ARCE-1 Orbital Debris Assessment Report (ODAR) and End of Life Plan (EOLP)

Revision 1.0

November 18, 2019

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This document is approved for unlimited release.

Revision	Description	Initials
1.0	Initial Revision (Unrestricted)	PJJ

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Chapter 1

ARCE-1 ODAR/EOLP

1.1 Purpose

This document provides the orbital debris assessment (ODA) and end of life plan (EOLP) for the ARCE-1 CubeSats. The NASA Procedural Requirements 8715.6B [1] are used as guidance for implementing the U.S. Government Orbital Debris Mitigation Standard Practices provided in NASA-STD-8719.14B [2].

1.1.1 Software

This analysis was supported by NASA DAS version 2.1.1 [3].

1.2 ODAR Evaluation Matrix

Table 1.2.1: Final Orbital Debris Assessment Report Evaluation: ARCE-1 Mission

Requirement	Description	Assessment	Comments
4.3-1.a	25 year limit	Compliant	Stowed lifetime = 3.083yr; Deployed/Tumbling lifetime = 2.36yr; Deployed/Nominal lifetime = 2.45 yr
4.3-1.b	< 100 object$\times$year limit	Compliant	3 satellites with max 3.083 year life
4.3-2	GEO $\pm$200km	N/A	
4.4-1	< 0.001 explosion risk	Compliant	
4.4-2	passivate energy sources	Compliant	Battery passivation not possible due to mission design
4.4-3	limit BU long term risk	Compliant	
4.4-4	limit BU short term risk	Compliant	
4.5-1	< 0.001 10cm impact risk	Compliant	
4.5-2	post-mission disposal risks	N/A	
4.6-1.a-c	disposal method	Compliant	Uncontrolled atmospheric re-entry

Table 1.2.1 – *Continued on next page*

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Requirement	Description	Assessment	Comments
4.6-2	GEO disposal	N/A	
4.6-3	MEO disposal	N/A	
4.6-4	disposal reliability	N/A	
4.7-1	ground population risk	Compliant	
4.8-1	tether risk	N/A	

1.3 References

[1] NASA Office of Safety and Mission Assurance NPR-8715.6B, "NASA Procedural Requirements for Limiting Orbital Debris and Evaluating the Meteoroid and Orbital Debris Environments," 2017.

[2] NASA Office of Safety and Mission Assurance STD-8719.14B, "Process for Limiting Orbital Debris," 2019.

[3] "NASA Debris Assessment Software version 2.1.1." https://orbitaldebris.jsc.nasa.gov/mitigation/das.html, 2017.

[4] A. Mehrparvar, D. Pignatelli, J. Carnahan, R. Munakat, W. Lan, A. Toorian, A. Hutputanasin, and S. Lee, "Cubesat design specification rev. 13," *The CubeSat Program, Cal Poly San Luis Obispo, US*, 2015.

[5] Shenzen NTEK Testing Technology Co., Ltd., "Material Safety Data Sheet, Tenergy 30016-04," 2019.

Chapter 2

Orbital Debris Assessment

2.1 Program Management and Mission Overview

2.1.1 Program Sponsor

The ARCE research and technology development program is sponsored by the University of South Florida with support from DEFENSEWERX.

2.1.2 Personnel

The PI, Program Manager and multiple current and former students contribute to this project.

PI

Dr. Robert H. Bishop, Dean of Engineering and Professor of Electrical Engineering, University of South Florida.

- Education:
  - Texas A&M University, Aerospace Engineering, B.S.
  - Texas A&M University, Aerospace Engineering, M.S.
  - Rice University, Electrical and Computer Engineering, Ph.D.
- Professional Experience:
  - University of South Florida, Dean of Engineering, 2014-present
  - Marquette University, Dean of Engineering, 2010-14
  - The University of Texas at Austin, Department Chair, 2003-09
  - The University of Texas at Austin, Associate Department Chair, 1995-2000
  - The University of Texas at Austin, Faculty, 1990-2010
  - The Boeing Company, Welliver Faculty Fellow, 1996
  - Jet Propulsion Laboratory, Faculty Fellow, 1992-93
  - The Charles Stark Draper Laboratory, Engineering Staff, 1980-90
  - NASA Johnson Space Center, Cooperative Education, 1977-78

Program Manager

Peter J. Jorgensen, Electrical Engineering Ph.D. candidate, University of South Florida.

- Education:
  - Marquette University, Mechanical Engineering, B.S.
  - Marquette University, Mechanical Engineering, M.S.
  - University of South Florida, Electrical Engineering, Ph.D. candidate
- Professional Experience:

  - ARCE Lab, Program Manager, 2017-present
  - University of South Florida, Graduate Research Assistant, 2015-present
  - Marquette University, Graduate Research Assistant, 2013-14
  - Marquette University, Undergraduate Research Assistant, 2012-13
  - Marquette University Spacecraft Engineering, Co-Founder, 2011-14

Students

The ARCE program employs multiple current and former students as interns. Current students are typically in their third or later year in undergraduate or in Master's programs.

