Vigoride-3 Spacecraft

Orbital Debris Assessment Report (ODAR)

Rev 1

12/15/2021

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Revision History

Revision Number	Updates	Page #	Author	Date
1	Initial Release	All	Sam Avery	12/15/21

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Momentus

Orbital Debris Self-Assessment Evaluation

Reqm't #	Launch Vehicle				Spacecraft			Comments
	Compliant or N/A	Not Compliant	Std. Non-Compliant	Incomplete	Compliant or N/A	Not Compliant	Incomplete	*For all incompletes, include risk assessment (low, medium, or high risk) of non-compliance & Project Risk Tracking #*
4.3-1.a *MRD 25-year limit*	☑	☐	☐	☐	☑	☐	☐	See comment 1. Debris released but compliant.
4.3-1.b *MRD<100 object x year limit*	☑	☐	☐	☐	☑	☐	☐	See comment 1. Debris released but compliant.
4.3-2 *GEO MRD*	☑	☐	☐	☐	☑	☐	☐	See comment 1. Debris released but compliant.
4.4-1 *<0.001 Explosion Risk*	☑	☐	☐	☐	☑	☐	☐	See comment 1.
4.4-2 *Passivate Energy Sources*	☑	☐	☐	☐	☑	☐	☐	See comment 1.
4.4-3 *Limit Intentional BU*	☑	☐	☐	☐	☑	☐	☐	See comment 1. No intentional breakups.
4.4-4 *Limit Intentional BU*	☑	☐	☐	☐	☑	☐	☐	See comment 1. No intentional breakups.
4.5-1 *<0.001 10cm Impact Risk*	☑	☐	☐	☐	☑	☐	☐	See comment 1.
4.5-2 *<0.01 Small MMOD Impacts*	☐	☐	☐	☐	☑	☐	☐	See comment 1.
4.6-1a-c *LEO Disposal*	☑	☐	☐	☐	☑	☐	☐	See comment 1.
4.6-2 *Storage or Earth-escape*	☑	☐	☐	☐	☑	☐	☐	See comment 1.
4.6-3 *Long-term Reentry*	☑	☐	☐	☐	☑	☐	☐	See comment 1.
4.6-4 *Disposal Reliability*	☑	☐	☐	☐	☑	☐	☐	See comment 1.
4.7-1 *Reentry Risk*	☑	☐	☐	☐	☑	☐	☐	See comment 1.
4.8-1 *Special Classes*	☐	☐	☐	☐	☑	☐	☐	No special classes.

Comment 1. This ODAR analyzes only the Vigoride-3 ("VR-3") 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 VR-3 spacecraft. 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:

- Sam Avery

Foreign Government or space agency participation:

- None

Schedule of Upcoming Mission Milestones:

- Launch - June 2022

Mission Overview:

This ODAR evaluates the Momentus VR-3 demonstration mission, which is targeted to launch on a SpaceX Falcon 9 rocket in June 2022. For the demonstration mission, VR-3 will exhibit the capacity to transport and deploy multiple payloads. Each deployed payload is a commercial smallsat individually licensed and authorized to operate by its respective national jurisdiction.[1] The necessary de-orbit and debris analysis for each deployed payload will be addressed through the licensing process for the relevant payload.[2]

Launch Vehicle:

- Falcon 9

Expected Launch Site:

- Vandenberg Air Force Base (VAFB)

Operational Mission Duration:

- Planned for 180 days.

The VR-3 concept of operations is as follows:

1. Launch vehicle arrives at initial orbit (maximum 600 km altitude circular sun-synchronous orbit ("SSO"))
2. VR-3 separates from launch vehicle

[1] General information regarding the payloads is provided in Table 1 in the application narrative.
[2] In the event the payload owners are unable to secure the requisite licensing for their respective payloads, Momentus will launch VR-3 with a mass dummy, which will not be deployed from VR-3.

3. VR-3 undergoes commissioning and preliminary testing
4. VR-3 deploys payloads 1 to 5
5. VR-3 conducts orbit raising maneuvers to second orbit (maximum 603 km circular SSO)
6. VR-3 performs detailed system functional testing
7. VR-3 conducts orbit reduction maneuvers to third orbit (525 km circular SSO)
8. VR-3 deploys payload 6; VR-3 (via Fossa Systems deployers) deploys payloads 7 to 15[3]
9. VR-3 conducts orbit and inclination adjustment maneuvers to a fourth and final end-of-life orbit (maximum 1,050 km x 350 km elliptical with a ~98° inclination), by first reducing perigee to 350 km and then raising apogee to 1,050 km.[4] As discussed below in Section 5, Momentus will ensure that its maneuvers through the orbits of inhabitable spacecraft will not create risk to such spacecraft.

VR-3 is planned to operate with an approximately 50% margin of propellant, in addition to the propellant necessary to achieve the operational concept. Momentus calculates that this reserve will be sufficient to support all contingencies during the VR-3 mission, including orbital debris and object avoidance maneuvers throughout the mission life. Additionally, our calculations suggest we would have sufficient propellant remaining at the conclusion of the mission to conduct further perigee reduction maneuvers, which could reduce to months the demise of the VR-3.

[3] Deployment of payloads 6 through 15 will be deployed on a best-efforts basis at a targeted altitude of 525 km.
[4] If VR-3 is unable to achieve a 350 km perigee, Momentus will not conduct any apogee-raising maneuvers.

Table 1: Orbital Parameters	**VR-3 Insertion Orbit**[6]	**Second Orbit**	**Third Orbit**	**VR-3 Final Orbit**
Apogee Altitude	600 km (max)	603 km (max)	525 km	1,050 km (max)
Perigee Altitude	600 km (max)	603 km (max)	525 km	350 km
Inclination	~97.5° (SSO)	~97.5 (SSO)	~97.5° (SSO)	~98° (Elliptical)
Period	96 mins	96 mins	95 mins	98 mins
Argument of Perigee	N/A	N/A	N/A	N/A
Local Time of the Ascending Node (LTAN)	~01:00	~01:00	~01:00	N/A
Maximum De-Orbit Life	VR-3[5] ~23 years	VR-3[6] ~23 years	VR-3[7] ~12 years	VR-3 ~5 years

[5] This is the deorbit duration, if VR-3 fails after deployment.
[6] This is the deorbit duration, if VR-3 achieves the second orbit and then the propulsion system fails.
[7] This is the deorbit duration, if VR-3 achieves the third orbit and then the propulsion system fails.

II. Spacecraft Description

Physical Description:

VR-3 has the following subsystems: Propulsion System, Structures, Mechanisms, Electric Power System, and Avionics.

VR-3 includes a primary and a secondary structural assembly with: Propellant Tanks, MET, Reaction Control System thrusters, Solar Array Assemblies, a launch vehicle separation ring, one ISIS 12U cubesat deployers, one 3U cubesat deployer, and two PocketPod deployers.

