AeroCube-16 (AC16)

Orbital Debris Assessment Report (ODAR)

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1.0	29 June 2021	11	Initial Release	J. Wilson
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VERSION APPROVAL and FINAL APPROVAL*:

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* Approval signatures indicate responsibility that the information in the ODAR is correct.

** Signatures required only for Final ODAR

Self-Assessment of Requirements per NASA-STD 8719.14A

Requirement		Compliance Assessment	Comments
4.3-1a	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.	Compliant	AC16 will release no debris.
4.3-1b	The total object-time product shall be no larger than 100 object-years per mission.	Compliant	AC16 will release no debris.
4.3-2	For missions leaving debris in orbits with the potential of traversing GEO, released debris with diameters of 5 cm 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.	Compliant	AC16 will not operate in or near GEO.
4.4-1	For each spacecraft employed for a mission, the program or project shall demonstrate…that the integrated probability of explosion for all credible failure modes of each spacecraft is less than 0.001.	Compliant	
4.4-2	Design of all spacecraft shall include the ability and a plan to deplete all onboard sources of stored energy and disconnect all energy generation sources when they are no longer required for mission operations or post-mission disposal or control to a level which cannot cause an explosion or deflagration large enough to release orbital debris or break up the spacecraft.	Compliant	
4.4-3	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 does not exceed 100 object-years, and b) not generate debris larger than 1 mm that remains in Earth orbit longer than one year.	Compliant	AC16 has no planned explosions or intentional collisions.
4.4-4	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 verified to not exceed 10e-6.	Compliant	AC16 has no planned explosions or intentional collisions.
4.5-1	For each spacecraft in or passing through LEO, the program shall demonstrate that, during the orbital lifetime of each spacecraft, the probability of accidental collision with space objects larger than 10 cm in diameter is less an 0.001.	Compliant	
4.5-2	For each spacecraft, the program 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 requirements is less than 0.01.	Compliant	
4.6-1	A spacecraft with a perigee altitude below 2000 km shall be disposed of by one of the following three methods: a) leave the space structure in an orbit in which natural forces will lead to atmospheric reentry within 25 years, b) maneuver the space structure into a controlled de-orbit trajectory, c) maneuver the space structure into an orbit with perigee altitude above 2000 km and apogee less than GEO-500 km.	Compliant	AC16 will use natural orbit decay.
4.6-2	A spacecraft or orbital stage in an orbit near GEO shall be maneuvered at EOM to a disposal orbit above GEO.	Compliant	AC16 will not operate in or near GEO.
4.6-3	For space structures between LEO and GEO, a spacecraft shall be left in an orbit with a perigee greater than 2000 km above the Earth's surface and apogee less than 500 km below GEO, and a spacecraft shall not use nearly circular disposal orbits near regions of high-value operational space structures.	Compliant	AC16 will not operate in or near MEO.
4.6-4	NASA space programs shall ensure that all post-mission disposal operations to meet the above requirements are designed for a probability of success of no less than 0.90 at EOM.	Compliant	
4.7-1	For uncontrolled reentry, the risk of human casualty from surviving debris shall not exceed 0.0001.	Compliant	
4.8-1	Intact and remnants of severed tether systems in Earth orbit shall meet the requirements limiting the generation of orbital debris from on-orbit collisions and the requirements governing post-mission disposal.	Compliant	AC16 has no tether system.

NOTE: AeroCube-16 is currently manifested to fly as a secondary payload. Compliance with requirements levied by NASA-STD 8719.14A on the launch vehicle will be the responsibility of the primary payload and/or launch provider.

Section 1: Program Management and Mission Overview

Mission Directorate: The Aerospace Corporation, xLab
Program Executive: Lynn Friesen

System Engineer: Darren Rowen, The Aerospace Corporation
Project Manager: David Wu, The Aerospace Corporation

Foreign government or space agency participation: none

Nominal Schedule of Mission Design and Development:

Event	Date
Project initiation	25 Mar 2020
System Requirements Review (SRR)	15 Apr 2020
Bus Design Review	18 Aug 2020
Test Readiness Review (TRR)	16 Mar 2022
Pre-Ship Review	30 May 2022
Delivery	01 Jul 2022
Target launch date	01 Sep 2022

Brief Description of the Mission: The AeroCube-16 (AC16) program is a technology demonstration in Low Earth Orbit, consisting of a pair of 6U CubeSats hosting several advanced materials experiments. Technical data from AeroCube-16, including results from this experiment, will be used to validate ground test data and inform future research.

