz-2

Expected Launch Site:

¹ In the event the customers are unable to secure the requisite licensing for their respective payloads, Momentum will launch VR-1 with the applicable mass dummy that will not be deployed.

- Baikonur Cosmodrome, Kazakhstan

Operational Mission Duration:

- Planned for 180 days.

The VR-1 general concept of operations is as follows:

1. Launch vehicle arrives at initial orbit (500-565 km altitude circular)
2. VR-1 separates from launch vehicle
3. VR-1 undergoes commissioning and preliminary testing
4. VR-1 deploys Payloads 1 and 2
5. VR-1 conducts orbit raising maneuvers to second orbit (max. 585 km circular)
6. VR-1 performs detailed system functional testing
7. VR-1 conducts de-orbit maneuvers (targeting 450 km perigee or less)

Table 1: Orbital Parameters

	Insertion and Payloads 1 and 2 Orbit	VR-1 Transfer Orbit	VR-1 End-of-Life Orbit
Apogee Altitude	565 km (max)	585 km (max)	585 km (max)
Perigee Altitude	565 km (max)	585 km (max)	450 km ²
Inclination	~97° (Sun-Synchronous)	~97° (Sun-Synchronous)	~97°
Period	96 mins	96 mins	90-96 mins
Argument of Perigee	N/A	N/A	N/A
Local Time of the Ascending Node (LTAN)	~11:00	~11:00	~11:00
Maximum De-Orbit Life	VR-1 23 years ³ Payload 1 7 years Payload 2 5 years	VR-1 18 years ⁴	VR-1 4 years

² The minimum possible perigee as a result of de-orbit maneuvers is expected to be 300 km.

II. Spacecraft Description

Physical Description:

VR-1 has the following subsystems: Propulsion System, Structures, Mechanisms, Electric Power System, and Avionics.

VR-1 includes a primary and a secondary structural assembly with: Propellant Tanks, MET, Reaction Control System thrusters, Solar Array Assemblies, a payload adapter ring for interfacing with the launch vehicle, and one 12U cubesat deployer.

The VR-1 spacecraft bus includes two spring-loaded UHF antennas which are deployed after separation from the launch vehicle by a burn wire. In addition, VR-1 includes two 4-panel 150W deployable solar arrays which are deployed using a frangibolt Hold Down and Release Mechanism (HDRM). Both of these deployments are controlled by a software timer via the flight computer.

The Payloads are fully stowed in their deployers and their power is inhibited prior to on-orbit deployment. The Payloads are expected to follow the form and mass characteristics of a standard 3U cubesat and standard 1.5U cubesat. The VR-1 spacecraft platform components all have their power inhibited until launch vehicle separation occurs.

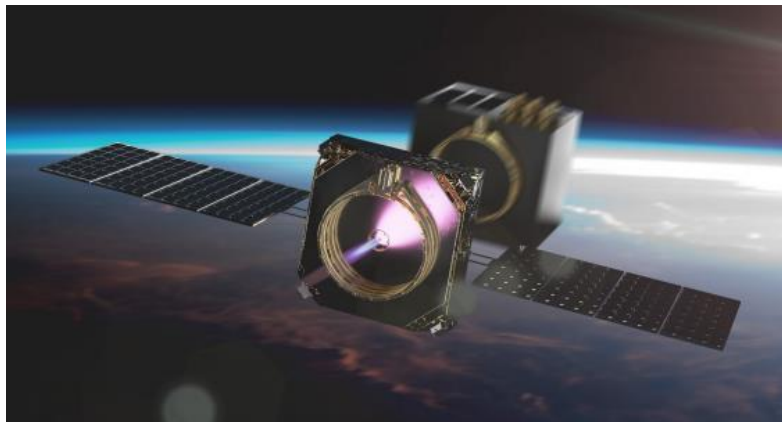


Figure 1. Artist rendering of Vigoride deploying a customer spacecraft.

³ This is the de-orbit duration if VR-1 has both a propulsion system failure *and* a solar array deployment failure after deployment from the launch vehicle.

⁴ This is the de-orbit duration if VR-1 has a propulsion system failure after raising the orbit to 585 km altitude.

Table 2. General Spacecraft Description

Criteria	Description	Notes
Spacecraft Total Launch Mass	166 kg	Includes 6 kg of propellant and planned 9 kg of deployable payloads.
Spacecraft Launch Dry Mass	160 kg	
Propulsion System	MET and resistojet reaction control thrusters. <i>See Propulsion System Description.</i>	Propulsion system operates using non-toxic and low-pressure liquid water propellant.
Body Dimensions	0.75x0.69x0.76 m ³	
Deployed Solar Array Dimensions	1.4x0.64x0.03 m ³	Dimensions per solar array wing.
Identification of all Fluids	<ul style="list-style-type: none"> • Liquid/vapor water mixture (propellant) • Nitrogen (tank pressurant) • Helium (tank pressurant) <i>See Fluids Description.</i>	
Fluids in Pressurized Batteries	None. VR-1 uses unpressurized lithium ion cells.	
Attitude Determination and Control	Attitude Determination <ul style="list-style-type: none"> • Star Tracker • Sun Sensors • Magnetometers • Gyroscope Attitude Control <ul style="list-style-type: none"> • Magnetic Torque Rods • Reaction Wheels • Reaction Control Thrusters 	

	See <i>Attitude Determination and Control System Description</i> .	
Range Safety or Pyrotechnic Devices	None.	
Electrical Generation and Storage System	Two 150W solar array wings for power generation. One Lithium-Ion 7S1P battery (~28V) and one Lithium-Ion 1S4P battery (~4.2V) are included and charged prior to launch vehicle integration. A separate failsafe deployment mechanism includes a Lithium-Ion 1S1P battery (~4.2V).	
Other Stored Energy	<ul style="list-style-type: none"> • Solar array spring energy stored in hinges. • Clampband separation system spring energy. • CubeSat deployer hinged door spring energy. 	
Radioactive Materials	Not applicable.	