- 3 M.S. students
  - 1x Electrical Engineering
  - 2x Mechanical Engineering
- 4 undergraduate students
  - 3x Electrical Engineering
  - 1x Mechanical Engineering
- 2 recent B.S. graduates
  - 2x Electrical Engineering

2.1.3 Foreign Interests

None.

2.1.4 Mission Schedule

The ARCE program schedule is shown in Table 2.1.1.

2.1.5 Mission Overview

ARCE (AR-kee), the Articulated Reconnaissance and Communications Expedition, is a CubeSat program performing fundamental research and development using leading technologies in support of tactical global communications. The ARCE program is run by the University of South Florida (USF).

The ARCE-1 mission consists of a set of three 0.5U CubeSats that will perform Earth-to-space, space-to-Earth, and space-to-space ad-hoc networking. A single fixed ground station will be used for primary C2 and messaging. The ARCE-1 CubeSats consist of a main flight computer, software defined radio, deployed solar panels, custom EPS circuits, a GPS module, 3-axis electromagnet torque rods, a MEMS IMU, and various on-board sensors.

The three ARCE-1 CubeSats will be launched simultaneously into low Earth orbit. They will deploy solar panels and antennas on a delay (as required), and begin commissioning operations. Upon contact from the command and control ground station in Tampa, FL, the ARCE-1 CubeSats will begin attitude control maneuvers and the communications mission. The satellites are subject to natural orbital decay and contain no maneuvering capability beyond attitude-controlled differential drag. As such, they will continue to orbit until they naturally decay due to drag.

Table 2.1.1: ARCE Program Schedule

Milestone	Due Date	Status
Mission Design and CONOPS	September 2017	Complete
PDR	January 2018	Complete
CDR	June 2018	Complete
Ground Station Development	October 2018	Complete
Subsystems Development	June 2019	Complete
Flight Units Build	October 2019	In Progress
Frequency Licenses	October 2019	In Progress
Environmental Testing	October 2019	In Progress
Functional Testing	November 2019	
Day-in-the-life Testing	November 2019	
Final Stow and Delivery	December 2019	
Launch	NET 15 December 2019	

Documentation	Due Date	Status
MSPSP	August 2019	Complete
Venting Analysis	August 2019	Complete
Materials List	August 2019	Complete
Environmental Test Report	November 2019	
Functional Test Report	November 2019	
Mass Properties Report	November 2019	
Flight Readiness Review	November 2019	
Mission Readiness Review	November 2019	

2.1.6 Launch

The anticipated launch window is January through March 2020. The nominal mission duration is 12 months with operations and experiments to extend as long as the satellites remain functional.

The deployment profile is 450km circular orbit, inclination of 97 degrees.

2.1.7 Spacecraft Maneuverability

The ARCE-1 CubeSats have 3-axis attitude control via electromagnet torque rods. This allows for marginal maneuverability via flying differential drag profiles.

The ARCE-1 satellites have no other attitude or positional maneuverability (i.e. no thrusters or momentum wheels).

Full attitude control is nominally designed for zeroing the attitude rate after launch, and then Sun-vector tracking to maximize power generation (referred to as "Deployed/Nominal"). Both the rate zeroing and Sun tracking will begin only after receiving an enable command from the ground.

In the case where the solar panels deploy and attitude control is not active, the satellite will tumble (referred to as "Deployed/Tumbling").

2.1.8 Orbit Selection Criteria

The ARCE-1 CubeSats were designed with a minimal orbit requirement of inclination greater than 45°to enable command and control from the ground station in Tampa, Florida. These satellites are a ride share and so no other input was given to the desired final orbit.

The only other constraint on the final orbit is the de-orbit life analysis of the stowed ARCE-1 satellite, which indicates a maximum circular orbit altitude of 600km (resulting in lifetime of 24.8 years). The orbit anticipated, 450km, puts the life at a max of 3.083 years even if the solar panels fail to deploy. With panels deployed, the lifetime will be 2.36 years (Deployed/Tumbling) or 2.45 years (Deployed/Nominal).

2.1.9 Interaction with Other Spacecraft

The ARCE-1 CubeSats are not designed to physically interact with any other spacecraft. There is a small risk of these satellites colliding with other satellites launched from the same vehicle due to the deployment profile (the three 0.5U ARCE-1 CubeSats will share a 3U dispenser with another 1.5U CubeSat, so four total spacecraft will be released in the same moment). This collision risk is subject to the release conditions from the CubeSat dispenser and orbital conditions upon release.

To minimize this risk, the ARCE-1 CubeSats are designed with separation springs in the end rails to help push them away from neighboring satellites upon deployment from the dispenser.

2.2 Spacecraft Description

2.2.1 Spacecraft Physical Description

ARCE-1 satellites are designed and built according to the CubeSat Design Specification Rev. 13 (CDS) [4]. However, there is no official specification for a 0.5U satellite, so the design adapts the 1U specification by including all major external dimensions while shrinking the main body volume from 10-cm $\times$ 10-cm $\times$ 10-cm to 10-cm $\times$ 10-cm $\times$ 5-cm (external dimensions are to machinist tolerance of $\pm$ 0.005 inch (0.127 mm)).