VR-3 includes two 5-panel 600W deployable solar arrays which are deployed using a frangibolt Hold Down and Release Mechanism (HDRM). The solar array deployment is 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 will follow the form and mass characteristics of a standard cubesat of the relative U-size of the payload. The VR-3 spacecraft platform components all have their power inhibited until launch vehicle separation occurs.

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

Table 2. General Spacecraft Description

Criteria	Description	Notes
Spacecraft Total Launch Mass	411.5 kg	Includes 120 kg of propellant.
Spacecraft Launch Dry Mass	291.5 kg	
Propulsion System	Redundant MET and reaction control thrusters. See *Propulsion System Description*.	Propulsion system operates using non-toxic and low-pressure liquid water propellant.
Body Dimensions	1.2x1.2x1.1 m^3	
Deployed Solar Array Dimensions	1.07x2.76x0.03 m^3	Dimensions per solar array wing.
Identification of all Fluids	• Liquid/vapor water mixture (propellant) • Helium (tank pressurant) • Dynalene HC-50 (Potassium Formate/H2O Solution – for cooling) See *Fluids Description*.	
Fluids in Pressurized Batteries	None. VR-3 uses unpressurized lithium ion cells.	
Attitude Determination and Control	Attitude Determination • Star Trackers • Sun Sensors • Gyroscopes Attitude Control	

	• Reaction Control Thrusters See *Attitude Determination and Control System Description*.	
Range Safety or Pyrotechnic Devices	None	
Electrical Generation and Storage System	Two 600W solar array wings for power generation. Two 960 Wh batteries are included and charged prior to launch vehicle integration.	
Other Stored Energy	• Solar array spring energy stored in hinges. • Clampband separation system spring energy. • Payload deployer hinged door spring energy.	
Radioactive Materials	Not applicable.	

Propulsion System Description

The Vigoride-3 fully redundant 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 150 mN per thruster. The VR-3 mission will nominally include 120 kg of liquid water propellant at launch. The 120 kg of water is split into equal parts in the four on-board propellant tanks. The maximum expected total impulse is approximately 400 kNs.

In addition, there are eight reaction control thrusters each with estimated maximum thrust of 30 mN and specific impulse of 120 seconds. These reaction control thrusters are also redundant and use the same stored liquid water as a propellant.

Fluids Description

The propulsion system includes four monocoque tanks with liquid water propellant pressurized using inert gaseous Helium. Each diaphragm tank is expected to include 30 kg of propellant. At spacecraft integration the propellant tanks are pressurized to 18 psig. The tanks are expected to remain within 20% of this pressure during transportation to the launch site, during launch, and post launch until thruster operations.

Attitude Determination and Control System Description

The VR-3 spacecraft includes 3-axis control with reaction control thrusters. For attitude determination, the spacecraft includes redundant star trackers, sun sensors, and gyroscopes, providing nominally >1° pointing knowledge.

- A sun tracking mode that is optimized for solar power generation from the spacecraft. 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

Payload Re-Contact Mitigation

Momentus will plan to support at least three re-contact mitigation strategies, for deployments from VR-3:

1. Deployment of payloads 1, 2, 3/5, and 4 will be spaced apart by at least 90 minutes, or 1 full orbit. Payloads 3 and 5 will be deployed simultaneously through a single door of a quad pack deployer with a separation spring built in to provide spacing, consistent with industry practices. Similarly, the Fossa Systems deployers will deploy its nine payloads (payloads 7 to 15) in three groups of two satellites and one group of three satellites. For each group, the satellites will have separation springs built in to provide spacing upon deployment.
2. Momentus will optimize deployment orientation and sequence to minimize recontact.
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 sublimate within minutes of exposure to sunlight.

Assessment of spacecraft compliance with Requirements 4.3-1 and 4.3-2 (per DAS v3.1.2)

- **4.3-1, Mission Related Debris Passing Through LEO:** COMPLIANT[8]
- **4.3-2, Mission Related Debris Passing Near GEO:** COMPLIANT

[8] The 9 PocketQubes to be deployed from VR-3 are each smaller than a 1U standard cubesat along at least one dimension. Per NASA Requirement 4.3-1b, these objects are considered mission-related debris. The calculations show that VR-3 is nonetheless compliant with NASA requirement. The computations indicating compliance are described in greater detail on p. 28 of this ODAR.

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 spacecraft:

1) Rupture of the propellant tank or pressurant tank (H_20, 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:

- 192 Lithium-ion battery cells. At the End of Mission, the battery cell maximum charge voltage may be reduced.

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).

Supporting Rationale and FMEA details:

- **Pressure Tank Explosion:**
    - **Effect:** A rupture of one propellant or pressurant tank would release water and Helium. Due to the low pressure of the propellant (18 psi), the penetrating energy of any debris would be relatively low. In addition, a Helium pressurant tank (250 psi) rupture would be insufficient to penetrate the surrounding 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 the propellant tanks is at least 2, for the pressurant tanks is 40, and for the surrounding structure is greater than 2.
- **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, although 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: qualification 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 to test the upper limit of the cells' capability. No failures were observed or identified via spacecraft 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 spacecraft 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 spacecraft 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 interface includes a printed circuit board and standoffs from any conductive materials, 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:
  - At End-of-Life, VR-3 can reduce stored energy in the battery and limit power generation capability of the solar arrays. In case of a battery failure, the cells are, at a minimum, doubly contained within aluminum structural walls to prevent debris generation.
  - All liquid water propellant has low stored energy (at 18 psi) and is chemically stable. The Helium pressurant tanks, which have a maximum pressure of 250 psi and a factor of safety of 40, do not contain enough stored energy to penetrate or break apart the spacecraft structure.

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

While the calculated risk of on-orbit collision with large debris or other operational space stations is low, Momentus shall monitor the VR-3 throughout the operational life of the spacecraft to ensure near real-time collision avoidance, as ground station available allows, and orbital maintenance maneuvers are executed as needed.[9] The VR-3 mission will launch with a substantial propellant reserve which is intended to provide sufficient propellant to perform contingency operations (e.g., as needed collision avoidance maneuvers) during the mission while also retaining ample propellant to execute de-orbit maneuvers necessary to achieve end-of-mission timeline targets. Additionally, this monitoring shall assess, on an ongoing basis, the accuracy with which the targeted orbital parameters are to be maintained.[10] Furthermore, the proposed operation of the VR-3 does not rely on or otherwise necessitate coordination with any other operational space stations and no assessment of successful coordination with such an operator has been performed to date.

Protection of other spacecraft, including the International Space Station ("ISS").