Propulsion System Description

The Vigoride propulsion system energizes distilled water into plasma using RF microwave energy. The plasma is expelled out of the thruster using a nozzle to produce thrust at a specific impulse (Isp) exceeding traditional chemical propulsion systems. The expected thrust and Isp will vary with input power levels but will not exceed 15 mN. The VR-1 mission will nominally include 6+/-1 kg of liquid water propellant at launch. The 6 kg of water is roughly split into two parts: 4 kg total in two diaphragm tanks; and 2 kg total in two prototype propellant tanks. The maximum expected total impulse is approximately 25 kNs.

In addition, there are four experimental reaction control thrusters with estimated maximum thrust of 5 mN and specific impulse of 80 seconds. These reaction control thrusters use the same stored liquid water as a propellant.

Fluids Description

The propulsion system includes two diaphragm tanks with liquid water propellant pressurized using inert gaseous nitrogen. Each diaphragm tank is expected to include 2 kg of propellant. In addition, there are two prototype propellant tanks filled with water propellant and pressurized at launch using inert gaseous helium. These prototype propellant tanks are expected to include 1 kg of propellant. At spacecraft integration the diaphragm tanks are pressurized to 44 psi at 68°F, one prototype propellant tank at 50 psi at 140°F, and another prototype propellant tank at the vapor pressure of water at 3 psi at 140°F. The tanks are expected to remain within 20% of these pressures during transportation to the launch site, during launch, and post launch until thruster operations.

At the end of the mission, following a de-orbit maneuver, the propellant flow valve will be fully opened to allow all propellant and pressurant to vent into space and remove thrusting capability from the system. The spacecraft will be oriented such that any resultant thrust from the drain operations will result in a lower orbital altitude.

Attitude Determination and Control System Description

The VR-1 spacecraft includes 3-axis control with magnetic torque rods for coarse pointing and detumbling, reaction wheels for fine control (1° pointing accuracy), and experimental reaction control thrusters. For attitude determination, the spacecraft includes a star tracker, sun sensors, magnetometers, and a gyroscope, providing nominally >3° pointing knowledge.

- A sun tracking mode that is optimized for solar power generation from the satellite. The spacecraft's body will be oriented in two axes, and on-board Solar Array Drive Assemblies (SADAs) will rotate the panels along the third axis.
- A targeted tracking mode will allow the thrust axis to be pointed in any direction in inertial space.

III. Spacecraft Debris Released during Normal Operations

Table 3. Payload Release Description

	Payload 1⁵	Payload 2
Dimensions	~11x11x20 cm ³	~11x11x34 cm ³
Mass	~3 kg	~6 kg
Operator	Steamjet	Spire
Time of Release	within 1 month post-launch	within 1 month post-launch
Release Velocity	<2 m/s (CubeSat Deployer)	<2 m/s (CubeSat Deployer)
Expected Apogee	565 km (max)	565 km (max)
Expected Perigee	565 km (max)	565 km (max)
Expected Inclination	SSO	SSO
Orbital Lifetime	~7 years	~5 years

Payload Re-Contact Mitigation

Momentum will plan to support at least three re-contact mitigation strategies:

1. Payload deployments will be spaced apart by at least 90 minutes, or 1 full orbit.
2. Payload deployments will alternate between along-track deployment with the velocity vector and with the anti-velocity vector.

⁵ The de-orbit analysis for customer satellite payloads will be addressed through the licensing process for the relevant payloads. Nonetheless, the expected masses and dimensions in the chart for the Payloads are representative of prospective customer satellite payloads. As a courtesy, Momentum has performed some preliminary debris analysis on the Payloads to provide a sense of the longest expected orbital lifetime based on expected area-to-mass ratios and deployment orbits.

3. On-board propulsion may also be used for maneuvers to minimize the risk of re-contact.

Persistent Liquids and Propellant-Related Debris

During primary mission operations, any water released into space through the MET or the reaction control thrusters will be vaporized at sufficiently high temperature (>500K) to prevent the formation of debris. In the off-nominal case of a leak or flow of liquid water, there is potential for the creation of small water ice crystals. Any generated water ice crystals are expected to sublime within minutes of exposure to sunlight.

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**

IV. Intentional Breakups and Potential for Explosions

Potential causes of spacecraft breakup during deployment and mission operations:

There are two potential scenarios that could potentially lead to a breakup of the satellite:

- 1) Rupture of the propellant tank (H₂O, N₂, He)
- 2) Lithium-ion battery cell failure

Summary of failure modes and effects analyses of all credible failure modes which may lead to an accidental explosion:

- In-mission 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 failure modes and effects analysis (“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 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 including method of passivation and amount which cannot be passivated:

- Twelve (12) Lithium-ion battery cells.

