Gluon Spacecraft Orbital Debris Assessment Report (ODAR)

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Document History:

Date	Author	Modification	Version
March 10, 2023	Isabella Katzman	Created file	A

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Orbital Debris Self-Assessment Evaluation

The table below is the Atomos orbital debris self-assessment, following the format in Appendix A.2.2 of the NASA-STD-8719.14C [1]. The launch vehicle ODAR is not covered here.

Requirement #	Launch Vehicle				Spacecraft			Comments
	Compliant or N/A	Not Compliant	Incomplete	Standard Non-Compliant	Compliant or N/A	Not Compliant	Incomplete	
4.3-1a	☒	☐	☐	☐	☒	☐	☐	
4.3-1b	☒	☐	☐	☐	☒	☐	☐	
4.3-2	☒	☐	☐	☐	☒	☐	☐	No debris released in GEO.
4.4-1	☒	☐	☐	☐	☒	☐	☐	
4.4-2	☒	☐	☐	☐	☒	☐	☐	
4.4-3	☒	☐	☐	☐	☒	☐	☐	No intentional collision or explosion planned
4.4-4	☒	☐	☐	☐	☒	☐	☐	No intentional collision or explosion planned
4.5-1	☒	☐	☐	☐	☒	☐	☐	
4.5-2	☒	☐	☐	☐	☒	☐	☐	
4.6-1(a)	☒	☐	☐	☐	☒	☐	☐	
4.6-1(b)	☒	☐	☐	☐	☒	☐	☐	
4.6-1(c)	☒	☐	☐	☐	☒	☐	☐	
4.6-2	☒	☐	☐	☐	☒	☐	☐	Gluon does not go to GEO
4.6-3	☒	☐	☐	☐	☒	☐	☐	Gluon does not go beyond LEO
4.6-4	☒	☐	☐	☐	☒	☐	☐	
4.7-1	☒	☐	☐	☐	☒	☐	☐	
4.8-1	☒	☐	☐	☐	☒	☐	☐	No tethered systems used.

Assessment Report Format

This ODAR follows the format recommended in NASA-STD-8719.14-C [1], Appendix A.1, and includes the content indicated at a minimum in Sections 2 through 8 for the January 2024 SpaceX Rideshare Mission. Sections 9 through 14 apply to the launch vehicle ODAR and are not covered here.

1. Program Management and Mission Overview

HQ Mission Directorate Sponsoring the Mission: None.

Program Executive: Scott Piggott (Chief Engineer)

Program Manager: Isabella Katzman

Foreign government or space agency participation: No foreign government or space agency participation.

Schedule of mission design and development milestones:

- Gluon Spacecraft Assembly Readiness Review – May 2023
- Environmental Readiness Review – September 2023
- Pre-Ship (to launch site) Review – November 2023
- Launch – January 2024

Mission Overview:

This is a technology demonstration mission, that involves two Atomos-owned and operated spacecraft: Meson and Gluon. Meson is a small, Solar-Electric Propulsion (SEP) utility Orbital Transfer Vehicle (OTV). Meson is design for RPO, docking and refueling with Atomos's other spacecraft Gluon. Gluon's primary purpose is to support Meson's RPO, docking and refueling operations. Meson will obtain its own FCC license and will submit its own ODAR.

The first mission spacecraft will launch on a single slot on a SpaceX rideshare mission. Meson will launch mated to Gluon via a Motorized Light Band (MLB). The mated stack (defined and Meson mated to Gluon) will attach to the launch vehicle via a secondary MLB on the Meson spacecraft. Once deployed on orbit, the spacecraft stack will lower its altitude using Meson's propulsion system. The two spacecraft will then separate from each other. Meson will then perform RPO and dock to Gluon. Following the RPO and docking activities, the two spacecraft will participate in inter-vehicle refueling operations. At this time, undocking and additional RPO and docking operations can occur. At the end of mission life, Meson will use its onboard propulsion system to lower the altitude of the spacecraft stack, then undock from Gluon and the two spacecraft will passivate and re-enter into Earth atmosphere separately, in an un-docked state.

Launch Vehicle: SpaceX Falcon

Launch Site: Vandenberg, CA

Proposed Launch Date: January 2024

Mission Duration:

- Maximum Gluon Operational Lifetime: 6 months
- Maximum post-mission orbit lifetime: 5 years

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

Orbit	Apogee Altitude	Perigee Altitude	Inclination	Duration
Deployment Orbit	515 km +/- 25 km	515 km +/- 25 km	90 degrees	1 month
Demonstration Mission Orbit	500 km	500 km	90 degrees	5 months

Spacecraft's maneuver capability and time period, including both attitude and orbit control:

Gluon provides three 1 Nms reaction wheels and three 1.6 Am^2 torque rods for attitude control. Gluon additionally carries an experimental propulsive system, not intended to be used for nominal operations. Gluon will test the capabilities of the experimental thruster.

Reason for selection of operational orbit(s):

Atomos's operational orbit selection was primarily driven by the desire for a cost-efficient, easy access pathway to space. Therefore, Atomos selected to ride on a SpaceX rideshare mission to LEO.