The ARCE-1 CubeSats are made up of the following components:

- Aluminum structure (6061)
- Custom interface motherboard including:
  - EPS battery charge circuitry
  - EPS distribution circuitry
  - Flight computer (Raspberry Pi)
  - On-board temperature and voltage sensors
  - MEMS IMU and magnetometer
  - Electromagnet torque rod control circuitry
- 3-axis torque rods (X and Y axes have mu-metal core, Z axis is air-core)
- Deployed solar panels (four panels)
- Deployed 2.4GHz monopole antennas (two antennas)
- Battery (one battery made of two cells in series to make a pack, two packs in parallel)
- Software defined radio

- Custom RF front end board
- GPS and patch antenna

Components and Materials

The components and materials are listed in the Appendices as inputs to the DAS simulations.

2.2.2 Operational Configuration

Figure 2.1 shows the ARCE-1 CubeSat in its nominal mission configuration, with solar panels and antennas deployed. Table 2.2.1 shows the stowed and deployed external dimensions.

Table 2.2.1: External Dimensions

	Stowed	Deployed
Length (X) (mm):	104.51 $\pm$0.627	396.2 $\pm$0.5
Width (Y) (mm):	108.3 $\pm$2	149.6 $\pm$2
Height (Z) (mm):	63.5 $\pm$0.127	74.5 $\pm$0.127

2.2.3 Mass Properties

The ARCE-1 CubeSats are built to the CubeSat Design Specification such that the center of mass is nearly the volume center of the spacecraft, as shown in Table 2.2.2.

Table 2.2.2: Center of Mass Locations with respect to Volume Center

	Stowed	Deployed
X (mm):	1.622	1.623
Y (mm):	-4.994	-5.006
Z (mm):	1.802	1.811

Wet/Dry Mass

The ARCE-1 wet and dry mass is 0.929kg. The satellite does not include any fluids or consumables.

2.2.4 Fluids

The ARCE-1 CubeSats do not include any fluids or gasses.

2.2.5 Propellant Systems

The ARCE-1 CubeSats do not include any propulsion systems.

2.2.6 Attitude Control Systems

The ARCE-1 CubeSats include 3-axis electromagnet torque rods for attitude control:

- X-axis: mu-metal core with 28AWG magnet wire winding
- Y-axis: mu-metal core with 28AWG magnet wire winding
- Z-axis: air core with 28AWG magnet wire winding

The attitude is determined by full-state estimation by an extended Kalman filter that synthesizes attitude measurements from the MEMS magnetometer and position and velocity from the GPS.

The nominal attitude points the +Z solar panels towards the sun, with a secondary attitude constraint that puts the antennas parallel to the Earth below the satellite.

2.2.7 Range Safety and Pyrotechnics

The ARCE-1 CubeSats do not include any range safety devices or pyrotechnics.

2.2.8 Power Generation and Storage

The ARCE-1 CubeSats include deployed solar panels, a custom battery charger circuit, COTS batteries, and custom distribution circuits.

The solar panels are Alta Devices CubeSat Solar Assemblies bonded to custom PCBs. These PCBs are connected by steel hinges with springs. The hinges are affixed to the PCBs and the CubeSat structure exterior with epoxy. The solar panels feed into the satellite through custom protection circuitry into the battery charger circuit. The solar panels also feed directly into the distribution circuits. There is no power disconnect between the solar power and battery charger or distribution circuits.

The battery is made from four (4) Tenergy 30016-04 Li-ion 18650 cells, with capacity of 2600mAh (9.62Wh) per cell for a total of 38.48Wh of energy storage capacity. Total lithium content is estimated to be 3.12g (0.3×Cell Capacity (Ah)×# cells). The battery chemistry is listed as percentile ranges for compounds:

- 30-40% metal oxide
- 15-20% graphite
- 8-13% organic electrolyte
- 3-5% aluminum
- 6-9% copper

Each battery cell has over-charge, over-discharge, and over-current protection. Two batteries are installed in series to make a pack, and there are two packs in parallel. If any cell in the packs operates out of bounds of the protection circuitry, it will cut off power completely until the fault condition is returned to normal. This prevents damage to the cells that could result in catastrophic failure.

Further, the battery charge circuit is designed to stop charging the battery packs upon reaching a battery voltage of approximately 80% of the maximum charge voltage and to prevent discharging below 40% of the minimum charge voltage; this is to extend battery lifetime as well as promote safe operating conditions.

2.2.9 Other Stored Energy

The ARCE-1 CubeSats do not include stored energy other than the batteries discussed above.

2.2.10 Radioactive Materials

The ARCE-1 CubeSats do not include any radioactive materials.

2.2.11 Planned Proximity Operations

The ARCE-1 CubeSats are not designed to perform any proximity or docking operations.

In the case of an anticipated collision with other debris, the only mitigation available to the satellites is via differential drag by means of controlled attitude.