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:

- **Pressure Tank Explosion:**
 - **Effect:** A rupture of one propellant tank would release water and nitrogen or helium. Due to the low pressure (50 psi), the penetrating energy of any debris would be relatively low. The tank is enclosed in the solid aluminum structural walls of the spacecraft. These aluminum walls would contain any released debris within the body of the spacecraft.
 - **Probability:** Very low. A structural failure of the tank would need to occur, and the mechanisms by which these failures occur are very well understood. The factor of safety for all vessels is 2, and the surrounding structure has a higher factor of safety.
- **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 vessel due to the lack of penetration energy and multiple enclosures surrounding the batteries.
 - **Probability:** Extremely Low. Estimated 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:* All of the following testing has or will be performed prior to flight: protoflight level sine burst, sine, and random vibration testing in all three axes, thermal vacuum cycling and extensive functional testing, system rate-limited charge and discharge cycles, and subsystem and component level functional testing. The testing helps prove that no internal short circuit sensitivity exists.
 - *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 the feasibility of an out-of-control thermal rise in the cell. Cells are 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 devices failure of terminal contact with conductors not at battery voltage levels (due to abrasion or inadequate proximity separation).
 - *Mitigation 3:* Qualification testing of short circuit protection on each external circuit, design of battery packs and insulators such that no contact with nearby board traces is possible without being caused by some other mechanical failure, and observation of such other mechanical failures by protoflight level environmental tests (sine burst, 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 Faults 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 with 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 or short-circuit through battery pack case or due to moisture-based degradation of insulators.
 - *Mitigation 6:* The battery holder and case design are made of non-conductive plastic and operation in vacuum ensures 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 the 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.

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 postmission 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:
 - VR-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, the 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.
 - As discussed above in the propulsion system section, all energy will be released from the propulsion system prior to spacecraft deactivation. The spacecraft will be oriented such that any thrust generated from propellant release results in an orbit lowering maneuver. All thruster valves will be opened until all

propellant and pressurant are completely released. No attempt will be made to activate the RF microwave element, which will result in a “cold gas” thruster firing.

Requirement 4.4-3: Limiting the long-term risk to other space systems from planned breakups:

- Compliance statement:
 - 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:
 - Not applicable. There are no planned breakups.

V. Spacecraft Potential for On-Orbit Collisions

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:**
 - 0.00000; 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:**
 - 0.00000; COMPLIANT

Identification of all systems or components required to accomplish any postmission disposal operation, including passivation and maneuvering:

- None are specifically required, but the propulsion system is expected to be used for a postmission de-orbit maneuver to decrease the time until atmospheric re-entry to less than 1 year. The flight computer, radio hardware, battery system, and control boards will be used to vent all propellant and to disconnect the battery from the solar array current.

VI. Spacecraft Postmission Disposal Plans and Procedures

Description of spacecraft disposal option selected:

- VR-1 will de-orbit naturally by atmospheric re-entry without any intervention. However, VR-1 will attempt a de-orbit maneuver to reduce the time to atmospheric re-entry to less than a year.

Plan for any spacecraft maneuvers required to accomplish postmission disposal:

- No maneuvers are required for postmission disposal. However, VR-1 will attempt a de-orbit maneuver as a proof of concept for future missions. The maneuver will be performed using the on-board propulsion system to lower the orbital perigee to 300 km altitude. Note that there is no planned controlled re-entry.

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

- Spacecraft Final Mass: 151 kg (worst case mass)
- Cross-sectional Area: 0.59 m² (estimated average area in tumbling)
- Area to mass ratio: 0.006 m²/kg

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)

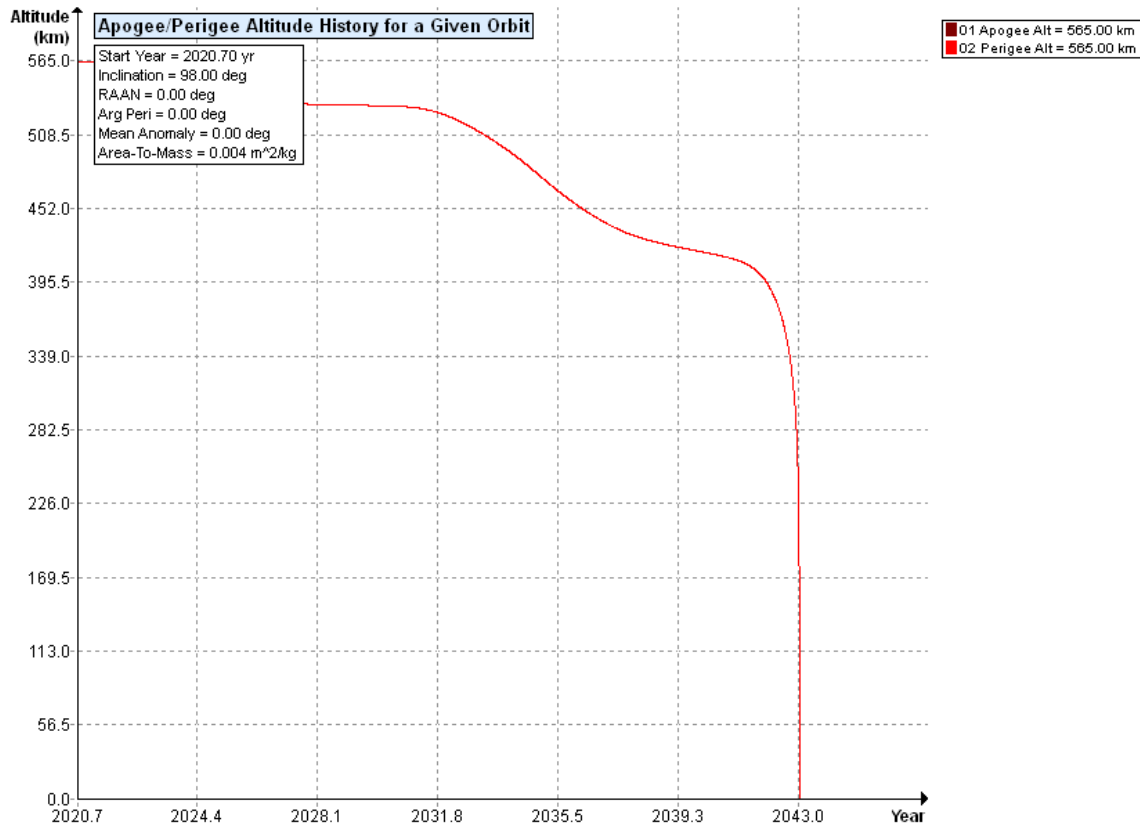
1. Atmospheric reentry option:
 - a. Leave the space structure in an orbit in which natural forces will lead to atmospheric reentry within 25 years after the completion of mission but no more than 30 years after launch; or
 - b. Maneuver the space structure into a controlled de-orbit trajectory as soon as practical after completion of mission.
2. Storage orbit option: Maneuver the space structure into an orbit with perigee altitude greater than 2000 km and apogee less than GEO - 500 km.
3. Direct retrieval: Retrieve the space structure and remove it from orbit within 10 years after completion of mission.