Identification of the anticipated launch vehicle and launch site: AC16 is manifested as part of the upcoming Rocket Lab RASR-5 mission from Wallops Flight Facility in Virginia. The mission orbit will be circular between 495 km – 525 km and will be inclined about 50.0°.

Identification of the proposed launch date and mission duration: The AC16 mission anticipates a launch in September 2022. The main mission phase is approximately 12 months.

Description of the launch and deployment profile: The AC16 spacecraft will be deployed from the launch vehicle from a CubeSat dispenser. Typically, the launch vehicle will optimize separation timing to reduce the likelihood of collision between CubeSats. Each AC16 spacecraft will fill the entirety of a 6U flight qualified spacecraft dispenser.

Reason for selection of operational orbit: As a secondary payload, AC16 has no control over the selection of operational orbit. AC16 can perform its mission in any LEO orbit, although the altitude must be low enough to ensure natural decay and reentry within the timeframe specified by NPR8751.6A. The altitude to which the deployment vehicle and its payloads will be delivered (including AC16) satisfies that requirement.

Identification of any interaction or potential physical interference with other operational spacecraft: As one of many CubeSats deployed on the mission, there is a small risk of contact between AC16 and another CubeSat. The timing of satellite deployments from the dispenser is intended to mitigate this risk as much as possible. Debris mitigation for the deployment process is the responsibility of the launch vehicle. In the event of contact shortly after deployment, the relative velocities between CubeSats are on the order of centimeters per second, which would not provide enough force to cause catastrophic breakup of the satellites or generate significant amounts of debris (the glass coverings of solar cells may crack). The launch vehicle trajectory and mission plan are designed to ensure there is no risk to the primary payload. There is no anticipated risk to any other operational spacecraft.

Section 2: Spacecraft Description

Physical Description: The AC16 spacecraft are 6U CubeSats with outer dimensions of 36.6 cm x 22.6 cm x 11 cm. Deployable solar panels extend off the long axis of the spacecraft with dimensions 36 cm x 10 cm. The exterior bus is made from 7075-T6 aluminum and houses all payload and electronics components.

Total spacecraft mass at launch: The AC16 spacecraft, will weigh about 9.37 kg at launch.

Dry mass of spacecraft at launch: The AC16 spacecraft's propulsion system contains only ~1.9 grams of propellant. The dry mass is still about 9.37 kg.