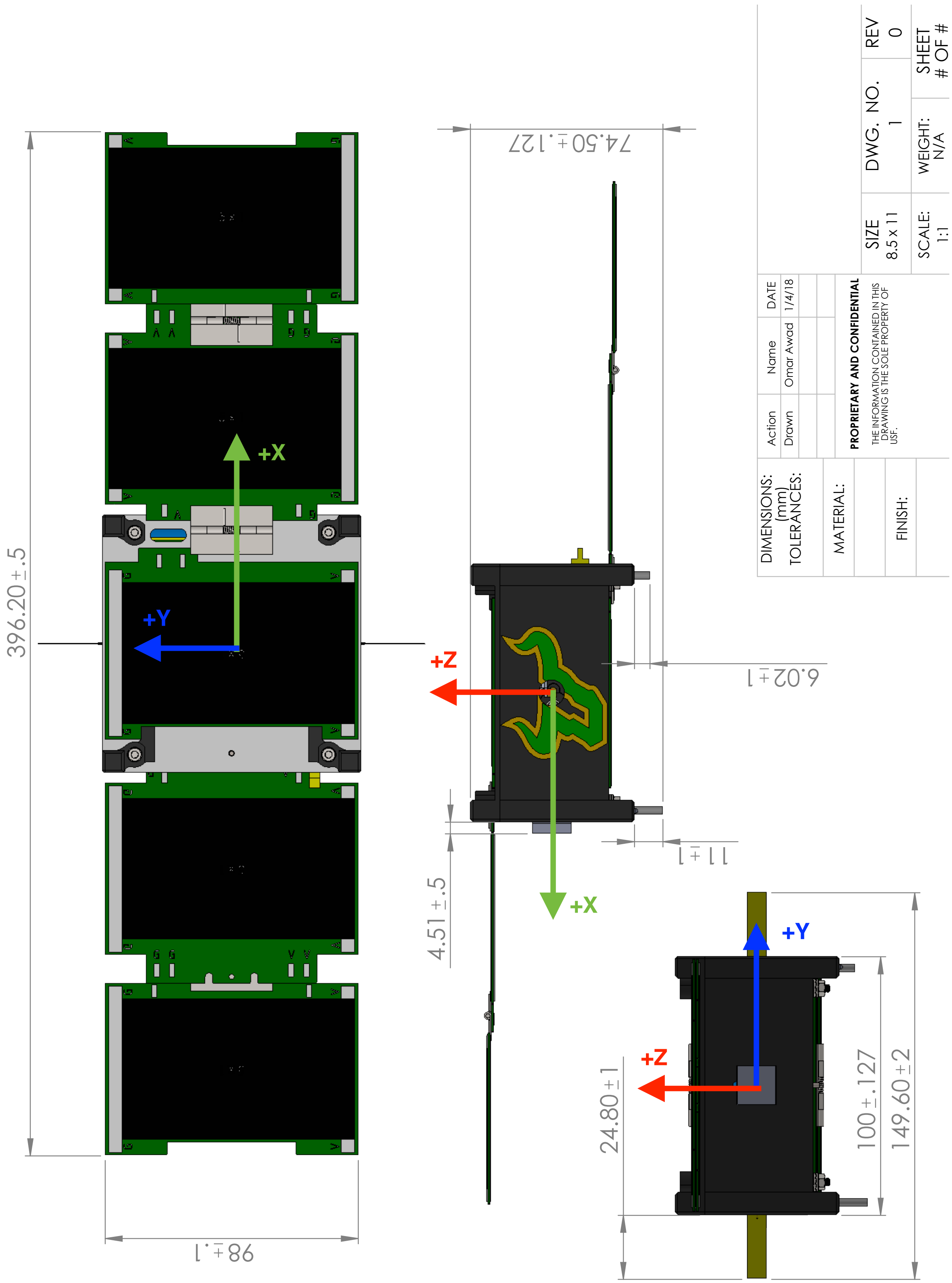

Figure 2.1: ARCE-1 deployed dimensions

2.3 Assessment of Spacecraft Debris Released during Normal Operations

2.3.1 Identification of Debris

The ARCE-1 CubeSats are smaller than 1U, which means they are classified as debris under Section 4.3.1.4 of NASA-STD-8719.14B [2]: "satellites smaller than a 1U standard CubeSat are treated as mission-related debris and follow the same requirements for mission-related debris from LEO to GEO."

There is no other debris released from the ARCE-1 satellites during nominal deployment, operations, or post-mission disposal.

Refer to Section 2.2 for size, mass, and material information about the ARCE-1 CubeSats.

2.3.2 Rationale for Debris

The satellites are classified as debris; the rationale for launching these satellites is to perform the research and technology development mission outlined during the mission design and CONOPS phases of the project.

Specifically, the 0.5U bus size was selected to promote the development of a miniaturized avionics system capable of robust communications under low size, weight, and power, and low cost constraints.

2.3.3 Time of Release

The ARCE-1 CubeSats are expected to be released within a number of minutes after launch of the rocket.

2.3.4 Release Velocity

Based on simulations, the release velocities of the ARCE-1 CubeSats are as follows:

- ARCE-1a: 1.78 m/s
- ARCE-1b: 1.65 m/s
- ARCE-1c: 1.49 m/s

2.3.5 Expected Orbital Parameters

The anticipated orbital parameters for the ARCE-1 CubeSats are:

- perigee: 450 km
- apogee: 450 km
- inclination: 97 degrees

2.3.6 Calculated Orbital Lifetime

The initial debris orbit is assumed to be the nominal launch orbit of 450 km circular, inclination of 97 degrees.