Analysis:

VR-1 will follow a concept of operations to ensure a safe disposal within 25 years of the end of the mission. To demonstrate the thruster, the orbit apogee will be initially raised. Following mission completion, the thruster will be used to lower the perigee and reduce orbit lifetime to approximately 4 years. In the event of both a propulsion system failure *and* solar array

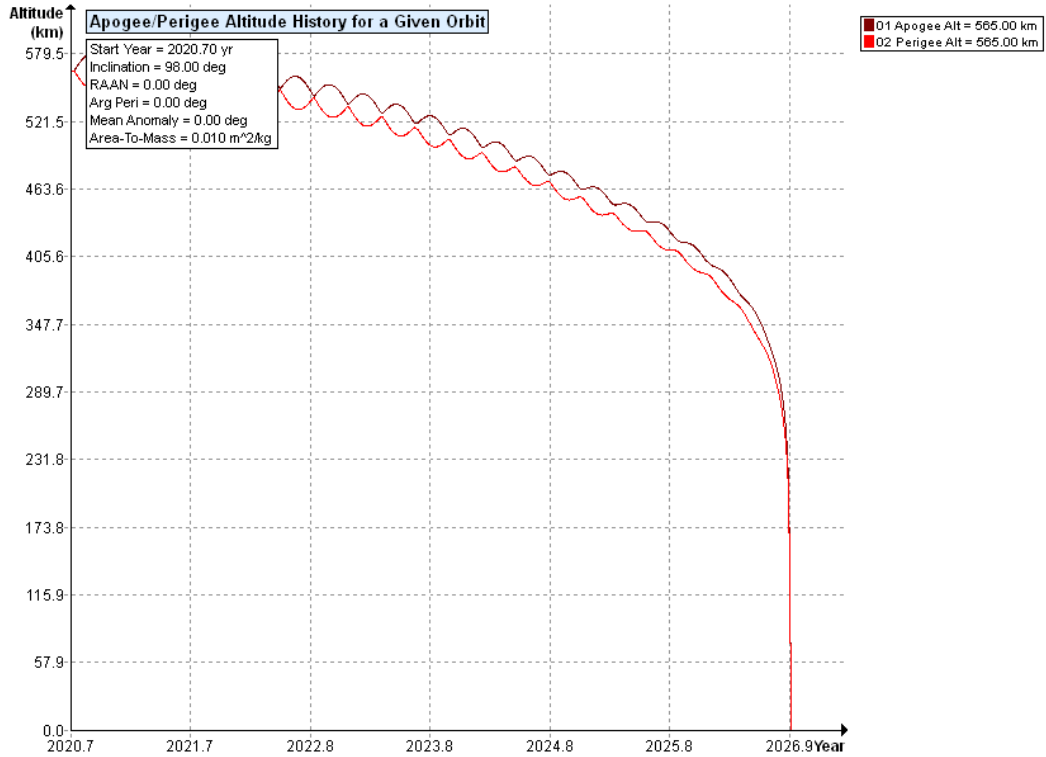
deployment failure on launch, VR-1 is expected to undergo atmospheric re-entry within 23 years. Additionally, the expected decay time for Payload 1 is expected to be less than 7 years and for Payload 2 is less than 5 years. See Table 1 *supra*.