Based on current operational mission planning, it is expected that VR-3 will not be placed in or otherwise operate within a 10 km sphere centered around any orbital NASA assets. However, in the unlikely scenario where co-location or conjunction becomes possible, Momentus is prepared to implement a collision avoidance concept of operations and any maneuvers necessary to mitigate such risk. Momentus' primary means of notification of a potential close approach is via CDM messages produced by the 18SPCS and posted to space-track.org. In addition, Momentus is currently investigating commercial services, like Kayhan Space, that provide more detailed conjunction analysis and advanced warning services.

In order to determine whether the risk of a close approach is high enough to warrant avoiding a potential collision by performing a maneuver, or some other trajectory modification, Momentus will be screening CDM messages and perform detailed analysis if the probability of collision ("PoC") is greater than 1E-4 and the overall miss distance is < 1 km. In this scenario, the event will be re-analyzed using high fidelity ephemeris from the Momentus asset and, if possible, high-fidelity ephemeris from the other asset's owner/operator. If the result of this analysis yields a PoC of greater than 1E-3, Momentus will coordinate with the other owner operator on next steps. If the PoC is greater than 1E-2 or the miss distance is < 500m and the owner/operator cannot be contacted, Momentus will perform an avoidance maneuver while coordinating with the 18SPCS.

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[9] VR-3 is capable of adjusting orbits at speeds that support dynamic collision avoidance. To clarify, while the VR-3 is capable of near real-time orbital adjustments when VR-3 is capable of communication with the MOC, which is in turn dependent upon ground station availability.

[10] The Momentus assessment of the VR-3's accuracy for orbital parameter maintenance indicates performance will be within the following ranges: Apogee, ±1km; Perigee, ±200m; Inclination, <1%: and the Right Ascension of the Ascending Node(s), <1%.

If it is necessary to share trajectory or maneuver information with 18SPCS, Momentus will be sharing planned maneuvers and as measured ephemeris via on-board GPS with the 18SPCS via space-track.org. These will be uploaded as OPM files in accordance with the current protocols laid out in the Combined Force Space Component Command satellite operator safety handbook.[11]

In order to effectively identify close approaches with other potentially maneuverable assets and communicate with the other operator to ensure comprehensive situation awareness and coordinate mitigation efforts, Momentus operations plans to identify such potential assets by: 1) looking at objects originating from the same launch vehicle; 2) looking at high risk or high value objects such as the ISS; 3) looking at objects in the same or similar orbit plans; and 4) looking at objects that have frequent low probably of conjunction events. For these assets, Momentus will attempt to establish contact with the asset operators and coordinate any maneuvers that have the potential to impact other operators well in advance of any potential collision.

To clarify, VR-3's capability to conduct collision avoidance or orbital maintenance maneuvers will be constrained by the availability of uplink and downlink opportunities and as a result such maneuvers may not be feasible during those parts of orbit that are outside of ground station range. The amount of reserves remaining following an orbital debris avoidance maneuver would depend on the nature and duration of the avoidance maneuver. Anecdotally, however, a single kg of propellant has the potential to power kilometers of orbital adjustment. Additionally, there is historical evidence that collision avoidance maneuvers are rare, and conjunction avoidance is usually accomplished with orbital adjustments of less than 1 km. Accordingly, Momentus expects to have sufficient propellant reserves to conduct multiple contingency operations, including during spacecraft disposal.

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:**
    - 2.7973E-4; COMPLIANT.

[11] *See* Spaceflight Safety Handbook for Satellite Operators: 18 SPCS Processes for On-Orbit Conjunction Assessment & Collision Avoidance, Version 1.5, August 2020. 18th Space Control Squadron, Combined Force Space Component Command, Vandenberg AFB.

- For completeness, the Large Object Impact and Debris Generation Probability was analyzed for the final orbit showing compliance with a probability of 5.8655E-5.

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:**
    - 8.9078E-06; COMPLIANT

- For completeness, the Small Object Impact and Debris Generation Probability was analyzed for the final orbit showing compliance with a probability of 1.0442E-5.

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 reentry. The flight computer, radio hardware, battery system, and control boards will be used to reduce stored energy.

VI. Spacecraft Postmission Disposal Plans and Procedures

Description of spacecraft disposal option selected:

- VR-3 will de-orbit naturally by atmospheric reentry without any intervention. However, VR-3 will attempt a de-orbit maneuver (discussed below) to reduce the time to atmospheric reentry.

Plan for any spacecraft maneuvers required to accomplish postmission disposal:

- No maneuvers are required for postmission disposal. However, VR-3 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 350 km altitude. Note that there is no planned controlled reentry.

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

- Spacecraft Final Mass: 344.5 kg
- Cross-sectional Area: 3.3 m^2 (estimated average area in tumbling)
- Area to mass ratio: 0.010 m^2/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-3 will follow a concept of operations to ensure a safe disposal within 25 years of the end of the mission under all scenarios.[12]

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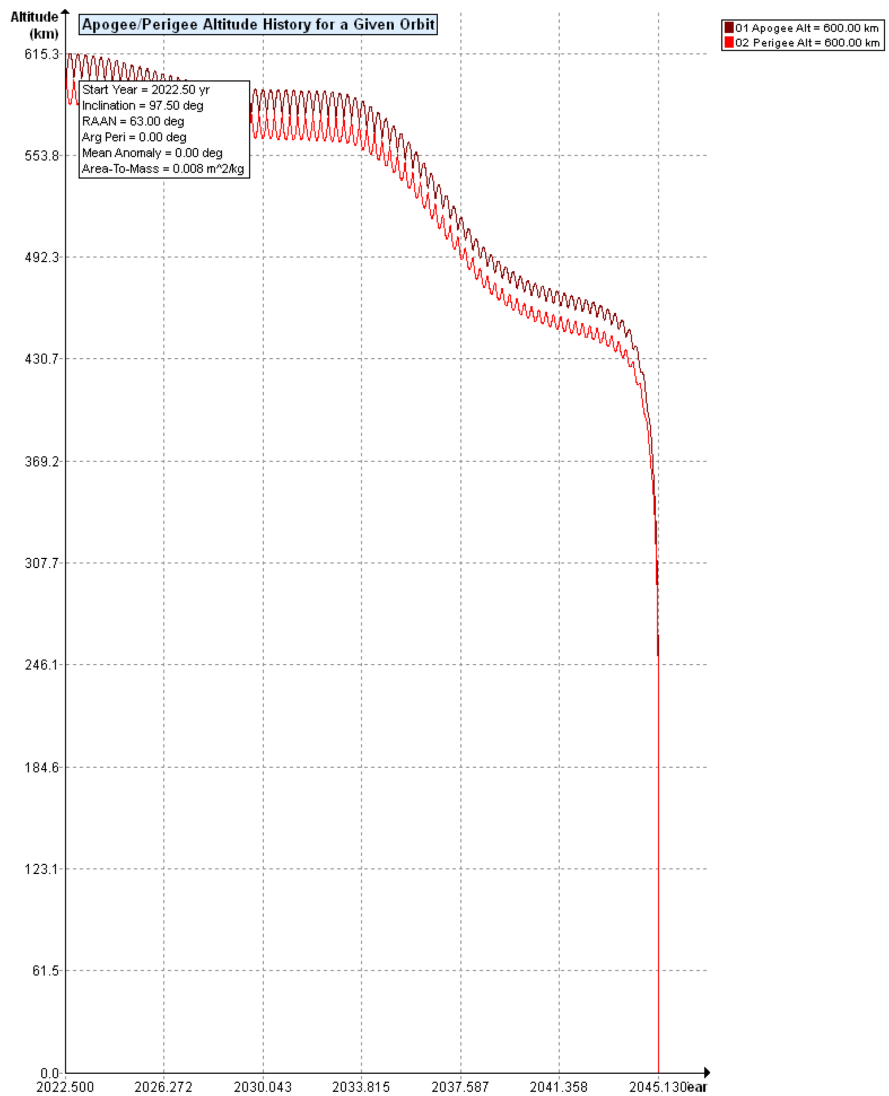
[12] The VR-3 concept of operations results in a calculated worst case maximum de-orbit life of 23 years.