The lifetime as calculated by NASA DAS 2.1.1 is:

- Stowed: 3.083 years
- Deployed/Tumbling: 2.36 years
- Deployed/Nominal: 2.45 years

See DAS symmary data in Appendix A, Stowed configuration DAS data in Appendix B, Deployed/Tumbling configuration DAS data in Appendix C, and Deployed/Nominal configuration DAS data in Appendix D

The mission as a whole releases less than the 100 object-year limit (3 satellites $\times$ 3.083 years).

2.3.7 Compliance Assessment

- Requirement 4.3-1a: 25 year limit: Compliant
- Requirement 4.3-1b: $<$ 100 object$\times$year limit: Compliant
- Requirement 4.3-2: GEO $\pm$200km: N/A

2.4 Assessment of Spacecraft Intentional Breakups and Potential for Explosions

2.4.1 Potential Causes of Breakup

Under nominal operations, including deployment of solar panels and antennas, there is no intentional breakup or creation of debris (other than the satellite units themselves, as covered in Section 2.3).

2.4.2 Failure Mode Analysis for Explosion Risk

The possible failure modes for the ARCE-1 CubeSats includes mechanical failure as a result of mechanical stresses (static, vibration, and shock loading, and thermal expansion and contraction).

To verify the ARCE-1 CubeSats can safely withstand the launch and space environments without potential for accidental breakup or explosion, a series of verification tests will be performed, including:

- random vibration testing at Protoflight levels;
- static load analysis for mechanical design and bonding methods at Protoflight levels;
- extensive functional testing before, after, and during (as possible) the listed tests;
- operational testing under nominal and expected extreme conditions;
- specific testing to certify the battery according to UN 38.3 requirements.

All verification tests will be performed at Protoflight levels with respect to the expected launch environment and the expected operational thermal environment for the satellite.

The battery cells are sensitive to mechanical impact (such an event could rupture the cell) as well as extreme temperatures. However, the Material Safety Data Sheet for the batteries [5] lists this risk as "[mechanical impact] may result in rupture in extreme cases," and while the launch environment is difficult, the expected shock, quasi-static, and vibration loading are not expected to result in "extreme" impacts for the battery. Finally, the auto-ignition temperature is 130°C, well above the expected maximum operational temperature of 45°C predicted by simulation.

2.4.3 Breakup Plan

There are no planned breakup events for the ARCE-1 CubeSats.

2.4.4 Passivated Components

Possible passivated components:

- Burning propellants: N/A
- Venting lines and tanks: N/A
- Venting pressurized systems: N/A
- Discharging batteries and preventing re-charging:
  - the ARCE-1 charging system cannot be shut down. This is by design to support automated system recovery in the event of on-orbit anomalies.
- Depressurizing gas and liquid filled batteries: N/A
- Deactivating range safety systems: N/A
- De-energizing ADCS components:
  - the electromagnet torque rods are designed to be used in a manner that prevents permanent magnetic fields from developing. The ADCS controller can be shut down via ground command, thus disabling and de-energizing the ADCS components.

2.4.5 Passivation Rationale

The ARCE-1 satellites must be autonomously resilient against on-orbit anomalies. This is supported by automatic power cycling upon fault identification: upon a severe fault condition, the satellite will power cycle, boot into a minimum baseline code, and await command from the ground station.

2.4.6 Compliance Assessment

- Requirement 4.4-1: < 0.001 probability of explosion: Compliant
- Requirement 4.4-2: Passivate energy sources: Compliant
- Requirement 4.4-3: limit breakup risk (long term): Compliant
- Requirement 4.4-4: limit breakup risk (short term): Compliant

2.5 Assessment of Spacecraft Potential for On-Orbit Collisions

2.5.1 Probability of Collision with Large Objects

See Appendix A for ARCE-1 Probability of Collision simulations data.

Based on the DAS output, there is no risk of collision.

2.5.2 Post-Mission Disposal Risk

No systems are required for post-mission disposal of the ARCE-1 CubeSats; disposal is by means of uncontrolled atmospheric re-entry.

2.5.3 Compliance Assessment

- Requirement 4.5-1: $<$ 0.001 10cm impact risk: Compliant
- Requirement 4.5-2: post-mission disposal risks: N/A

2.5.4 Debris Avoidance Capability

The ARCE-1 CubeSats have no maneuvering capability (aside from marginal differential-drag via attitude control). The following measures may assist in reducing the covariance for orbital conjunction analysis:

- on-board GPS and extended Kalman filter state estimation;
- external reflective coating (aluminum tape).

Any GPS-derived orbit information, including derived TLEs, will be forwarded to CSpOC and/or other stakeholders as required.

2.6 Assessment of Spacecraft Post-Mission Disposal Plans and Procedures

2.6.1 Spacecraft Disposal

The ARCE-1 CubeSats will undergo uncontrolled atmospheric re-entry for disposal.

2.6.2 Systems for Post-Mission Disposal

There are no on-board systems required to enable or promote safe disposal (the satellite will naturally de-orbit within the 25 year limit).