VR-1 Failure at Launch Insertion Orbital Decay (565x565 km)⁶

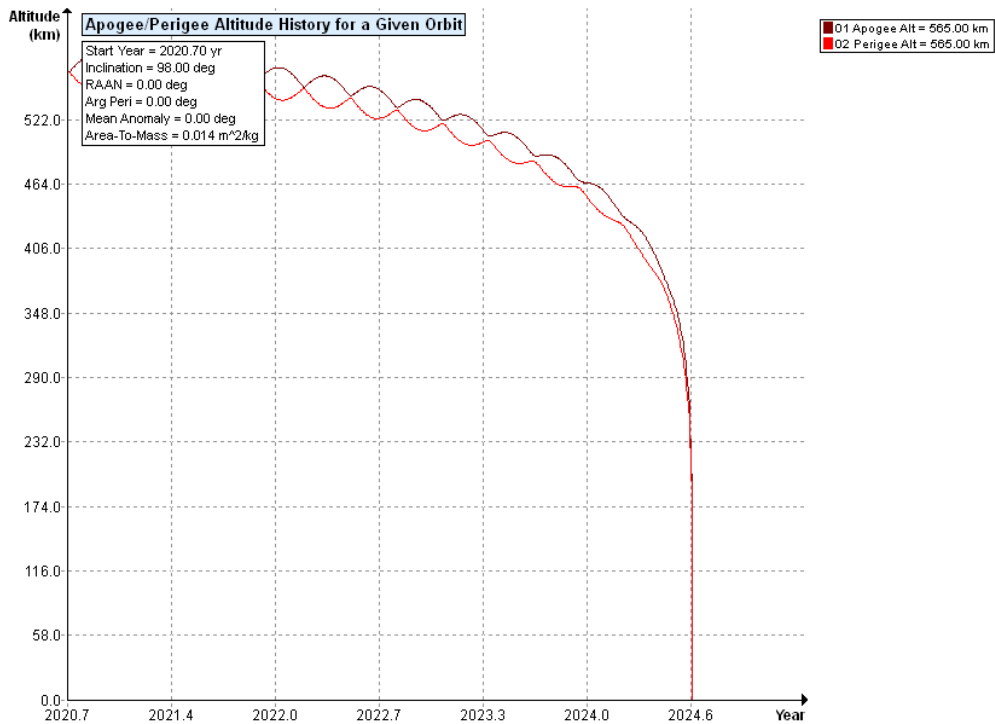


⁶ VR-1 has an initial Area-to-Mass ratio of 0.004 m²/kg prior to deployment of its solar arrays, and a final Area-to-Mass ratio of 0.006 m²/kg post deployment of its solar arrays.

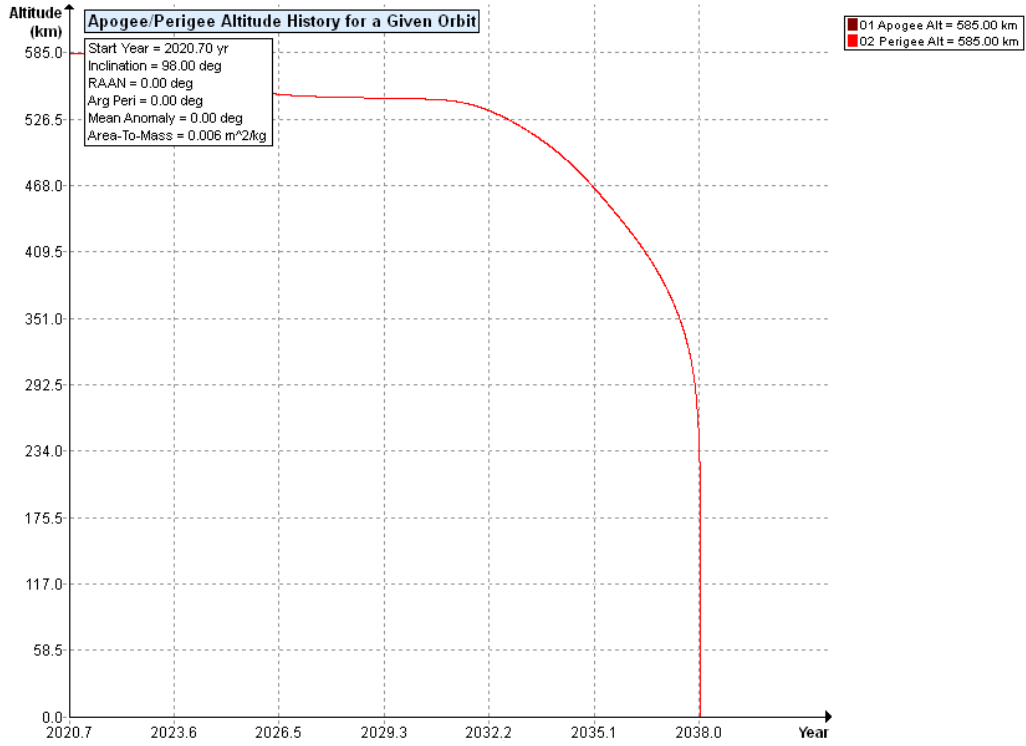
Payload 1 Expected Orbital Decay (565x565 km)



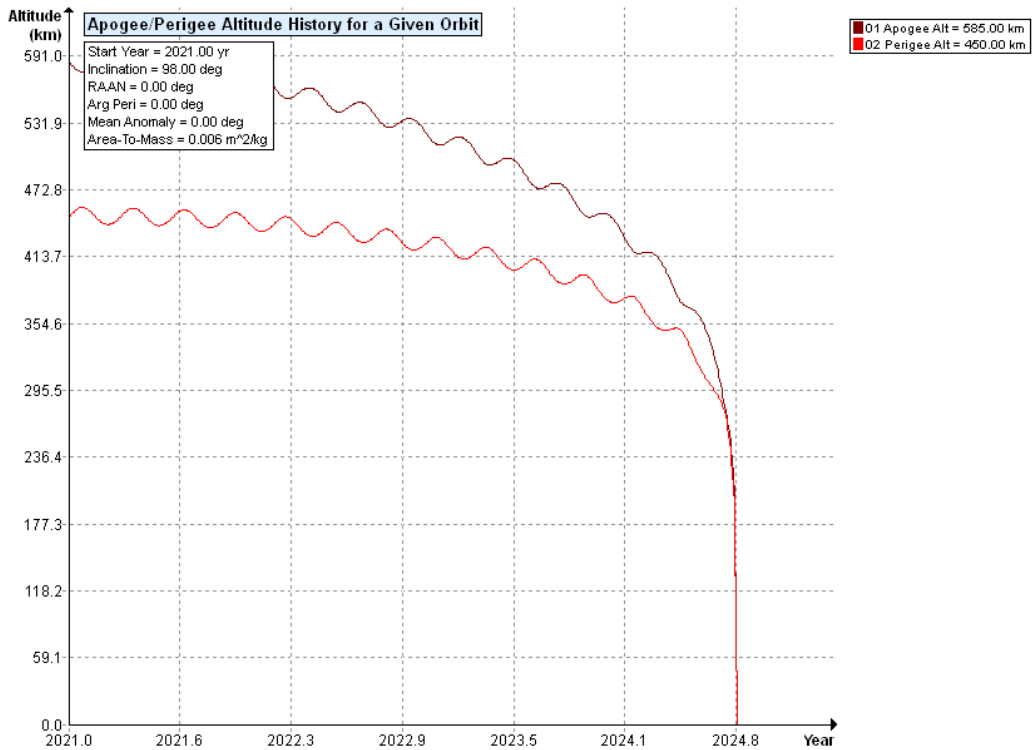
Payload 2 Expected Orbital Decay (565x565 km)



VR-1 Postmission Failure Orbital Decay (585x585 km)



VR-1 Postmission De-Orbit Orbital Decay (450x585 km)



Requirement 4.6-2. Disposal for space structures near GEO.