Interaction or potential physical interference with other operational spacecraft:

The only planned interaction and interference with another operational spacecraft is Meson, Atomos's other spacecraft. The planned interactions involve RPO and docking. The associated potential interference is limited to communications with the ground (via satellite relays) during the final stages of close-range RPO. This interference has been assessed by Atomos and operational mitigation strategies, such as duty cycling communication, and inter-vehicle communication has been adopted, to enable safe interactions between the two operational spacecraft. Additionally, Atomos has fully defined the on-orbit operations related to approach and docking to minimize risk of physical interference between the two spacecraft. This includes ground in the loop, safe holding trajectories and abort maneuvers. When performing final approach and docking, Meson's closing velocity relative to Gluon shall be below 4 cm/s. Should misalignment be sufficient to disable docking, the impact to the two spacecraft will be non-critical and no debris will be released. Additional details about RPO and docking controls can be found below in Section 3, description of planned proximity operations or docking with another spacecraft.

2. Spacecraft Description

Physical Description:

Gluon is a spacecraft with the following subsystems: Structure, Experimental Thruster Payload, Communication, GNC, Power, Avionics.

Mounted externally to Gluon's primary structure are three body-mounted solar arrays, a GPS antenna and communication antennas. Integrated within Gluon's structure low-thrust experimental propulsive system, the passive side of the docking and refueling interface, the lower half of the MLB, and RPO-enabling fiducials and a camera. Internal to the spacecraft exists a propellant tank filled with ammonia, the spacecraft bus intended to refuel Meson, and the attitude determination and control system.

Additional system details are found in this section below.

Illustration:

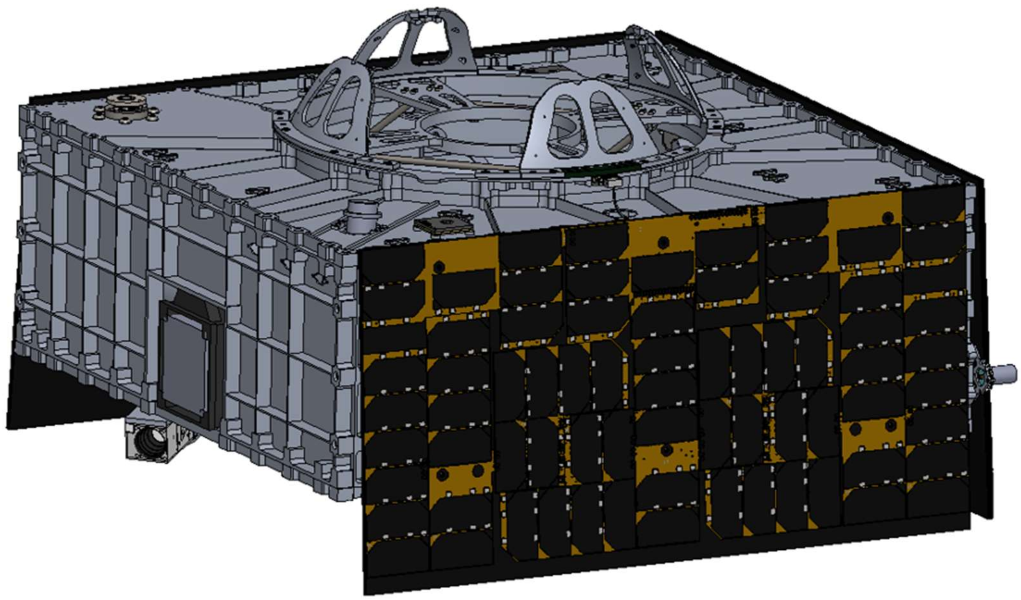

Figure 1: Gluon Spacecraft

Spacecraft Mass at Launch:

Criteria	Mass	Notes
Spacecraft Total Launch Mass	72.98 kg	
Spacecraft Launch Dry Mass	67.96 kg	
Ammonia Propellant Mass	5 kg	Mixed-phase (Liquid/gaseous) Ammonia , intended for refueling partner spacecraft Meson
ASCENT Propellant Mass	20 g	ASCENT propellant used in experimental propulsion system.

Onboard Fluids:

Gluon is equipped with a single propellant storage tank. The tank dimensions are 27.79 inches in length (without fittings) and 6.035 inches outer diameter. The tank will be filled prior to launch with 5 kg of liquid ammonia. The tank will be launched nearly full, allowing sufficient ullage for gaseous ammonia to form as a result of the launch conditions. By launch, the tank will be fully qualified in compliance with the SpaceX Rideshare Payload User's Guide (October 2022) [2], and acceptance testing performed. Ammonia will exist in the liquid and gaseous phases. All fluid lines will be evacuated prior to launch. The ammonia will be transferred to Meson on-orbit following successful RPO and docking operations.

At End-of-Mission (EOM) any remaining propellant in Gluon's tank and lines will be vented.

The following table outlines the notable pressures and temperatures related to the storage and usage of ammonia house in the storage tank.