A high-drag flight profile may be commanded to increase de-orbit rate, subject to operational capability beyond the anticipated mission lifetime of 1 year.

2.6.3 Area to Mass Ratios

The average cross-sectional area calculations were done using NASA-STD-8719.14B section 4.3.4.2.2(a) as a guide. In the stowed configuration, the ARCE-1 CubeSat is a convex shape. In the deployed configuration, the satellite is not convex.

The ARCE-1 satellites have area-to-mass ratios of:

- Stowed:
  - average area: 0.0096m^2
  - mass: 0.9288kg
  - ratio: 0.01033 m^2/kg
- Deployed/Tumbling:
  - average area: 0.02461 m^2
  - mass: 0.9288kg
  - ratio: 0.02650 m^2/kg
- Deployed/Nominal:
  - average area: 0.021924 m^2
  - mass: 0.9288kg
  - ratio: 0.02360 m^2/kg

Stowed Case Calculations

Based on NASA-STD-8719.14B section 4.3.4.2.2(a)(1):

the total surface area of the satellite is:

$$A_{total} = 2 \times (0.100m \times 0.100m) + 4 \times (0.100m \times 0.046m) = 0.0384m^2;$$

then, the average cross-sectional surface area is:

$$A = A_{total}/4 = 0.0384/4m^2 = 0.0096m^2;$$

finally, the area to mass ratio is:

$$A/m = 0.0096/0.9288\frac{m^2}{kg} = 0.01033\frac{m^2}{kg}.$$

Deployed/Tumbling Case Calculations

Based on NASA-STD-8719.14B section 4.3.4.2.2(a)(2)(b):

the view that provides the maximum surface area is slightly off of the +Z axis, yielding area of:

$$A_{max} = 0.03954149m^2;$$

the mutually-orthogonal views produce cross-sectional areas of:

$$A_1 = 0.00508m^2;$$

$$A_2 = 0.0046m^2;$$

then, the average cross-sectional surface area is:

$$A = (A_{max} + A_1 + A_2)/2m^2 = 0.02461m^2;$$

finally, the area to mass ratio is:

$$A/m = 0.02461/0.9288\frac{m^2}{kg} = 0.02650\frac{m^2}{kg}.$$

Deployed/Nominal Case Calculations

In the nominal case, the ARCE-1 CubeSat is attitude controlled such that the +Z axis is pointed toward the sun. Without knowing exact details of the final orbit other than apogee, perigee, and inclination, the best estimate for average area to mass ratio is calculated assuming that for about half of the orbit, the Z axis is roughly aligned with the velocity vector, and for the other half of the orbit the X axis or Y axis is aligned with the velocity vector. This yields the following average cross-sectional area:

$$A = 0.5 \times A_Z + 0.5 \times (\frac{A_X}{2} + \frac{A_Y}{2})m^2 = 0.0390008/2 + (\frac{0.00508}{2} + \frac{0.0046}{2})/2m^2 = 0.021924m^2;$$

then, the area to mass ratio is:

$$A/m = 0.021924/0.9288\frac{m^2}{kg} = 0.02360\frac{m^2}{kg}.$$

2.6.4 Controlled Re-entry Plan

N/A: the ARCE-1 CubeSats will undergo uncontrolled re-entry.

2.6.5 Compliance Assessment

- Requirement 4.6-1.a-c: disposal method: Compliant (uncontrolled atmospheric re-entry)
- Requirement 4.6-2: GEO disposal: N/A
- Requirement 4.6-3: MEO disposal: N/A
- Requirement 4.6-4: disposal reliability: N/A

2.7 Assessment of Spacecraft Reentry Hazards

2.7.1 Spacecraft Components and Materials

See Appendix A for ARCE-1 CubeSat components with cuboid size/shape, mass, and material.

2.7.2 Atmospheric Survivability Assessment

See Appendix A for ARCE-1 survivability in accordance with Requirement 4.7-1.

Output from the DAS simulation indicates components survive reentry (see Table 2.7.1; the same output was achieved for both stowed and deployed configuration simulations).

Table 2.7.1: ARCE-1 DAS Atmospheric Survivability Summary

Component	**Demise Altitude**	**Debris Casualty Area (m^2)**	**Impact Kinetic Energy (J)**
Separation Legs	0.000000	0.769055	0.088558
Spring Loaded Hinge	0.000000	1.560307	0.432898
Top Monofilament Guide	0.000000	0.403544	0.007449
Bottom Monofilament Guide	0.000000	0.407877	0.007376

2.7.3 Probability of Human Casualty

There are no components that survive atmospheric reentry with an impact energy greater than 15 Joules; therefore, there is no risk of human casualty due to atmospheric reentry survival.