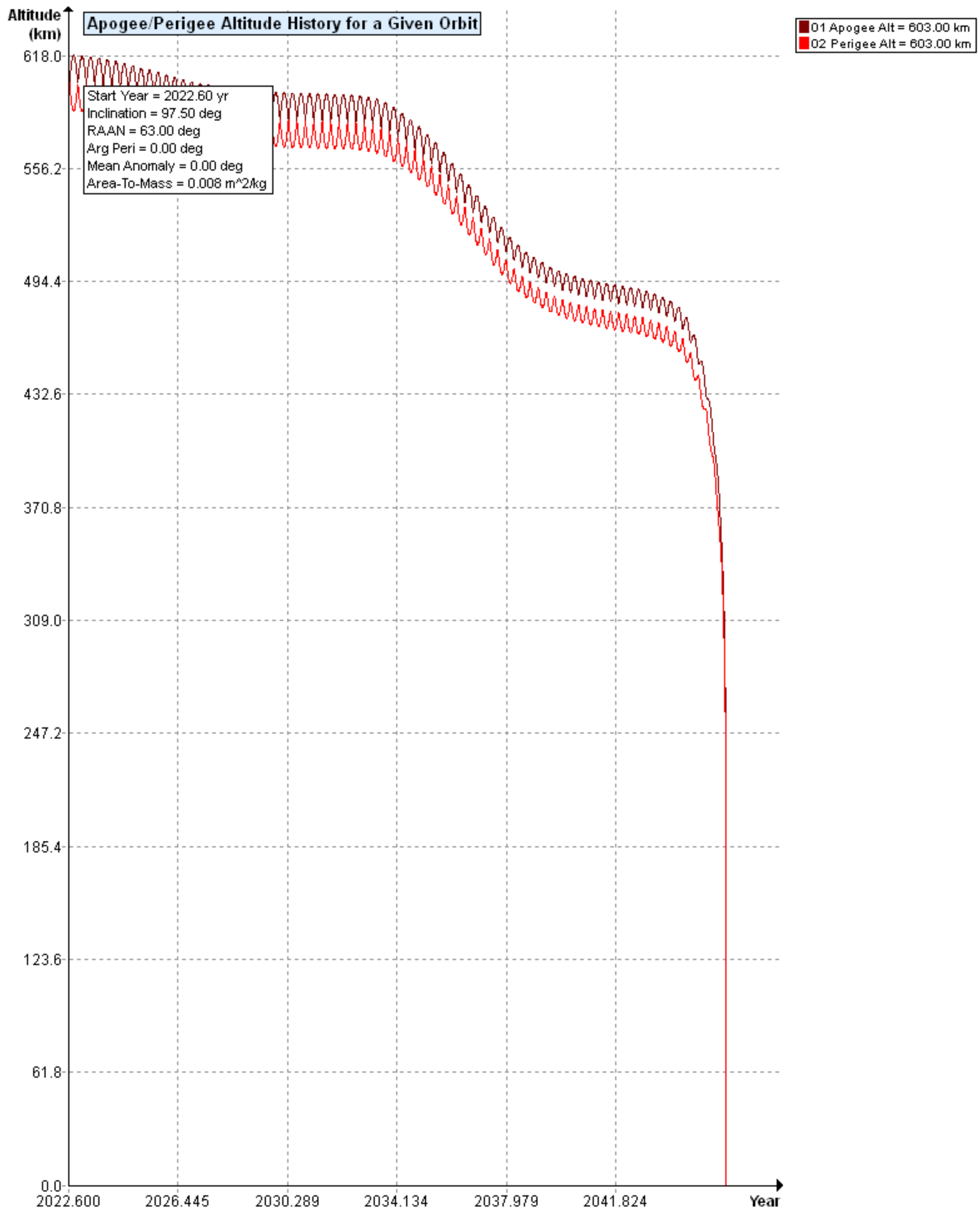
In the event of a propulsion system failure on launch, VR-3 is expected to undergo atmospheric reentry within 23 years. In the event of a propulsion system failure after achieving the target second orbit (603 x 603 km), VR-3 is expected to undergo atmospheric reentry also within 23 years. In the third orbit (525 x 525 km), VR-3 is expected to undergo atmospheric re-entry with 12 years. In the final orbit (1050 x 350 km), VR-3 is expected to undergo atmospheric re-entry within 5 years. At the conclusion of the mission, Momentus intends to conduct further perigee reduction maneuvers, which could reduce to months the demise of VR-3.