- Not applicable.

Requirement 4.6-3. Disposal for space structures between LEO and GEO.

- Not applicable.

Requirement 4.6-4. Reliability of Postmission Disposal Operations

- Not applicable. The satellite will reenter passively without post mission disposal operations within allowable timeframe.

VII. Spacecraft Reentry Hazards

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:

1. 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 VR-1 is compliant with the requirement. As shown below, three VR-1 components may survive re-entry. However, in each case the impact energy is less than 15 joules.

Analysis using DAS v2.1.1:

02 07 2020; 08:41:10AM Processing Requirement 4.3-2: Return Status : Passed

=====

No Project Data Available

=====

===== End of Requirement 4.3-2 =====

02 07 2020; 08:41:12AM Requirement 4.4-3: Compliant

===== End of Requirement 4.4-3 =====

02 07 2020; 09:04:58AM Processing Requirement 4.5-1: Return Status : Passed

=====

Run Data

=====

INPUT

Space Structure Name = Vigoride-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 = 0.006000 (m²/kg)
Start Year = 2020.700000 (yr)
Initial Mass = 166.000000 (kg)
Final Mass = 151.000000 (kg)
Duration = 1.000000 (yr)
Station-Kept = False
Abandoned = False
PMD Perigee Altitude = 450.000000 (km)
PMD Apogee Altitude = 585.000000 (km)
PMD Inclination = 98.000000 (deg)
PMD RAAN = 0.000000 (deg)
PMD Argument of Perigee = 0.000000 (deg)
PMD Mean Anomaly = 0.000000 (deg)

****OUTPUT****

Collision Probability = 0.000007

Returned Error Message: Normal Processing

Date Range Error Message: Normal Date Range

Status = Pass

=====

****INPUT****

Space Structure Name = Payload 1

Space Structure Type = Payload

Perigee Altitude = 565.000000 (km)

Apogee Altitude = 565.000000 (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 = 0.010000 (m²/kg)

Start Year = 2020.700000 (yr)

Initial Mass = 3.000000 (kg)

Final Mass = 3.000000 (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 = 0.000000

Returned Error Message: Normal Processing

Date Range Error Message: Normal Date Range

Status = Pass

=====

****INPUT****

Space Structure Name = Payload 2

Space Structure Type = Payload

Perigee Altitude = 565.000000 (km)

Apogee Altitude = 565.000000 (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 = 0.014000 (m²/kg)

Start Year = 2020.700000 (yr)

Initial Mass = 6.000000 (kg)

Final Mass = 6.000000 (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 = 0.000001
Returned Error Message: Normal Processing
Date Range Error Message: Normal Date Range
Status = Pass

=====

===== End of Requirement 4.5-1 =====

02 12 2020; 10:13:25AM	Mission Editor Changes Applied
02 12 2020; 10:13:31AM	Project Data Saved To File
02 12 2020; 10:13:40AM	Activity Log Started
02 12 2020; 10:13:40AM	Opened Project C:\Users\Sam\AppData\Local\NASA\DAS2.1.1\
02 12 2020; 10:13:54AM	Processing Requirement 4.3-1: Return Status : Not Run

=====

No Project Data Available

=====

===== End of Requirement 4.3-1 =====

02 12 2020; 10:13:58AM Processing Requirement 4.3-2: Return Status : Passed

=====

No Project Data Available

=====

===== End of Requirement 4.3-2 =====

02 12 2020; 10:14:01AM Requirement 4.4-3: Compliant

===== End of Requirement 4.4-3 =====

02 12 2020; 10:57:47AM Processing Requirement 4.5-1: Return Status : Passed

=====

Run Data

=====

****INPUT****

Space Structure Name = Vigoride-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 = 0.006000 (m²/kg)
Start Year = 2020.700000 (yr)
Initial Mass = 166.000000 (kg)
Final Mass = 151.000000 (kg)
Duration = 1.000000 (yr)
Station-Kept = False
Abandoned = False
PMD Perigee Altitude = 450.000000 (km)
PMD Apogee Altitude = 585.000000 (km)
PMD Inclination = 98.000000 (deg)
PMD RAAN = 0.000000 (deg)
PMD Argument of Perigee = 0.000000 (deg)
PMD Mean Anomaly = 0.000000 (deg)

****OUTPUT****

Collision Probability = 0.000007
Returned Error Message: Normal Processing
Date Range Error Message: Normal Date Range
Status = Pass

=====

****INPUT****

Space Structure Name = Payload 1
Space Structure Type = Payload
Perigee Altitude = 565.000000 (km)
Apogee Altitude = 565.000000 (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 = 0.010000 (m²/kg)
Start Year = 2020.700000 (yr)
Initial Mass = 3.000000 (kg)
Final Mass = 3.000000 (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 = 0.000000
Returned Error Message: Normal Processing
Date Range Error Message: Normal Date Range
Status = Pass

=====

****INPUT****

Space Structure Name = Payload 2
Space Structure Type = Payload
Perigee Altitude = 565.000000 (km)
Apogee Altitude = 565.000000 (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 = 0.014000 (m²/kg)
Start Year = 2020.700000 (yr)
Initial Mass = 6.000000 (kg)
Final Mass = 6.000000 (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 = 0.000001
Returned Error Message: Normal Processing
Date Range Error Message: Normal Date Range
Status = Pass