2.7.4 Compliance Assessment

- Requirement4.7-1: ground population risk: Compliant

2.7.5 Hazardous Materials

The only identified hazardous material on the ARCE-1 CubeSats are the batteries, specifically the battery pack mixture composed of:

- Chemicals and composition:
  - 30-40% metal oxide (CAS: N/A)
  - 15-20% graphite (CAS: 7782-42-5)
  - 8-13% organic electrolyte (CAS: N/A)
  - 3-5% aluminum (CAS: 7429-90-5)
  - 6-9% copper (CAS: 7440-50-8)

  [nosep]
- Material hazard to humans:
  - Not dangerous with normal use;
  - If battery is ruptured:
    - Inhalation: vapor or mist may cause respiratory irritation
    - Ingestion: serious chemical burns of mouth, esophagus, and gastrointestinal tract

        * Skin: severe irritation or burns
        * Eye: severe irritation or burns
- Launch state and quantity:
    - State: black and grey odorless solid
    - Quantity: about 200g (estimated 50g per cell, four total cells)
    - Pressure: N/A
    - Activity: battery charged but not active
- Orbital state and quantity:
    - State: black and grey odorless solid
    - Quantity: about 200g (estimated 50g per cell, four total cells)
    - Pressure: N/A
    - Activity: battery charge cycling between 40% and 80%
- EOM state and quantity:
    - State: black and grey odorless solid
    - Quantity: about 200g (estimated 50g per cell, four total cells)
    - Pressure: N/A
    - Activity: battery charge cycling between 40% and 80%
- Passivated state and quantity:
    - State: black and grey odorless solid
    - Quantity: about 200g (estimated 50g per cell, four total cells)
    - Pressure: N/A
    - Activity: battery charge cycling between 40% and 80%
- Atmospheric re-entry surviving state and quantity:
    - N/A

2.8 Assessment for Tether Missions

The ARCE-1 CubeSats do not include a tether.

2.8.1 Compliance Assessment

- Requirement 4.8-1: tether risk: N/A

Chapter 3

End of Mission Plan

3.1 End of Mission Plan

The Orbital Debris Assessment in Chapter 2 serves as the End of Mission Plan.

3.1.1 End of Life Variability

The ARCE-1 CubeSats are designed to perform mission tasks for at least one year in the space environment. However, reliability in space is not proven as these are the first of a new design of spacecraft that relies on components not specifically rated for use in space.

Nominal mission operations will continue for as long as is reasonable subject to spacecraft functionality and licensing (i.e. extension of FCC-regulated frequency allocation).

It is possible that newer versions of the ARCE-1 design will be flown in the near future; if this is the case, interoperability will be considered during the core design phase of any future ARCE missions.

3.1.2 End of Mission Plan Update

Concerning the above, the useful lifetime of ARCE-1 CubeSats may be subject to extension. If that becomes the case, this End of Mission Plan will be accordingly updated.

Appendix A

DAS Outputs Summary

NASA DAS v2.1.1 [3] was used to simulate orbital debris and lifetime for the ARCE-1 CubeSat in both stowed and deployed configurations.

A.1 DAS outputs summary

Table A.1.1: ARCE-1 DAS Simulation Summary

Requirement	Description	Return Status
	Stowed Configuration	
4.5-1	10cm impact risk	Passed
4.5-2	post-mission disposal risk	Compliant
4.6	post-mission disposal method	Passed
4.7-1	ground population risk	Passed
	Deployed/Tumbling Configuration	
4.5-1	10cm impact risk	Passed
4.5-2	post-mission disposal risk	Compliant
4.6	post-mission disposal method	Passed
4.7-1	ground population risk	Passed
	Deployed/Nominal Configuration	
4.5-1	10cm impact risk	Passed
4.5-2	post-mission disposal risk	Compliant
4.6	post-mission disposal method	Passed
4.7-1	ground population risk	Passed