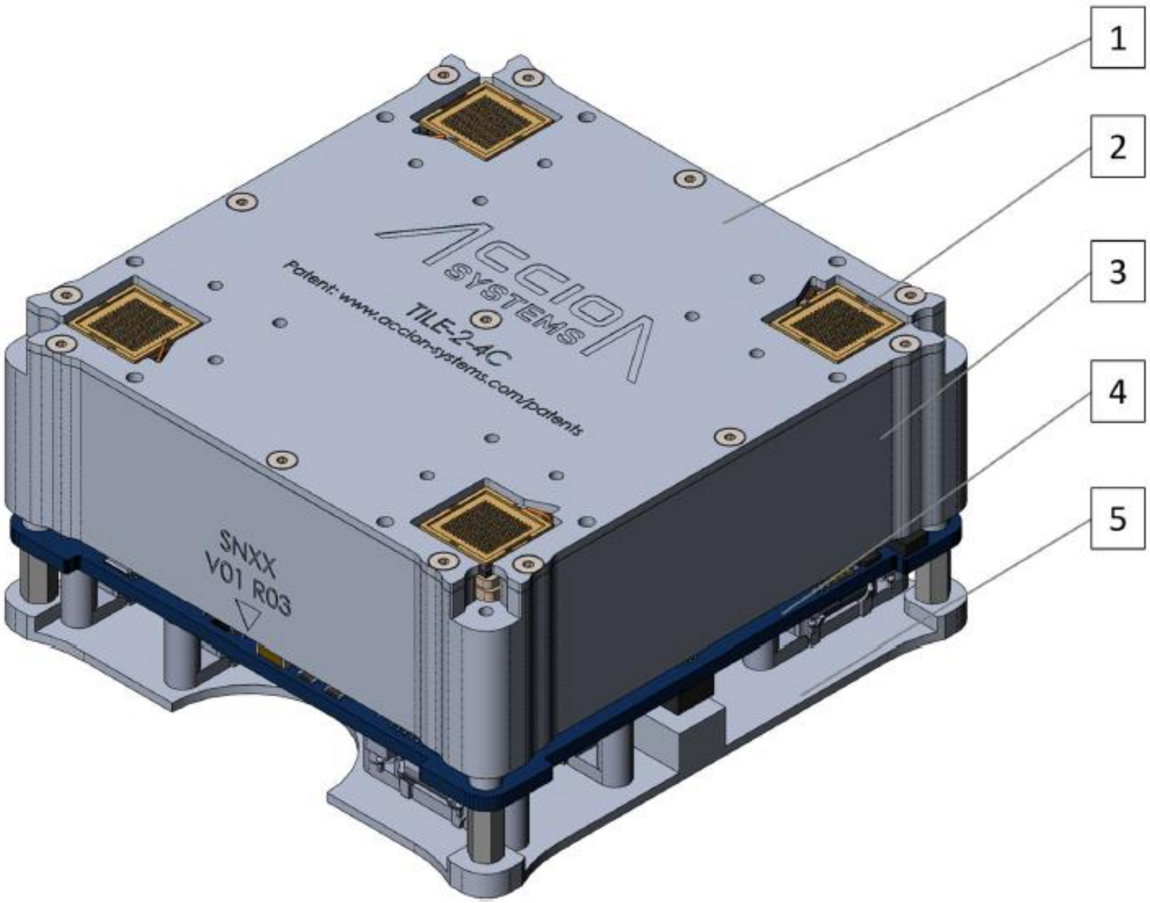
Description of all propulsion systems:

Each of the AeroCube-16 vehicles carries an electric propulsion system, Accion's TILE 2 Mk2. Accion's ion electrospray propulsion technology is based on the electrostatic extraction and acceleration of ions from an ionic liquid propellant—a near zero-vapor-pressure conductive salt that remains in the liquid phase over a wide range of temperatures. To extract these ions, electric fields on the order of 1 V/nm are used; such intense fields are routinely achieved at the tips of electrically stressed liquid menisci, which are micrometers in size and are produced in liquid surfaces at the end of sharpened structures like capillaries or needles that have been biased to high voltage with respect to a downstream electrode. From these emitters, ions are expelled thus producing thrust on a spacecraft.

Accion implements this technology in thruster chips containing dense arrays of emitters that fire in parallel when energized by a high-voltage supply. The emitters in each thruster chip are microelectrical-mechanical-systems (MEMS) fabricated and porous, and propellant flows via capillarity through the bulk of the material driven by the ion evaporation process and a very low-pressure differential provided by the propellant supply assembly. The combination of porous flow and the use of ionic liquids allow Accion's ion electrospray thrusters to achieve a high specific impulse (Isp > 1650 s) at high efficiency in a compact package.

Accion's TILE system is operated in an inherently charge-balanced mode where thrust-producing positive and negative ions are emitted simultaneously, eliminating the need for a separately powered and maintained neutralization cathode.

The TILE 2 Mk2 propulsion system combines four single thruster and PSS units into the four thruster units. Each thruster chip is assigned in the software to one of two channels: A or B. The two channels operate at opposite polarities (e.g. positive and negative voltage), and the polarities are switched at regular frequencies automatically by the TILE control software. For example, if channel A is at positive high-voltage, channel B will be at negative high-voltage. Any number of chips can be paired and fired together, but in order to maintain a charge neutral plume, at least two chips must be selected for firing.