Criteria	Value
Ground/Launch Maximum Expected Operating Pressure (MEOP)	325 psi
Post-separation MEOP	150 psi
Component Level Maximum Allowable Working Pressure (MAWP)	500 psi
Component Level Proof Pressure	750 psi
Component Level Design Burst Pressure	1500 psi
Allowable Temperature Range	-73 C to 93 C

The experimental propulsion system utilizes AFRL's ASCENT propellant. The experimental thruster is not pressurized. During normal course of thruster operations, electrostatic force is applied, which extracts and accelerates the propellant, thus generating thrust.

Propulsion System:

Gluon includes an experimental propulsion system, which will not be utilized for nominal operation. The experimental propulsion system utilizes AFRL's ASCENT propellant. The experimental thruster is not pressurized. During normal course of thruster operations, electrostatic force is applied, which extracts and accelerates the propellant, thus generating thrust.

Attitude Control System:

Gluon's attitude determination and control system is comprised of reaction wheels, torque rods, magnetometer, star tracker, IMU and GPS. Gluon will use its effectors to detumble the spacecraft after separation from the launch vehicle. To achieve a stable, power positive attitude, this operation is estimated to take several hours. Note that Meson and Gluon will be mated at this time, and Gluon will be responsible for all detumble operations. Gluon will detumble using the torque rods following all separation activities from Meson on orbit, including both intervehicle separation from the MLB and Atomos's docking interface. Additionally, Gluon will use its effectors for attitude control and pointing for communication with ground, solar array pointing, and holding attitude for RPO and docking operations with Meson.

Range Safety or other pyrotechnic devices:

<u>None.</u>

Electrical Generation and Storage System:

Gluon's power generation system consists of three body-mounted 0.4m x 0.8m panels. Two of which are populated with triple-junction solar cells and the third panel with silicon solar cells. The triple-junction panels will provide 100W to 150W of total power at Beginning-of-Life (BOL) when oriented in an optimal attitude, not to exceed 300W.

Power on Gluon will be stored in eight lithium-ion bus batteries, with each battery having a total capacity of 24,000 mAh. The batteries will be fully charged prior to launch. Gluon will launch in a powered off, quiescent state, as the batteries and EPS will be inhibited prior to spacecraft integration on the launch vehicle and will only be un-inhibited after deployment from the launch vehicle.

Identification of any other sources of stored energy not noted above:

None.

Identification of any radioactive materials on board:

None.

Description of any planned proximity operations or docking with other spacecraft:

Several RPO and docking attempts are expected throughout mission life. Meson, the active spacecraft, will perform RPO and dock with Gluon, the cooperative target. For each RPO and docking attempt, Meson will maneuver to Gluon using its onboard propulsion system and RPO sensor suite. For the duration of RPO, Gluon will hold its attitude. Just prior to docking, Gluon will disable its attitude control system to prevent adverse force. Therefore, Meson is primarily responsible for all controls and operations to mitigate the risk of a debris-generating collision or other harmful physical interference. Meson's RPO and docking concept of operations (CONOPS) has been fully defined and simulated to include safe trajectory holding points, ground in the loop participation and abort maneuvers.

Atomos defines "integrated operations" as the period when Meson and Gluon are within 100 meters of each other. Prior to arriving at integrated operations, both of our spacecraft are constantly on trajectories that allow them at least 24 hours of non-contact free-drift. This is done in order to minimize the chance of debris generation from an unplanned contact. If the Meson spacecraft detects that it has deviated from its trajectory by an amount that would compromise the 24 safety requirement, it will execute a breakout maneuver to restore the 24-hour safety net. Most points on this trajectory are indefinitely safe, with no anticipated possibility of contact.

Between arrival at integrated operations and "final approach," which is defined as within 10 meters, Meson's relative trajectory gives it at least 5 hours of free-drift prior to impacting Gluon. If Meson detects that it has deviated from the planned trajectory by enough to compromise the 5 hour safety period, it will autonomously execute a breakout maneuver that will establish a minimum 24-hour safe free-drift trajectory. This 5-hour period is sufficient to recover Meson from a safe-mode and execute a commanded breakout in the event of significantly off-nominal operations. This 5 hour period is a minimum, and most points on this trajectory are indefinitely safe, with no anticipated possibility of contact.

After initiating final approach from 10 meters to contact, long duration free drift without recontact is difficult to prove. To remove the probability of generating significant debris, the relative velocity between Meson and Gluon is held to a very low level. Meson approaches Gluon with a target velocity of 2.5 cm/s, and if it detects that it was exceeded the allowable approach velocity by more than 1.5 cm/s it will autonomously execute a breakout maneuver to establish a 24-hour safe free-drift. If Meson detects that it has encountered an anomaly during contact with Gluon, it will autonomously engage a small backup burn to establish a separation rate. In a worst case collision during this phase, the approach velocities are so low to prevent the generation of orbital debris.