=====

===== End of Requirement 4.5-1 =====

02 12 2020; 12:00:40PM Requirement 4.5-2: Compliant
02 12 2020; 12:00:41PM Processing Requirement 4.6 Return Status : Passed

=====

Project Data

=====

****INPUT****

Space Structure Name = Vigoride-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 = 0.006000 (m²/kg)

Start Year = 2020.700000 (yr)

Initial Mass = 166.000000 (kg)

Final Mass = 151.000000 (kg)

Duration = 1.000000 (yr)

Station Kept = False

Abandoned = False

PMD Perigee Altitude = 450.000000 (km)

PMD Apogee Altitude = 585.000000 (km)

PMD Inclination = 98.000000 (deg)

PMD RAAN = 0.000000 (deg)

PMD Argument of Perigee = 0.000000 (deg)

PMD Mean Anomaly = 0.000000 (deg)

****OUTPUT****

Suggested Perigee Altitude = 450.000000 (km)

Suggested Apogee Altitude = 585.000000 (km)

Returned Error Message = Passes LEO reentry orbit criteria.

Released Year = 2025 (yr)

Requirement = 61

Compliance Status = Pass

=====

****INPUT****

Space Structure Name = Payload 1

Space Structure Type = Payload

Perigee Altitude = 565.000000 (km)

Apogee Altitude = 565.000000 (km)

Inclination = 98.000000 (deg)

RAAN = 0.000000 (deg)

Argument of Perigee = 0.000000 (deg)

Mean Anomaly = 0.000000 (deg)

Area-To-Mass Ratio = 0.010000 (m²/kg)

Start Year = 2020.700000 (yr)

Initial Mass = 3.000000 (kg)

Final Mass = 3.000000 (kg)

Duration = 1.000000 (yr)

Station Kept = False

Abandoned = True

PMD Perigee Altitude = 554.664774 (km)

PMD Apogee Altitude = 568.309176 (km)

PMD Inclination = 98.020856 (deg)

PMD RAAN = 15.559274 (deg)

PMD Argument of Perigee = 25.901848 (deg)

PMD Mean Anomaly = 0.000000 (deg)

****OUTPUT****

Suggested Perigee Altitude = 554.664774 (km)

Suggested Apogee Altitude = 568.309176 (km)

Returned Error Message = Passes LEO reentry orbit criteria.

Released Year = 2026 (yr)

Requirement = 61

Compliance Status = Pass

=====

****INPUT****

Space Structure Name = Payload 2

Space Structure Type = Payload

Perigee Altitude = 565.000000 (km)
Apogee Altitude = 565.000000 (km)
Inclination = 98.000000 (deg)
RAAN = 0.000000 (deg)
Argument of Perigee = 0.000000 (deg)
Mean Anomaly = 0.000000 (deg)
Area-To-Mass Ratio = 0.014000 (m²/kg)
Start Year = 2020.700000 (yr)
Initial Mass = 6.000000 (kg)
Final Mass = 6.000000 (kg)
Duration = 1.000000 (yr)
Station Kept = False
Abandoned = True
PMD Perigee Altitude = 546.602173 (km)
PMD Apogee Altitude = 573.489589 (km)
PMD Inclination = 98.020305 (deg)
PMD RAAN = 15.630207 (deg)
PMD Argument of Perigee = 112.728135 (deg)
PMD Mean Anomaly = 0.000000 (deg)

****OUTPUT****

Suggested Perigee Altitude = 546.602173 (km)
Suggested Apogee Altitude = 573.489589 (km)
Returned Error Message = Passes LEO reentry orbit criteria.

Released Year = 2024 (yr)