	Description
1	System Shield
2	Accion Thruster chip attached to a PSS
3	Thruster Mounting Bracket
4	PPU Electronics Board
5	Thermal Management Plate

Figure 1. Accion's TILE 2 Mk2 propulsion system

The thruster operates using a dense array of emitters, firing in parallel. This is achieved by merging the working principles behind ion electrospray thrusters with recent developments in Micro Electro Mechanical Systems (MEMS) materials and processes. Emitters are fabricated on porous materials, so that propellant can flow via capillarity through the bulk of the material and driven by the ion evaporation process. **Therefore, no pressurization is required for pumping (or storing) the propellant.**

This system meets CubeSat specifications for on-board propulsion systems, namely it is non-toxic, non-flammable, and operates with no pressurization.

Identification of all fluids planned to be on board: The AC16 electric Accion's TILE 2 Mk2 propulsion system uses ionic liquid, a zero-vapor pressure conductive salt that remains in the liquid phase at room temperature. The liquid is stored on board with no pressurization. The total mass of propellant carried by the AC16 spacecraft is ~1.9 grams.

Description of all active and/or passive attitude control systems with an indication of the normal attitude of the spacecraft with respect to the velocity vector: AC16 has 3-axis attitude control via three torque rods and three "pico" reaction wheels. The torque rods are a mutually orthogonal triad of coiled wire, wrapped around a high magnetic permeability alloy that can generate a magnetic dipole of 0.42 A-m^2 when the satellite passes current through the wire. The rods generate negligible magnetic field when powered off. The torque rods are made from 0.4 cm-diameter mu-metal rods that are 6.6 cm long. The pico reaction wheels have flight heritage from Boeing's SENSE spacecraft. Attitude sensors include Earth nadir sensors, two-axis Sun sensors on various spacecraft surfaces, a 3-axis magnetometer, and two star trackers. A high-accuracy 3-axis rate gyro will be used to provide an inertial attitude reference when 0.7° or better pointing accuracy is required and the Sun and Earth are not simultaneously visible by an appropriate sensor, and a medium-resolution 3-axis rate gyro and 3-axis magnetometer will serve as a backup.

Description of any range safety or other pyrotechnic devices: AC16 has no pyrotechnic devices.

Description of the electrical generation and storage system: Power for the AC16 spacecraft is generated by solar cells mounted onto panels that will be deployed from both sides of the bus, as well as cells affixed to the spacecraft bus. These cells are capable of producing up to 25 W of power. Power is stored on-board with lithium-ion batteries. Each satellite has 2 batteries mounted in an aluminum 6061-T6 structure as a unit and are shock and thermally isolated by a thermoplastic mount. Each battery is composed of four cells and are rated at 9 W-hr for a total of 72 W-hr on the spacecraft. Specific details of the batteries' manufacture appear in Section 4.

Identification of any other sources of stored energy: There are no other sources of stored energy on AC16.

Identification of any radioactive materials on board: AC16 carries no radioactive materials.

Section 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: AC16 will release no objects into space during normal operations.

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

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

Release velocity of each object with respect to spacecraft: N/A

Expected orbital parameters (apogee, perigee, inclination) of each object after release: N/A

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

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

Requirement 4.3-1a: COMPLIANT
Requirement 4.3-1b: COMPLIANT
Requirement 4.3-2: COMPLIANT

Section 4: Assessment of Spacecraft Intentional Breakups and Potential for Explosion

Identification of all potential causes of spacecraft breakup during deployment and mission operations: There is no credible scenario that would result in spacecraft breakup during normal deployment and operations.

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

Battery risk: A possible malfunction of the lithium ion or lithium polymer batteries or of the control circuit has been identified as a potential, but low probability, cause of accidental breakup or explosion. Natural degradation of the solar cells and batteries will occur over the post-mission period and poses an increased chance of undesired battery-energy release. The battery capacity for storage will degrade over time, possibly leading to changes in the acceptable charge rate for the cells. Individual cells may also change properties at different rates due to time degradation and temperature changes. The control circuit may also malfunction due to exposure over long periods of time. The cell pressure relief vents could be blocked by small contaminants. Any of these individual or combined effects may theoretically cause an electro-chemical reaction that results in rapid energy release in the form of combustion.