3. Assessment of Spacecraft Debris Released during Normal Operations

Identification of any object (>1 mm) expected to be released from the spacecraft any time after launch, including object dimensions, mass, and material:

None.

Per the definition of debris in section 4.3.1.3 in the NASA-STD-8719.14C [1], there will be no debris released from Gluon.

Rationale/necessity for release of each object:

Not applicable.

Time of release of each object, relative to launch time:

Not applicable.

Release velocity of each object with respect to spacecraft:

Not applicable.

Expected orbital parameters (apogee, perigee, and inclination) of each object after release:

Not applicable.

Calculated orbital lifetime of each object, including time spent in LEO:

Not applicable.

Assessment of spacecraft compliance with Requirements 4.3-1 and 4.3-2:

Requirement 4.3-1. ***Planned debris release passing through LEO – released debris with diameters of 1mm or larger:***

a. *All debris released during the deployment, operation, and disposal phases shall be limited to a maximum orbital lifetime of 25 years from date of release.*

Not Applicable

b. *The total object-time product shall be less than 100 object-years per launch vehicle upper stage or per spacecraft.*

Not Applicable.

Requirement 4.3-2. ***Planned debris release passing near GEO:*** *For missions leaving debris in orbits with the potential of traversing GEO (GEO altitude +/- 200 km and +/- 15 degrees inclination), released debris with diameters of 5 mm or greater shall be left in orbits which will ensure that within 25 years after release the apogee will no longer exceed GEO - 200 km or the perigee will not be lower than GEO + 200* *km , and also ensures that the debris is incapable of being perturbed to lie within that GEO +/- 200 km and +/- 15 degree zone for at least 100 years thereafter.*

Not Applicable

4. Assessment of Spacecraft Intentional Breakups during Normal Operations

Identification of all potential causes of spacecraft breakup during deployment and mission operations:

Gluon has three potential causes of spacecraft breakup during deployment and mission operations:

1. Lithium Ion battery cell failure of EPS batteries or RCCT batteries
2. Rupture of ammonia (NH3) propellant tank
3. Ignition and deflagration of ASCENT propellant in experimental thruster

All three causes of spacecraft breakup are very low likelihood, and believed to be much less than 0.001. The EPS batteries provide the capability to vent internal pressure should battery cell failure occur. Although the possibility of battery failure is very unlikely, an FMEA was performed to analyze the probability of failure.

The following causes of spacecraft breakup were deemed to be not credible. The propellant tank rupture was determined to be not credible since burst pressure from qualification testing was determined to be 2000 psi, on orbit the maximum expected operating pressure will be 325 psi. In the event of thermal runaway from the heater on the propulsion tank, the pressure will not reach burst pressure.

The ASCENT propellant in the experimental thruster is not pressurized, so there is no risk of spacecraft breakup due to overpressure. Testing performed on the ASCENT propellant by Air Force Research Laboratory showed that arc energy magnitudes larger than the capability of the experimental thruster were required for ignition and deflagration of the propellant. Approximately, 87kJ of energy would be required to melt the primary non-pressurized containment vessel. This required thermal energy is four times greater than that released by combustion of the propellant, when fully loaded. Thus, in the unlikely event of propellant deflagration, containment of propellant within the thruster would be maintained.

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

- In the event of battery protection system failure there is a low likelihood of battery cell failure which could potentially result in explosion. Should battery cell rupture occur, the cells may vent gasses but should not expel debris into space. The battery protection system protects cells from being overcharged. Should the cells be overcharged or overheated, the cells current-interrupt device (CID) will cause a permanent open circuit across the cell.

Detailed plan for any designed spacecraft breakup, including explosions and intentional collisions:

There are no planned breakups in this mission.

List of components which are passivated at EOM. List includes method of passivation and amount which cannot be passivated:

At end of mission Atomos will passivate the following components.

- EPS Batteries: Passivated by cutting the batteries out of the loop to prevent batteries from being overcharged. There is minimal potential for explosion in the event of thermal runaway in the cells of the battery pack.
- Ammonia propellant tank: Any remaining propellant will be used to lower Meson's perigee to allow for earlier reentry, or will be vented into space by opening the vent valve.
- Experimental Thruster: Any remaining propellant will be emitted. In the event propellant is not emitted prior to reentry, it will burn up during reentry. The unpressurized propellant reservoir is emptied over the course via electrostatic emission and acceleration over several hundred hours of total operation, a process that does not include decomposition or combustion of the propellant.

Rationale for all items which are required to be passivated, but cannot be due to their design:

Not applicable. There are no items that require passivation but cannot be due to their design.

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

Requirement 4.4-1. ***Limiting the Probability of Accidental Explosion:*** *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 (i.e., every individual free-flying structural object), the program or project shall demonstrate, via failure mode and effects analyses, probabilistic risk assessments, or other appropriate 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.)*

Compliant

Battery explosion is extremely unlikely and probably of explosion is estimated to be <0.001 since multiple independent faults would need to occur as detailed below.