VR-3 Failure at Launch Insertion Orbital Decay (600x600 km)[13]

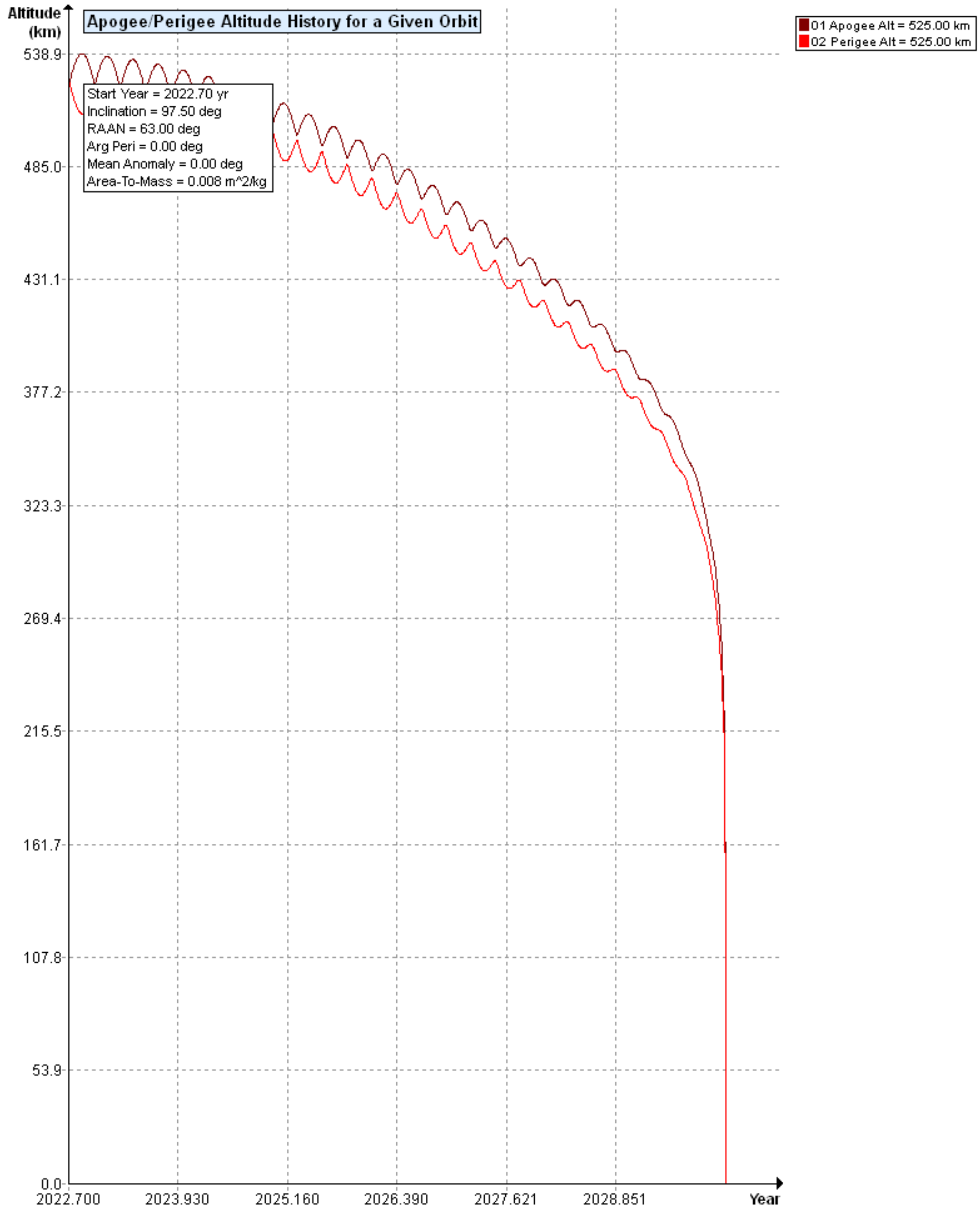


[13] VR-3 has an initial Area-to-Mass ratio of 0.008 m^2/kg including deployment of solar arrays.

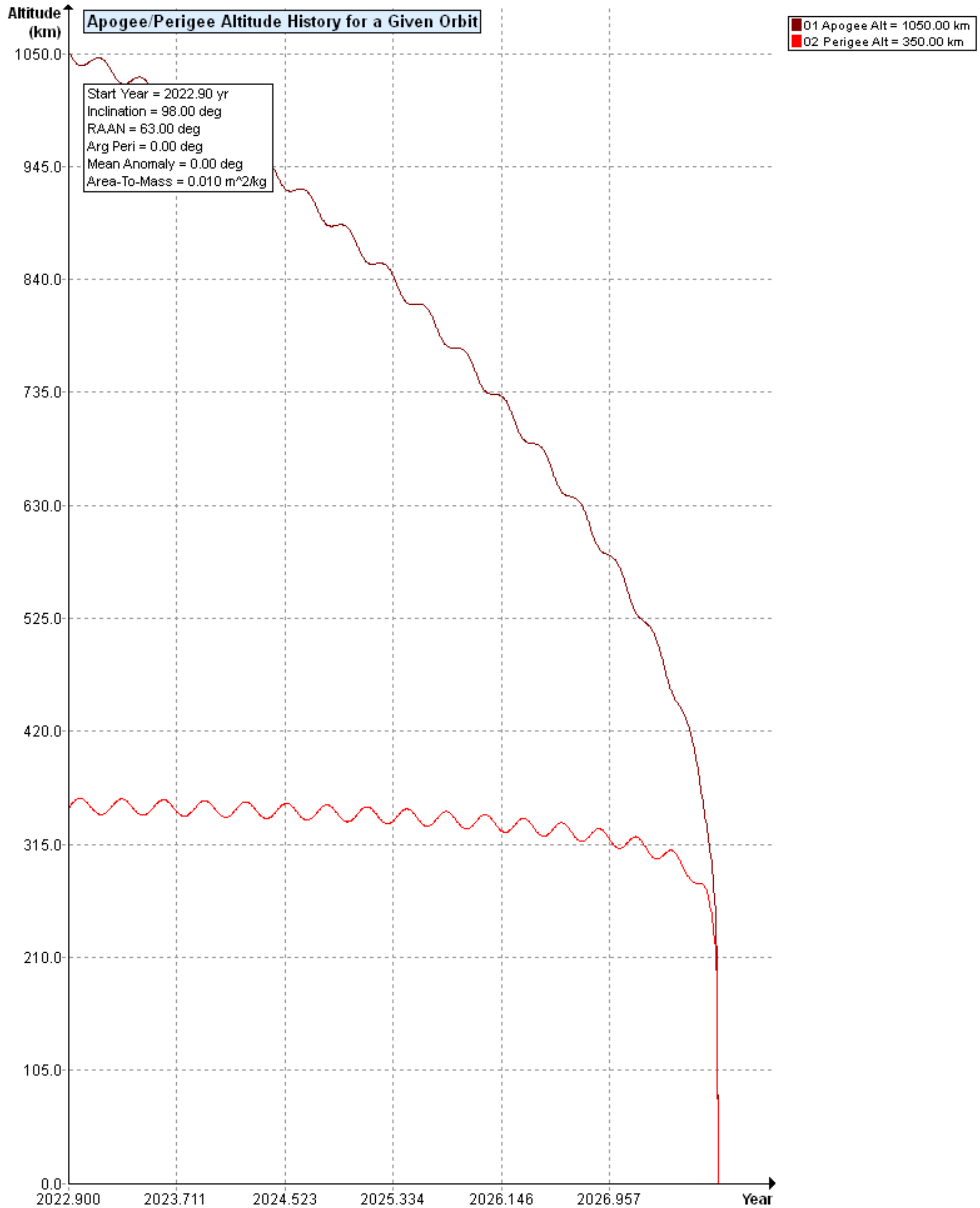
VR-3 Failure at Second Orbit - Orbital Decay (603x603 km)