Notwithstanding these potential sources of energy release, AC16 still meets Requirement 4.4-2 as the on-board batteries cannot “cause an explosion or deflagration large enough to release orbital debris or break up the spacecraft.” Underwriters Laboratories (UL) certifies the batteries used on AC16. In general, these batteries are similar in size and power to cell phone batteries.

Model Number (UL Listing)	Manufacturer	Number of Cells	Energy Stored
INR-18650A	Molicel	8	<=9 W-hr per cell <=72 W-hr total

The batteries are consumer-oriented devices. The batteries have been recognized as UL tested and approved. UL recognition has been determined through the UL Online Certifications Directory, which clearly shows that these cell batteries have undergone and passed UL Standards. Furthermore, safety devices incorporated in these batteries include pressure release valves, over-current charge protection, and over-current discharge protection.

The fact that the AC16 batteries are UL recognized indicates that they have passed the UL standard testing procedures that characterize their explosive potential. Of particular concern to NASA is UL Standard 1642, which specifically deals with the testing of lithium batteries. Section 20 Projectile Test of UL 1642 subjects the test battery to heat by flame while within an aluminum- and steel-wire-mesh octagonal box, “[where the test battery] shall remain on the screen until it explodes or the cell or battery has ignited and burned out” (UL 1642 20.5). To pass the test, “no part of an exploding cell or battery shall penetrate the wire screen such that some or all of the cell or battery protrudes through the screen” (UL 1642 20.1).

It is reasonable to expect the batteries on AC16 to experience similar conditions during their orbital life span. While the sources of failure would not be external heat on orbit, analysis of the expected mission thermal environment shows that given the low power dissipation for CubeSats, the batteries will be exposed to a maximum temperature well below their 212° F (100° C) safe operation limit. Continual charging with 2 to 6 W average power from the solar panels over an orbital life span greater than 15 years may expose the batteries to overcharging, which could cause similar heat to be generated internally. Through the UL recognition and testing, it has been shown that these batteries do not cause an explosion that would cause a fragmentation of the spacecraft.

In addition to the aforementioned certification of the AC16 batteries against explosion, ten potential failure modes for lithium batteries and their applicability or mitigation in AC16 are addressed in the following table:

	Failure Mode	Applicability or Mitigation

1	Internal short circuit	The AC16 body and internal design prevents deformation or crushing of the batteries that could lead to internal short circuit.
2	Internal thermal rise due to high load discharge rate	See Failure Mode #4.
3	Overcharging and excessive charge rate	The battery cells on AC16 have charge interrupt devices that activate during cell internal pressure buildup (due to cell internal chemical that forms a gas) that occurs during overcharging conditions.
4	Excessive discharge rate or short circuit due to external device failure	The bus batteries have an internal positive temperature coefficient (PTC) device that acts as a resettable fuse during external short circuit that limits the cell output current during such an event.
5	Inoperable vents	Vents have access through the structure that holds them and into the larger satellite volume. Venting will not be inhibited by physical obstructions.
6	Crushing	Satellite body and internal design prevent loads on battery cases.
7	Low level current leakage or short circuit through battery pack case or due to moisture-based degradation of insulators	Satellites are stored in a controlled environment.
8	Excess temperatures due to orbital environment and high discharge combined	Thermal sensors on the batteries provide telemetry on battery temperature. There is no cutoff for overheating batteries except whatever is inherent in the cell itself. However, as noted earlier in this section of the ODAR, the batteries on AC16 are UL-certified as non-explosive in over-heating scenarios.
9	Polarity reversal due to over-discharge	A 2.7 V discharge cutoff threshold circuit in AC16 has been verified in acceptance tests for the electric power system.
10	Excess battery temperatures due to post-mission orbital environment and constant overcharging	The circuit that charges the batteries cannot exceed 4.1 V and therefore will never overcharge the batteries.