Supporting Rationale and FMEA Details:
Battery Explosion:

- Effect: All failure modes below might result in battery explosion, with low probability of orbital debris generation. In the event a battery cell does explode, most debris from rupture will be contained within the spacecraft due to the multiple enclosure around the batteries. An explosive rupture of a battery cell could result in gas being vented from the cell.
- Probability: Extremely unlikely, multiple faults would need to occur to ultimately lead to battery cell explosion.

Failure mode 1: Internal short circuit

- Combined Faults Required for Failure: Environmental testing and functional EPS testing must fail to identify internal short circuits.
- Mitigation: Prior to flight all of the following tests will occur to show likelihood of internal short is minimal: sine sweep, random vibe all three axis, thermal vacuum cycling and functional testing, system and component functional testing including EPS system testing charging and discharging of batteries.

Failure mode 2: Internal thermal rise due to high discharge rate

- Combined Faults Required for Failure: Thermal design of spacecraft is incorrect and battery protection circuit fails to disconnect discharge path if discharge rate becomes too high.
- Mitigation: Battery cells tested throughout AI&T for high discharge rates in variety of flight like conditions to determine potential of out of control thermal rise in the cell. Additionally battery cells are tested in hot thermal cycles during thermal vacuum testing to ensure no failures occur. Finally batteries have overcurrent protection which disconnects the discharge path if the discharge rate is too high.

Failure mode 3: Excessive discharge rate due or short-circuit from external devices

- Combined Faults Required for Failure: An external device must short circuit and battery over current protection fails to disconnect discharge path if discharge rate becomes too high.
- Mitigation: Batteries have overcurrent protection which disconnects the discharge path in the event of a short circuit. Additionally, the switches that distribute power to external devices have overcurrent protection to shut off external devices in the event of a short circuit. Harnesses are designed to minimize potential of mechanical short between power pins. Spacecraft will undergo environmental testing consisting of vibration, and thermal vacuum cycle testing to observe if any mechanical failure could result in a short circuit from external devices.

Failure mode 4: Overcharging

- Combined Faults Required for Failure: Thermal design of spacecraft is incorrect and battery protection circuit fails to disconnect charging path in the event of overvoltage.
- Mitigation: Battery circuitry limits charge rate and minimum/maximum voltages of the batteries. Additionally if battery voltage is near max level, the battery protection circuity disconnects the charge path and only allows discharging. Battery cell charging tested in hot thermal cycles during thermal vacuum testing, to ensure battery protection circuitry functions as desired and no thermal runaway occurs during battery charging.

Failure mode 5: Crushing

- Combined Faults Required for Faults: Catastrophic failure must occur on external system, and failure must crush batteries resulting in an internal short, additionally spacecraft must be in naturally sustained orbit at time of failure.
- Mitigation: This failure mode is negated by moving parts, spacecraft is designed to prevent loads on battery cases.

Failure mode 6: Inoperable vents

- Combined Faults Required for Faults: Proper venting not properly installed by battery pack manufacturer, or during spacecraft assembly.
- Mitigation: Battery vents are not inhibited by battery case design or spacecraft.

Failure mode 7: Low level current leakage or short-circuit through battery pack case or due to moisture based degradation of 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.
- Mitigation: Battery case made out of non-conductive polycarbonate, operation in vacuum such that no moisture can affect insulators, satellites stored in controlled environment.

Failure mode 8: Excess temperature due to orbital environment and high discharge combined

- Combined faults required for realized failure: Thermal design of spacecraft must be inaccurate, and fault protections for battery over temperature and battery over current must fail.
- Mitigation: Spacecraft designed to ensure batteries remain within thermal operating limits. External loads will be shut off if battery temperatures become too high or if discharge rate is too high. Spacecraft testing will include thermal testing in hot cycles in vacuum to verify nominal functionality of battery discharging in hot temperatures.

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 and a plan to either 1) 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 2) control to a level which cannot cause an explosion or deflagration large enough to release orbital debris or break up the spacecraft. The design of depletion burns and ventings should minimize the probability of accidental collision with tracked objects in space.*

Burning residual propellants to depletion:

- Not Applicable.

Emitting propellant:

- The experimental propulsion system's ASCENT propellant will be emitted via electrostatic emission and acceleration over several hundred hours of total operation, a process that does not include decomposition or combustion of the propellant.

Venting pressurized systems including propellant lines and tanks:

- At EOM, Gluon will vent all residual propellant in the lines and tank, through the opening of vent valve and upstream valves to the propellant transfer valve.

Preventing recharging of batteries or other energy storage systems:

- Prevention of battery recharging will be done by overriding any limits on the battery-state-of-charge; setting the maximum battery values down to zero, such that the EPS will not attempt to charge the batteries and then burning the heaters until the batteries are dead. Additionally, the Power Distribution Unit (PDU) switch settings will be configured to a new default value such that no switches ever come on, ensuring that batteries cannot be recharged.

Deactivating range safety systems:

- Not Applicable.

De-energizing control moment gyroscopes:

- Not Applicable.