Apogee/Perigee Altitude History for a Given Orbit
Altitude (km)
618.0
556.2
494.4
432.6
370.8
309.0
247.2
185.4
123.6
61.8
0.0
2022.600
2026.445
2030.289
2034.134
2037.979
2041.824
Year
Start Year = 2022.60 yr
Inclination = 97.50 deg
RAAN = 63.00 deg
Arg Peri = 0.00 deg
Mean Anomaly = 0.00 deg
Area-To-Mass = 0.008 m^2/kg
01 Apogee Alt = 603.00 km
02 Perigee Alt = 603.00 km

VR-3 Failure at Third Orbit - Orbital Decay (525x525 km)



VR-3 Fourth Orbit Orbital Decay (1050x350 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 spacecraft 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 v3.1.2 reports that VR-3 is compliant with the requirement with a 1:100000000 risk of human casualty. As shown below, six VR-3 components may survive reentry. In each case, the impacting kinetic energy is less than 15 joules.

Analysis using DAS v3.1.2:

12 14 2021; 14:36:18PM Processing Requirement 4.3-1: Return Status : Passed

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

Project Data

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

Objects Passing Through LEO = True

Number of Objects = 1

INPUT

Quantity = 9

Final Area-To-Mass Ratio = 0.010000 (m^2/kg)

Perigee Altitude = 525.000000 (km)

Apogee Altitude = 525.000000 (km)

Inclination = 97.500000 (deg)

RAAN = -1.000000 (deg)

Argument of Perigee = -1.000000 (deg)

Mean Anomaly = -1.000000 (deg)

Released Year = 2022.500000 (yr)

OUTPUT

Perigee Altitude = -6378.136000 (km)

Apogee Altitude = -6378.136000 (km)

Inclination = 0.000000 (deg)

Lifetime = 5.236986 (yr)

Object Reentered within 25 years of Release = True

Object-Time = 46.940452 (obj-yrs)

Total Object-Time = 46.940452 (obj-yrs)

Status = Pass

Returned Error Message - Normal Processing

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

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

12 07 2021; 10:33:23AM Processing Requirement 4.3-2: Return Status : Passed

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

No Project Data Available

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

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

12 07 2021; 11:17:32AM Processing Requirement 4.5-1: Return Status : Passed

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

Run Data

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

INPUT

Space Structure Name = Vigoride-3

Space Structure Type = Payload

Perigee Altitude = 603.000 (km)

Apogee Altitude = 603.000 (km)

Inclination = 97.500 (deg)

RAAN = 0.000 (deg)

Argument of Perigee = 0.000 (deg)

Mean Anomaly = 0.000 (deg)

Final Area-To-Mass Ratio = 0.0080 (m^2/kg)

Start Year = 2022.500 (yr)

Initial Mass = 411.500 (kg)

Final Mass = 411.500 (kg)

Duration = 0.500 (yr)

Station-Kept = False

Abandoned = True

OUTPUT

Collision Probability = 2.7973E-04

Returned Message: Normal Processing

Date Range Message: Normal Date Range

Status = Pass

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

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

12 07 2021; 11:18:10AM Project Data Saved To File

12 07 2021; 11:18:10AM Project Data Saved To File

12 07 2021; 11:39:00AM Requirement 4.5-2: Compliant

==

Spacecraft = Vigoride-3

Critical Surface = Avionics

==

INPUT

Apogee Altitude = 603.000 (km)

Perigee Altitude = 603.000 (km)

Orbital Inclination = 97.500 (deg)

RAAN = 0.000 (deg)

Argument of Perigee = 0.000 (deg)

Mean Anomaly = 0.000 (deg)

Final Area-To-Mass = 0.0080 (m^2/kg)

Initial Mass = 411.500 (kg)

Final Mass = 411.500 (kg)

Station Kept = No

Start Year = 2022.500 (yr)

Duration = 0.500 (yr)

Orientation = Random Tumbling

CS Areal Density = 5.000 (g/cm^2)

CS Surface Area = 1.0000 (m^2)

Vector = (0.000000 (u), 0.000000 (v), 0.000000 (w))

CS Pressurized = No

Outer Wall 1 Density: 10.000 (g/cm^2) Separation: 50.000 (cm)

OUTPUT

Probability of Penetration = 8.9078E-06 (8.9078E-06)

Returned Error Message: Normal Processing

Date Range Error Message: Normal Date Range

=============== End of Requirement 4.5-2 ===============

12 07 2021; 11:39:08AM Processing Requirement 4.6 Return Status : Passed

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

Project Data

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

INPUT

Space Structure Name = Vigoride-3

Space Structure Type = Payload

Perigee Altitude = 603.000000 (km)

Apogee Altitude = 603.000000 (km)

Inclination = 97.500000 (deg)

RAAN = 0.000000 (deg)

Argument of Perigee = 0.000000 (deg)

Mean Anomaly = 0.000000 (deg)

Area-To-Mass Ratio = 0.008000 (m^2/kg)

Start Year = 2022.500000 (yr)

Initial Mass = 411.500000 (kg)

Final Mass = 411.500000 (kg)

Duration = 0.500000 (yr)

Station Kept = False

Abandoned = True

PMD Perigee Altitude = 590.082925 (km)

PMD Apogee Altitude = 614.910591 (km)

PMD Inclination = 97.508207 (deg)

PMD RAAN = 172.641335 (deg)

PMD Argument of Perigee = 54.836851 (deg)

PMD Mean Anomaly = 0.000000 (deg)

OUTPUT

Suggested Perigee Altitude = 590.082925 (km)

Suggested Apogee Altitude = 614.910591 (km)

Returned Error Message = Passes LEO reentry orbit criteria.