Through a combination of UL certification, compliance with AFSPCMAN 91-710 V3 requirements, and an understanding of the general behavior of the failure modes associated with these types of batteries, it is possible to conclude that the batteries meet Requirement 4.4-2.

Detailed plan for any designed breakup, including explosions and intentional collisions: AC16 has no plans for intentional breakups, explosions, or collisions.

List of components, which are passivated at EOM: No systems on the AC16 spacecraft require passivation at EOM.

Rationale for all items which are required to be passivated, but cannot due to their design: As described above, the batteries do not present a debris-generation hazard per Requirement 4.4-2, and in the interest of not increasing the complexity of the AC16 power system, it was decided not to passivate the batteries at EOM.

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

Requirement 4.4-1: COMPLIANT
Requirement 4.4-2: COMPLIANT
Requirement 4.4-3: COMPLIANT

Requirement 4.4-4: COMPLIANT

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

Collision probabilities have been calculated using DAS v3.1.2 with the following assumptions: 525 km x 525 km altitude orbit, 50.0° inclination; 9.37 kg mass, and 0.008564 m^2/kg area-to-mass ratio (the average area-to-mass configuration of the spacecraft post-mission).

Calculation of spacecraft probability of collision with space objects larger than 10 cm in diameter during the orbital lifetime of the spacecraft: Probability = 5.75×10^{-7}, per DAS v3.1.2.

Calculation of spacecraft probability of collision with space objects, including orbital debris and meteoroids, of sufficient size to prevent post-mission disposal: Because the mission has selected natural de-orbit (see Section 6) for disposal and no systems will be passivated at EOM (see Section 4), small debris do not pose a threat to post-mission disposal.

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

Requirement 4.5-1: COMPLIANT
Requirement 4.5-2: COMPLIANT

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

Description of spacecraft disposal option selected: The AC16 mission has selected atmospheric reentry for disposal. The vehicles use a 37 x 23 x 11 cm bus and weigh 9.37 kg each. The minimum cross-sectional area for AC16 will be approximately 240 cm^2, though the spacecraft will spend most of its time in a tumble state, with an average cross-sectional area of about 800 cm^2. DAS evaluates a lifetime of about 6.9 year, using the orbit assumptions listed at the beginning of Section 5. This lifetime is compliant with ODAR requirements.

Identification of all systems or components required to accomplish any post-mission disposal operation, including passivation and maneuvering: As discussed in Section 4, no disposal or passivation is planned for AC16. Natural orbit decay is sufficient to deorbit the spacecraft.

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

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

Preliminary plan for spacecraft controlled reentry: N/A

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

Requirement 4.6-1: COMPLIANT
Requirement 4.6-2: COMPLIANT
Requirement 4.6-3: COMPLIANT
Requirement 4.6-4: COMPLIANT

Section 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: The AC16 vehicles are primarily constructed of aluminum and PCB electronic board material. The only components with a higher density or resistance to melting are found in the battery (stainless steel), the torque rods (HyMu-80), and the reaction wheels (HyMu-80). However, since these parts are smalls, these parts are not expected to survive reentry.

Requirement 4.7-1 requires that all surviving debris from an uncontrolled spacecraft reentry have a risk of human casualty of less than 1:10,000. Human casualty is defined as an impact from an object with an energy of at least 15 J. As calculated by DAS, no part of the AC16 spacecraft is expected to survive reentry. The AC16 mission is fully compliant with Requirement 4.7-1.

Summary of objects expected to survive an uncontrolled reentry: None

Calculation of probability of human casualty for the expected year of uncontrolled reentry and the spacecraft orbital inclination: 1:100000000

Assessment of spacecraft compliance with Requirement 4.7-1:

Requirement 4.7-1: COMPLIANT

Section 8: Assessment for Tether Missions

The AC16 mission has no tether. All requirements are COMPLIANT.

Sections 9–14: Assessment of Launch Vehicle Debris

AC16 will fly as a secondary payload. Assessment of launch-vehicle debris is the responsibility of the primary payload. These sections are N/A for AC16.