Requirement 4.4-3. ***Limiting the long-term risk to other space systems from planned breakups for Earth and lunar missions:*** *Planned explosions or intentional collisions shall:*

a. Be conducted at an altitude such that for orbital debris fragments larger than 10 cm the object-time product is less than 100 object-years. For example, if the debris fragments greater than 10 cm decay in the maximum allowed 1 year, a maximum of 100 such fragments can be generated by the breakup.

Not Applicable. There are no planned breakups.

b. Not generate debris larger than 1 mm that remains in Earth orbit longer than one year.

Not Applicable. There are no planned breakups.

Requirement 4.4-4. ***Limiting the short-term risk to other space systems from planned breakups for Earth orbital missions:*** *Immediately before a planned explosion or intentional collision, the probability of debris, orbital or ballistic, larger than 1 mm colliding with any operating spacecraft within 24 hours of the breakup shall be less than 10-6.*

Not Applicable. There are no planned breakups.

5. Assessment of Spacecraft Potential for On-Orbit Collisions

Assessment of spacecraft compliance with Requirements 4.5-1 and 4.5-2:

Requirement 4.5-1. ***Limiting debris generated by collisions with large objects when in Earth orbit:*** *For each spacecraft and launch vehicle orbital stage, 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. For the purpose of this assessment, 100 years is used as the maximum orbital lifetime for the storage disposal option.*

The probability of collision with large objects in Earth Orbit was determined for Gluon by DAS 3.2.3 to be 1.6239E-5. Gluon is compliant with requirement 4.5-1.

Requirement 4.5-2. ***Limiting debris generated by collisions with small objects when operating in Earth 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 post mission disposal maneuver requirements is less than 0.01.*

As shown in requirement 4.6-1, Gluon does not require any post mission disposal maneuvers as Gluon will deorbit within 2.5 years of mission completion from the mission altitude of 500km. Gluon includes an experimental propulsion system, which is not intended to be used for collision avoidance, orbit raising/lowering, or station keeping. The experimental thruster is used solely to assess the system performance. Gluon is compliant with requirement 4.5-2.

Detailed description and assessment of the efficacy of any planned debris avoidance capability intended to help in meeting requirement 4.5-1, including any plans to move to less congested altitudes, as well as any tracking enhancements (e.g., GPS, laser retroreflector) that may assist in reducing the covariance of collision estimates. Note that significant risk remains for impact with debris objects less than 10 cm or that are otherwise untrackable from the Earth, so such measures are only expected to slightly influence the statistical probability of collision with dangerous objects.

Gluon includes an experimental thruster not baselined for collision avoidance. Gluon includes a GPS on board, ephemeris data will be uploaded to the 18th Space Defense Squadron (18SDS) to assist in reducing the covariance of collision estimates.

6. Assessment of Spacecraft Post-mission Disposal Plans and Procedures

Description of spacecraft disposal option selected:

Gluon will de-orbit naturally via atmospheric drag.

Identification of all systems or components required to accomplish any post mission disposal maneuvers. Plan for any spacecraft maneuvers required to accomplish post mission disposal:

No mission disposal maneuvers are required.

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

Due to the various pointing profiles that will occur throughout the duration of the mission, the average cross-sectional area is used for this analysis. The average cross-sectional areas is approximated per NASA STD 8719.14C Section 4.3.4.2.2.

Cross Sectional Area: 0.658 m^2
End of Mission Mass: 67.96 kg

End of Mission Area to Mass Ratio: .00968 m^2/kg

If appropriate, preliminary plan for spacecraft controlled reentry:

Not applicable.

Assessment of spacecraft compliance with Requirements 4.6-1 through 4.6-4:

Requirement 4.6-1. ***Natural reentry, direct reentry, or direct retrieval shall comply with the following:***

a. *Natural reentry: Leave the space structure in an orbit in which, using conservative projections for solar activity, atmospheric drag will limit the orbital lifetime to as short as practicable but no more than 25 years after the completion of mission.*

End of Mission:

Orbital lifetime analysis was performed in DAS 3.2.3, with the assumption that Gluon will have an uncontrolled reentry at the end of Mission. Figure 2 shows the orbital decay of the Gluon spacecraft at the end of mission, with altitude along the Y-axis, and time along the X-axis. After the initial orbit lowering of the spacecraft stack from the injection orbit to the mission orbit of 500km, no post mission disposal maneuvers are necessary to reenter Earth’s atmosphere within 25 years. Gluon will reenter Earth’s atmosphere by 2027 or 2.5 years from the end of mission.