Requirement = 61

Compliance Status = Pass

=====

===== End of Requirement 4.6 =====

02 12 2020; 12:03:13PM *****Processing Requirement 4.7-1

Return Status : Passed

*****INPUT*****

Item Number = 1

name = Vigoride-1

quantity = 1

parent = 0

materialID = 8

type = Box

Aero Mass = 151.000000

Thermal Mass = 151.000000

Diameter/Width = 0.600000

Length = 0.600000

Height = 0.250000

name = Structure

quantity = 2

parent = 1

materialID = 8

type = Box

Aero Mass = 7.700000

Thermal Mass = 7.700000

Diameter/Width = 0.250000

Length = 0.600000

Height = 0.250000

name = Diaphragm Tank

quantity = 2

parent = 1

materialID = 27

type = Sphere

Aero Mass = 1.800000

Thermal Mass = 1.800000

Diameter/Width = 0.200000

name = Prototype Tank

quantity = 2

parent = 1

materialID = 8

type = Box

Aero Mass = 1.800000

Thermal Mass = 1.800000

Diameter/Width = 0.150000

Length = 0.200000

Height = 0.150000

name = Chamber

quantity = 1

parent = 1

materialID = 54

type = Cylinder

Aero Mass = 0.030000

Thermal Mass = 0.030000

Diameter/Width = 0.030000

Length = 0.032000

name = Window

quantity = 1

parent = 1

materialID = 1

type = Cylinder

Aero Mass = 0.008000

Thermal Mass = 0.008000

Diameter/Width = 0.030000

Length = 0.015000

name = Reaction Wheels

quantity = 3

parent = 1

materialID = 54

type = Cylinder

Aero Mass = 0.080000

Thermal Mass = 0.080000

Diameter/Width = 0.080000

Length = 0.060000

name = Reaction Control Thruster

quantity = 4

parent = 1

materialID = 19

type = Box

Aero Mass = 0.085000

Thermal Mass = 0.085000

Diameter/Width = 0.050000

Length = 0.050000

Height = 0.040000

name = Shields

quantity = 4

parent = 1

materialID = 66

type = Flat Plate

Aero Mass = 0.025000

Thermal Mass = 0.025000

Diameter/Width = 0.060000

Length = 0.060000

name = 12U CubeSat Deployer

quantity = 1

parent = 1

materialID = 8

type = Box

Aero Mass = 7.500000

Thermal Mass = 7.500000

Diameter/Width = 0.400000

Length = 0.600000

Height = 0.400000

name = Radiator Plate

quantity = 1

parent = 1

materialID = 8

type = Box

Aero Mass = 3.500000

Thermal Mass = 3.500000

Diameter/Width = 0.600000

Length = 0.600000

Height = 0.020000

name = Solar Array

quantity = 2

parent = 1

materialID = 8

type = Flat Plate

Aero Mass = 2.600000

Thermal Mass = 2.600000

Diameter/Width = 0.600000

Length = 1.400000

name = 12U Cubesat Deployer

quantity = 1

parent = 1

materialID = 8

type = Box

Aero Mass = 7.500000

Thermal Mass = 7.500000

Diameter/Width = 0.400000

Length = 0.600000

Height = 0.400000

name = Payload Interface Adapter

quantity = 2

parent = 1

materialID = 8

type = Flat Plate

Aero Mass = 2.000000

Thermal Mass = 2.000000

Diameter/Width = 0.200000

Length = 0.300000

name = Payload Interface Plate

quantity = 1

parent = 1

materialID = 8

type = Box

Aero Mass = 28.000000

Thermal Mass = 28.000000

Diameter/Width = 0.500000

Length = 0.500000

Height = 0.200000

*****OUTPUT*****

Item Number = 1

name = Vigoride-1

Demise Altitude = 77.996971

Debris Casualty Area = 0.000000

Impact Kinetic Energy = 0.000000

name = Structure

Demise Altitude = 73.079941

Debris Casualty Area = 0.000000

Impact Kinetic Energy = 0.000000

name = Diaphragm Tank

Demise Altitude = 76.305695

Debris Casualty Area = 0.000000

Impact Kinetic Energy = 0.000000

name = Prototype Tank

Demise Altitude = 74.195885

Debris Casualty Area = 0.000000

Impact Kinetic Energy = 0.000000

name = Chamber

Demise Altitude = 75.450165

Debris Casualty Area = 0.000000

Impact Kinetic Energy = 0.000000

name = Window

Demise Altitude = 0.000000

Debris Casualty Area = 0.385906

Impact Kinetic Energy = 1.099563

name = Reaction Wheels

Demise Altitude = 0.000000

Debris Casualty Area = 1.343816

Impact Kinetic Energy = 11.484885

name = Reaction Control Thruster

Demise Altitude = 76.865089

Debris Casualty Area = 0.000000

Impact Kinetic Energy = 0.000000

name = Shields

Demise Altitude = 0.000000

Debris Casualty Area = 1.742400

Impact Kinetic Energy = 2.833753

name = 12U CubeSat Deployer

Demise Altitude = 74.378731

Debris Casualty Area = 0.000000

Impact Kinetic Energy = 0.000000

name = Radiator Plate

Demise Altitude = 73.798882
Debris Casualty Area = 0.000000
Impact Kinetic Energy = 0.000000

name = Solar Array
Demise Altitude = 76.512390
Debris Casualty Area = 0.000000
Impact Kinetic Energy = 0.000000

name = 12U Cubesat Deployer
Demise Altitude = 74.378731
Debris Casualty Area = 0.000000
Impact Kinetic Energy = 0.000000

name = Payload Interface Adapter
Demise Altitude = 71.954910
Debris Casualty Area = 0.000000
Impact Kinetic Energy = 0.000000

name = Payload Interface Plate
Demise Altitude = 48.403793
Debris Casualty Area = 0.000000

Impact Kinetic Energy = 0.000000

*****INPUT****

Item Number = 2

name = Payload 1

quantity = 1

parent = 0

materialID = 8

type = Box

Aero Mass = 3.000000

Thermal Mass = 3.000000

Diameter/Width = 0.110000

Length = 0.200000

Height = 0.110000

name = P

quantity = 1

parent = 1

materialID = 8

type = Box

Aero Mass = 3.000000

Thermal Mass = 3.000000

Diameter/Width = 0.110000

Length = 0.200000

Height = 0.110000

*****OUTPUT****

Item Number = 2

name = Payload 1

Demise Altitude = 77.992981

Debris Casualty Area = 0.000000

Impact Kinetic Energy = 0.000000

name = P

Demise Altitude = 66.314087

Debris Casualty Area = 0.000000

Impact Kinetic Energy = 0.000000

*****INPUT****

Item Number = 3

name = Payload 2

quantity = 1

parent = 0

materialID = 8

type = Box

Aero Mass = 6.000000

Thermal Mass = 6.000000

Diameter/Width = 0.110000

Length = 0.340000

Height = 0.110000

name = P

quantity = 1

parent = 1

materialID = 8

type = Box

Aero Mass = 6.000000

Thermal Mass = 6.000000

Diameter/Width = 0.110000

Length = 0.340000

Height = 0.110000

*****OUTPUT****

Item Number = 3

name = Payload 2

Demise Altitude = 77.995995

Debris Casualty Area = 0.000000

Impact Kinetic Energy = 0.000000

name = P

Demise Altitude = 64.176277

Debris Casualty Area = 0.000000

Impact Kinetic Energy = 0.000000

===== End of Requirement 4.7-1 =====

VIII. Tether Missions

Not applicable.