Released Year = 2045 (yr)

Requirement = 61

Compliance Status = Pass

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

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

12 07 2021; 11:40:10AM *********Processing Requirement 4.7-1

Return Status : Passed

***********INPUT****

Item Number = 1

name = Vigoride-3

quantity = 1

parent = 0

materialID = 8

type = Box

Aero Mass = 411.500000

Thermal Mass = 411.500000

Diameter/Width = 1.200000

Length = 1.200000

Height = 1.100000

name = Primary Radiator Segment

quantity = 4

parent = 1

materialID = 8

type = Flat Plate

Aero Mass = 3.500000

Thermal Mass = 3.500000

Diameter/Width = 0.400000

Length = 0.400000

name = Secondary Radiator

quantity = 1

parent = 1

materialID = 8

type = Flat Plate

Aero Mass = 3.400000

Thermal Mass = 3.400000

Diameter/Width = 0.500000

Length = 0.500000

name = Side Radiator Plate

quantity = 2

parent = 1

materialID = 8

type = Flat Plate

Aero Mass = 6.000000

Thermal Mass = 6.000000

Diameter/Width = 0.350000

Length = 1.200000

name = Corner Brackets

quantity = 4

parent = 1

materialID = 8

type = Box

Aero Mass = 1.100000

Thermal Mass = 1.100000

Diameter/Width = 0.100000

Length = 0.350000

Height = 0.100000

name = Comms Panel

quantity = 2

parent = 1

materialID = 8

type = Flat Plate

Aero Mass = 1.100000

Thermal Mass = 1.100000

Diameter/Width = 0.150000

Length = 0.350000

name = Lower Payload Deck Segment

quantity = 4

parent = 1

materialID = 8

type = Flat Plate

Aero Mass = 4.500000

Thermal Mass = 4.500000

Diameter/Width = 0.500000

Length = 0.500000

name = Structure

quantity = 1

parent = 1

materialID = 8

type = Box

Aero Mass = 24.000000

Thermal Mass = 24.000000

Diameter/Width = 0.600000

Length = 0.600000

Height = 0.350000

name = Propellant Tanks

quantity = 4

parent = 1

materialID = 8

type = Box

Aero Mass = 39.709999

Thermal Mass = 9.710000

Diameter/Width = 0.300000

Length = 0.350000

Height = 0.300000

name = Water Propellant

quantity = 4

parent = 9

materialID = 75

type = Box

Aero Mass = 30.000000

Thermal Mass = 30.000000

Diameter/Width = 0.310000

Length = 0.310000

Height = 0.310000

name = Launch Vehicle Adapter

quantity = 1

parent = 1

materialID = 8

type = Flat Plate

Aero Mass = 4.000000

Thermal Mass = 4.000000

Diameter/Width = 0.600000

Length = 0.600000

name = Solar Array Panel

quantity = 10

parent = 1

materialID = 8

type = Box

Aero Mass = 2.460000

Thermal Mass = 2.460000

Diameter/Width = 0.350000

Length = 1.100000

Height = 0.020000

name = Battery Assembly

quantity = 2

parent = 1

materialID = 8

type = Box

Aero Mass = 8.000000

Thermal Mass = 8.000000

Diameter/Width = 0.200000

Length = 0.250000

Height = 0.100000

name = Power Supply Unit

quantity = 2

parent = 1

materialID = 8

type = Box

Aero Mass = 1.200000

Thermal Mass = 1.200000

Diameter/Width = 0.100000

Length = 0.250000

Height = 0.050000

name = Microwave Source Box

quantity = 2

parent = 1

materialID = 8

type = Box

Aero Mass = 4.000000

Thermal Mass = 4.000000

Diameter/Width = 0.200000

Length = 0.200000

Height = 0.200000

name = Feed System Box

quantity = 2

parent = 1

materialID = 8

type = Box

Aero Mass = 0.500000

Thermal Mass = 0.500000

Diameter/Width = 0.100000

Length = 0.200000

Height = 0.030000

name = Power Distribution Unit

quantity = 2

parent = 1

materialID = 8

type = Box

Aero Mass = 1.600000

Thermal Mass = 1.600000

Diameter/Width = 0.100000

Length = 0.250000

Height = 0.050000

name = Diaphragm Tank Middle

quantity = 2

parent = 1

materialID = 27

type = Cylinder

Aero Mass = 0.250000

Thermal Mass = 0.250000

Diameter/Width = 0.150000

Length = 0.300000

name = Diaphragm Tank End 1

quantity = 2

parent = 1

materialID = 27

type = Sphere

Aero Mass = 0.100000

Thermal Mass = 0.100000

Diameter/Width = 0.150000

name = Diaphragm Tank End 2

quantity = 2

parent = 1

materialID = 27

type = Sphere

Aero Mass = 0.100000

Thermal Mass = 0.100000

Diameter/Width = 0.150000

name = Diaphragm Tank Liner

quantity = 2

parent = 1

materialID = 8

type = Cylinder

Aero Mass = 1.200000

Thermal Mass = 1.200000

Diameter/Width = 0.200000

Length = 0.200000

name = Plumbing Lines

quantity = 20

parent = 1

materialID = 59

type = Cylinder

Aero Mass = 0.030000

Thermal Mass = 0.030000

Diameter/Width = 0.005000

Length = 0.500000

name = Plumbing Fittings

quantity = 20

parent = 1

materialID = 59

type = Cylinder

Aero Mass = 0.050000

Thermal Mass = 0.050000

Diameter/Width = 0.020000

Length = 0.020000

name = Thruster

quantity = 1

parent = 1

materialID = 58

type = Cylinder

Aero Mass = 1.000000

Thermal Mass = 1.000000

Diameter/Width = 0.100000

Length = 0.070000

name = Window

quantity = 1

parent = 1

materialID = 1

type = Cylinder

Aero Mass = 0.010000

Thermal Mass = 0.010000

Diameter/Width = 0.050000

Length = 0.015000

name = Reaction Control Thruster

quantity = 4

parent = 1

materialID = 59

type = Box

Aero Mass = 0.160000

Thermal Mass = 0.160000

Diameter/Width = 0.050000

Length = 0.050000

Height = 0.040000

name = RCS Fasteners

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 1

quantity = 1

parent = 1

materialID = 8

type = Box

Aero Mass = 22.500000

Thermal Mass = 22.500000

Diameter/Width = 0.400000

Length = 0.600000

Height = 0.400000

name = 12U Cubesat Deployer 2

quantity = 1

parent = 1

materialID = 8

type = Box

Aero Mass = 22.500000

Thermal Mass = 22.500000

Diameter/Width = 0.400000

Length = 0.600000

Height = 0.400000

name = Deployer Mass Dummy

quantity = 2

parent = 1

materialID = 8

type = Box

Aero Mass = 8.000000

Thermal Mass = 8.000000

Diameter/Width = 0.400000

Length = 0.600000

Height = 0.400000

name = 3U Cubesat Deployer

quantity = 1

parent = 1

materialID = 8

type = Box

Aero Mass = 6.400000

Thermal Mass = 6.400000

Diameter/Width = 0.150000

Length = 0.400000

Height = 0.150000

name = PocketPod Deployer

quantity = 2

parent = 1

materialID = 8