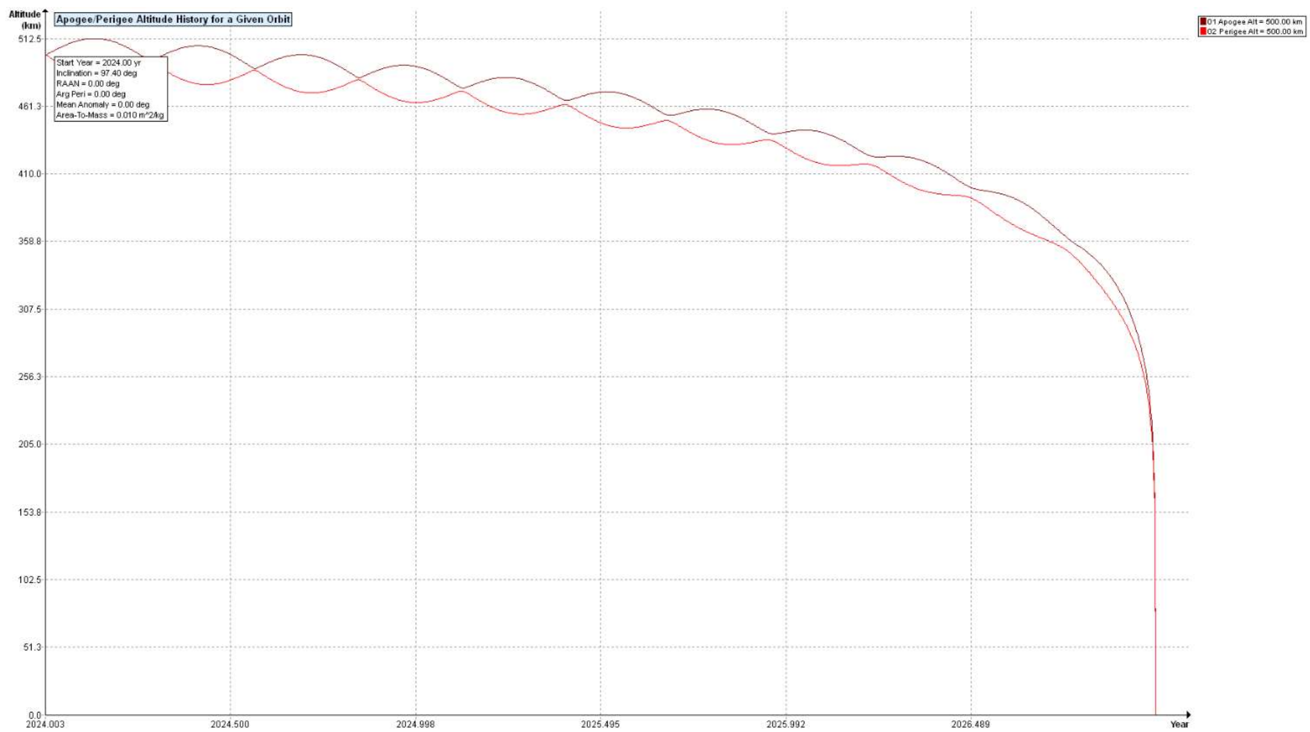

Figure 2: Gluon End of Mission Reentry

b. Direct reentry: Maneuver the space structure into a controlled de-orbit trajectory as soon as practical after completion of mission.

Not Applicable. Planned for and compliant with natural reentry.

c. Direct retrieval: Retrieve the space structure and remove it from orbit preferably at completion of mission, but no more than 5 years after completion of mission.

Not Applicable. Planned for and compliant with natural reentry.

Requirement 4.6-2. *Storage and Earth escape shall comply with the following:*

a. Storage between LEO and GEO: (1) Maneuver to a highly eccentric disposal orbit (e.g., GEO transfer orbit) where (i) perigee altitude remains above 2000 km for at least 100 years, (ii) apogee altitude remains below 35,586 km for at least 100 years, and (iii) the time spent by the space structure between 20,182 +/- 300 km is limited to 25 years or less over 200 years; or, (2) Maneuver to a near-circular disposal orbit to (i) avoid crossing 20,182 +/- 300 km, the GEO zone, and the LEO zone for at least 100 years, and (ii) limit the risk to other operational constellations, for example, by avoiding crossing the altitudes occupied by known missions of 10 or more spacecraft using near-circular orbits, for 100 years.

Not Applicable.

b. Storage above GEO: Maneuver to a disposal orbit above GEO with a predicted minimum perigee altitude of 35,986 km for a period of at least 100 years after disposal.

Not Applicable.

c. Earth escape: Maneuver to a heliocentric, Earth-escape trajectory.

Not Applicable.

Requirement 4.6-3. ***Long-term reentry for space structures in Medium Earth Orbit (MEO), Tundra orbits, highly inclined GEO, and other orbits shall:***

a. Maneuver to a disposal orbit where orbital resonances will increase the eccentricity for long-term reentry of the space structure,

Not Applicable.

b. Limit the postmission orbital lifetime to as short as practicable but no more than 200 years,

Not Applicable.

c. Limit the time spent by the space structure in the LEO zone, the GEO zone, and between 20,182 +/- 300 km to 25 years or less per zone, and

Not Applicable.

d. Limit the probability of collisions with debris 10 cm and larger to less than 0.001 (1 in 1,000) during orbital lifetime.

Not Applicable.