type = Box

Aero Mass = 1.000000

Thermal Mass = 1.000000

Diameter/Width = 0.150000

Length = 0.300000

Height = 0.100000

name = Payload Interface Adapter

quantity = 6

parent = 1

materialID = 8

type = Flat Plate

Aero Mass = 1.000000

Thermal Mass = 1.000000

Diameter/Width = 0.200000

Length = 0.300000

name = Structural Fasteners

quantity = 150

parent = 1

materialID = 57

type = Cylinder

Aero Mass = 0.010000

Thermal Mass = 0.010000

Diameter/Width = 0.010000

Length = 0.020000

name = Microwave Filament

quantity = 2

parent = 1

materialID = 43

type = Cylinder

Aero Mass = 0.005000

Thermal Mass = 0.005000

Diameter/Width = 0.010000

Length = 0.010000

**************OUTPUT****

Item Number = 1

name = Vigoride-3

Demise Altitude = 77.999573

Debris Casualty Area = 0.000000

Impact Kinetic Energy = 0.000000

****

name = Primary Radiator Segment

Demise Altitude = 69.527718

Debris Casualty Area = 0.000000

Impact Kinetic Energy = 0.000000

****

name = Secondary Radiator

Demise Altitude = 71.498245

Debris Casualty Area = 0.000000

Impact Kinetic Energy = 0.000000

****

name = Side Radiator Plate

Demise Altitude = 71.182632

Debris Casualty Area = 0.000000

Impact Kinetic Energy = 0.000000

****

name = Corner Brackets

Demise Altitude = 75.407799

Debris Casualty Area = 0.000000

Impact Kinetic Energy = 0.000000

****

name = Comms Panel

Demise Altitude = 73.669365

Debris Casualty Area = 0.000000

Impact Kinetic Energy = 0.000000

****

name = Lower Payload Deck Segment

Demise Altitude = 69.265938

Debris Casualty Area = 0.000000

Impact Kinetic Energy = 0.000000

****

name = Structure

Demise Altitude = 57.507236

Debris Casualty Area = 0.000000

Impact Kinetic Energy = 0.000000

****

name = Propellant Tanks

Demise Altitude = 69.896706

Debris Casualty Area = 0.000000

Impact Kinetic Energy = 0.000000

****

name = Water Propellant

Demise Altitude = 64.804359

Debris Casualty Area = 0.000000

Impact Kinetic Energy = 0.000000

****

name = Launch Vehicle Adapter

Demise Altitude = 71.467361

Debris Casualty Area = 0.000000

Impact Kinetic Energy = 0.000000

****

name = Solar Array Panel

Demise Altitude = 75.508453

Debris Casualty Area = 0.000000

Impact Kinetic Energy = 0.000000

****

name = Battery Assembly

Demise Altitude = 59.681911

Debris Casualty Area = 0.000000

Impact Kinetic Energy = 0.000000

****

name = Power Supply Unit

Demise Altitude = 73.165268

Debris Casualty Area = 0.000000

Impact Kinetic Energy = 0.000000

****

name = Microwave Source Box

Demise Altitude = 69.239006

Debris Casualty Area = 0.000000

Impact Kinetic Energy = 0.000000

****

name = Feed System Box

Demise Altitude = 75.091507

Debris Casualty Area = 0.000000

Impact Kinetic Energy = 0.000000

****

name = Power Distribution Unit

Demise Altitude = 71.682846

Debris Casualty Area = 0.000000

Impact Kinetic Energy = 0.000000

****

name = Diaphragm Tank Middle

Demise Altitude = 0.000000

Debris Casualty Area = 1.319117

Impact Kinetic Energy = 13.947527

****

name = Diaphragm Tank End 1

Demise Altitude = 0.000000

Debris Casualty Area = 1.074385

Impact Kinetic Energy = 10.209887

****

name = Diaphragm Tank End 2

Demise Altitude = 0.000000

Debris Casualty Area = 1.074385

Impact Kinetic Energy = 10.209887

****

name = Diaphragm Tank Liner

Demise Altitude = 74.709526

Debris Casualty Area = 0.000000

Impact Kinetic Energy = 0.000000

****

name = Plumbing Lines

Demise Altitude = 77.388634

Debris Casualty Area = 0.000000

Impact Kinetic Energy = 0.000000

****

name = Plumbing Fittings

Demise Altitude = 72.069672

Debris Casualty Area = 0.000000

Impact Kinetic Energy = 0.000000

****

name = Thruster

Demise Altitude = 65.484589

Debris Casualty Area = 0.000000

Impact Kinetic Energy = 0.000000

****

name = Window

Demise Altitude = 0.000000

Debris Casualty Area = 0.393613

Impact Kinetic Energy = 0.854857

****

name = Reaction Control Thruster

Demise Altitude = 70.742699

Debris Casualty Area = 0.000000

Impact Kinetic Energy = 0.000000

****

name = RCS Fasteners

Demise Altitude = 0.000000

Debris Casualty Area = 1.742400

Impact Kinetic Energy = 2.833804

****

name = 12U Cubesat Deployer 1

Demise Altitude = 64.941818

Debris Casualty Area = 0.000000

Impact Kinetic Energy = 0.000000

****

name = 12U Cubesat Deployer 2

Demise Altitude = 64.941818

Debris Casualty Area = 0.000000

Impact Kinetic Energy = 0.000000

****

name = Deployer Mass Dummy

Demise Altitude = 73.155983

Debris Casualty Area = 0.000000

Impact Kinetic Energy = 0.000000

****

name = 3U Cubesat Deployer

Demise Altitude = 68.830597

Debris Casualty Area = 0.000000

Impact Kinetic Energy = 0.000000

****

name = PocketPod Deployer

Demise Altitude = 75.628426

Debris Casualty Area = 0.000000

Impact Kinetic Energy = 0.000000

****

name = Payload Interface Adapter

Demise Altitude = 74.238533

Debris Casualty Area = 0.000000

Impact Kinetic Energy = 0.000000

****

name = Structural Fasteners

Demise Altitude = 75.561356

Debris Casualty Area = 0.000000

Impact Kinetic Energy = 0.000000

****

name = Microwave Filament

Demise Altitude = 0.000000

Debris Casualty Area = 0.744200

Impact Kinetic Energy = 2.287653

****

***********INPUT****

Item Number = 2

name = PocketQubes

quantity = 10

parent = 0

materialID = 8

type = Box

Aero Mass = 0.250000

Thermal Mass = 0.250000

Diameter/Width = 0.050000

Length = 0.050000

Height = 0.050000

name = P

quantity = 10

parent = 1

materialID = 8

type = Box

Aero Mass = 0.250000

Thermal Mass = 0.250000

Diameter/Width = 0.050000

Length = 0.050000

Height = 0.050000

*************OUTPUT****

Item Number = 2

name = PocketQubes

Demise Altitude = 77.992119

Debris Casualty Area = 0.000000

Impact Kinetic Energy = 0.000000

****

name = P

Demise Altitude = 68.443680

Debris Casualty Area = 0.000000

Impact Kinetic Energy = 0.000000

****

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

VIII. Special Classes

Not applicable.