Requirement 4.6-4. ***Reliability of post mission disposal maneuver operations in Earth orbit:*** *NASA space programs and projects shall ensure that all post mission disposal operations to meet Requirements 4.6-1, 4.6-2, and 4.6-3 are designed for a probability of success as follows:*

a. Be no less than 0.90 at EOM, and

In the event the spacecraft were to fail, requirement 4.6-1 shows that Gluon will reenter within 2.5 years of end of mission even when in a random tumble. Gluon is compliant with requirement 4.6-4.

b. For controlled reentry, the probability of success at the time of reentry burn must be sufficiently high so as not to cause a violation of Requirement 4.7-1 pertaining to limiting the risk of human casualty.

Not Applicable.

7. Assessment of Spacecraft Reentry Hazards

Detailed description of spacecraft components by size, mass, material, shape, and original location on the space vehicle, if the atmospheric reentry option is selected:

Component	Quantity	Material	Shape	Mass (kg)	Diameter/Width (m)	Length (m)	Height (m)
X- Panel	1	Aluminum 7075-T6	Flat Plate	8.2	0.78	0.82	
X+ Panel	1	Aluminum 7075-T6	Flat Plate	4.8	0.78	0.82	
Side Panel	4	Aluminum 7075-T6	Flat Plate	3.35	0.26	0.773	
Prop Tank	1	Aluminum 6061-T6	Cylinder	2.98	0.07626	0.6952	
EPS p80	1	Aluminum	Box	0.614	0.0947	0.0948	0.0648
Batteries	8	Lexan	Box	0.476	0.1	0.1	0.0392
Flight Computer	1	Aluminum 6061-T6	Box	3.54	0.15	0.231	0.13
Reaction Wheels	3	Aluminum	Box	1.38	0.146	0.146	0.04
Torque Rods	3	Copper Alloy	Cylinder	0.644	0.02	0.3	
Star Tracker	1	Aluminum	Box	0.27	0.05	0.095	0.04
Solar Panel	3	Fiberglass	Flat Plate	1.35	0.4	0.76	
Passive DLM	1	Aluminum 6061-T6	Flat Plate	3	0.5	0.5	
Bottom Half Lightband	1	Aluminum 7075-T6	Flat Plate	2.29	0.609	0.609	
Ballast	5	Steel AISI 316	Flat Plate	0.8	0.1	0.1	
Prop Feed Valves	5	Stainless Steel	Cylinder	0.2	0.04	0.1	
Harnessing Connectors	40	Stainless Steel	Box	0.05	0.025	0.03	0.012
Mounting Brackets	12	Aluminum 6061-T6	Flat Plate	0.1455	0.075	0.085	
Harnessing Cables	120	Copper Alloy	Cylinder	0.016	0.005	0.1	
Payload Thruster	4	Aluminum 6061-T6	Box	0.162	0.0495	0.0507	0.0465
Thruster plate	4	Molybdenum	Flat Plate	0.016	0.0465	0.0495	

Thruster Cathode	1	Aluminum 6061-T6	Box	0.083	0.035	0.0673	0.0324
Thruster Avionics	1	Aluminum 6061-T6	Box	0.589	0.104	0.104	0.065

Figure 3: Gluon Component List

Summary of objects expected to survive an uncontrolled reentry, using NASA DAS, NASA ORSAT, or comparable software:

Only the thruster plate is expected to survive uncontrolled reentry per DAS. The thruster plate will reenter the Earth's atmosphere with 1J of kinetic energy, which is considerably less than the maximum allowable kinetic energy of 15J. The thruster plate will reenter with a casualty area of 1.39 m^2.

Calculation of risk of human casualty for the expected year of uncontrolled reentry and the spacecraft orbital inclination:

Even with the thruster plate surviving, DAS calculates the potential risk of human casualty for the uncontrolled reentry of Gluon at 0.

Assessment of spacecraft compliance with Requirement 4.7-1:

Requirement 4.7-1. ***Limit the risk of human casualty:*** *The potential for human casualty is assumed for any object with an impacting kinetic energy in excess of 15 joules:*

a. For uncontrolled reentry, the risk of human casualty from surviving debris shall be less than 0.0001 (1:10,000).

Risk of human casualty from surviving debris is 0. Gluon complies with requirement 4.7-1.

b. For controlled reentry, the selected trajectory shall ensure that no surviving debris impact with a kinetic energy greater than 15 joules is closer than 370 km from foreign NASA-STD-8719.14C 50 of 77 landmasses, or is within 50 km from the continental U.S., territories of the U.S., and the permanent ice pack of Antarctica.

Not Applicable.

c. *For controlled reentry, the product of the probability of failure to execute the reentry burn and the risk of human casualty assuming uncontrolled reentry shall be less than 0.0001 (1:10,000). d. For long-term reentry of space structures in MEO, Tundra orbits, highly inclined GEO, and other orbits: Surviving debris shall have less than 7 m2 total debris casualty area or 0.0001 (1 in 10,000) risk of human casualty.*

Not Applicable.

8. Assessment for Special Classes of Space Missions

Not Applicable. There are no tethers in this mission.

Appendix – References

[1] NASA, "NASA-STD-8719.14C," 2021.

[2] SpaceX, "Rideshare Payload User's Guide," 2022.