Appendix B

DAS Inputs and Outputs - Stowed Configuration

```
10 21 2019; 13:16:01PM    Activity Log Started
10 21 2019; 13:22:34PM    Project Data Saved To File
10 21 2019; 13:22:46PM    Project Data Saved To File
10 21 2019; 13:22:46PM    Saved Project As C:\Users\user\Sterk\ARCE\DAS10-21S\
10 21 2019; 13:23:02PM    Mission Editor Changes Applied
10 21 2019; 13:27:09PM    Processing Requirement 4.5-1: Return Status: Passed
==============
Run Data
==============
**INPUT**

    Space Structure Name = ARCE-1
    Space Structure Type = Payload
    Perigee Altitude = 450.000000 (km)
    Apogee Altitude = 450.000000 (km)
    Inclination = 97.000000 (deg)
    RAAN = 0.000000 (deg)
    Argument of Perigee = 0.000000 (deg)
    Mean Anomaly = 0.000000 (deg)
    Final Area-To-Mass Ratio = 0.010330 (m^2/kg)
    Start Year = 2019.000000 (yr)
    Initial Mass = 0.928832 (kg)
    Final Mass = 0.928832 (kg)
    Duration = 5.000000 (yr)
    Station-Kept = False
    Abandoned = True
    PMD Perigee Altitude = -1.000000 (km)
    PMD Apogee Altitude = -1.000000 (km)
    PMD Inclination = 0.000000 (deg)
    PMD RAAN = 0.000000 (deg)
    PMD Argument of Perigee = 0.000000 (deg)
    PMD Mean Anomaly = 0.000000 (deg)

**OUTPUT**

    Collision Probability = 0.000000
    Returned Error Message: Normal Processing
    Date Range Error Message: Normal Date Range
    Status = Pass
==============
=============== End of Requirement 4.5-1 ===============
```

```
10 21 2019; 13:27:15PM    Requirement 4.5-2:  Compliant
10 21 2019; 13:27:20PM    Processing Requirement 4.6: Return Status: Passed
==============
Project Data
==============
**INPUT**

    Space Structure Name = ARCE-1
    Space Structure Type = Payload
    Perigee Altitude = 450.000000 (km)
    Apogee Altitude = 450.000000 (km)
    Inclination = 97.000000 (deg)
    RAAN = 0.000000 (deg)
    Argument of Perigee = 0.000000 (deg)
    Mean Anomaly = 0.000000 (deg)
    Area-To-Mass Ratio = 0.010330 (m^2/kg)
    Start Year = 2019.000000 (yr)
    Initial Mass = 0.928832 (kg)
    Final Mass = 0.928832 (kg)
    Duration = 5.000000 (yr)
    Station Kept = False
    Abandoned = True
    PMD Perigee Altitude = -1.000000 (km)
    PMD Apogee Altitude = -1.000000 (km)
    PMD Inclination = 0.000000 (deg)
    PMD RAAN = 0.000000 (deg)
    PMD Argument of Perigee = 0.000000 (deg)
    PMD Mean Anomaly = 0.000000 (deg)

**OUTPUT**

    Suggested Perigee Altitude = 450.000000 (km)
    Suggested Apogee Altitude = 450.000000 (km)
    Returned Error Message = Reentry during mission (no PMD req.).
    Released Year = 2022 (yr)
    Requirement = 61
    Compliance Status = Pass
==============
=============== End of Requirement 4.6 ===============
10 21 2019; 13:27:20PM    Processing Requirement 4.7-1: Return Status: Passed
**INPUT**
```

See Appendix E for the data input for DAS simulation of Requirement 4.7-1.

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

name = ARCE-1
Demise Altitude = 77.999336
Debris Casualty Area = 0.000000
Impact Kinetic Energy = 0.000000
```

```
*************************************
name = Structure Lid
Demise Altitude = 75.156044
Debris Casualty Area = 0.000000
Impact Kinetic Energy = 0.000000

*************************************
name = Structure Case
Demise Altitude = 76.299614
Debris Casualty Area = 0.000000
Impact Kinetic Energy = 0.000000

*************************************
name = M3 Bolts
Demise Altitude = 77.225639
Debris Casualty Area = 0.000000
Impact Kinetic Energy = 0.000000

*************************************
name = M3 Nuts
Demise Altitude = 75.995667
Debris Casualty Area = 0.000000
Impact Kinetic Energy = 0.000000

*************************************
name = M3 Lock Washers
Demise Altitude = 76.271591
Debris Casualty Area = 0.000000
Impact Kinetic Energy = 0.000000

*************************************
name = Separation Spring Plunger
Demise Altitude = 76.754341
Debris Casualty Area = 0.000000
Impact Kinetic Energy = 0.000000

*************************************
name = Separation Legs
Demise Altitude = 0.000000
Debris Casualty Area = 0.769055
Impact Kinetic Energy = 0.088558

*************************************
name = Housing Plate
Demise Altitude = 77.654449
Debris Casualty Area = 0.000000
Impact Kinetic Energy = 0.000000

*************************************
name = Housing Cap
Demise Altitude = 77.918602
Debris Casualty Area = 0.000000
Impact Kinetic Energy = 0.000000
```

```
************************************
name = 18650 Battery
Demise Altitude = 75.015045
Debris Casualty Area = 0.000000
Impact Kinetic Energy = 0.000000

************************************
name = M2 Bolt
Demise Altitude = 77.427200
Debris Casualty Area = 0.000000
Impact Kinetic Energy = 0.000000

************************************
name = M2 Screw
Demise Altitude = 77.515945
Debris Casualty Area = 0.000000
Impact Kinetic Energy = 0.000000

************************************
name = Structure Spacer
Demise Altitude = 77.983162
Debris Casualty Area = 0.000000
Impact Kinetic Energy = 0.000000

************************************
name = Separation Switch
Demise Altitude = 77.902260
Debris Casualty Area = 0.000000
Impact Kinetic Energy = 0.000000

************************************
name = Servo Arm
Demise Altitude = 77.857788
Debris Casualty Area = 0.000000
Impact Kinetic Energy = 0.000000

************************************
name = Servo Screw
Demise Altitude = 77.515762
Debris Casualty Area = 0.000000
Impact Kinetic Energy = 0.000000

************************************
name = Servo
Demise Altitude = 76.284401
Debris Casualty Area = 0.000000
Impact Kinetic Energy = 0.000000

************************************
name = Face Mounted Solar Panel
Demise Altitude = 77.649307
Debris Casualty Area = 0.000000
Impact Kinetic Energy = 0.000000
```

```
*************************************
name = Hinge Mounted Solar Panel 1
Demise Altitude = 77.585281
Debris Casualty Area = 0.000000
Impact Kinetic Energy = 0.000000

*************************************
name = Hinge Mounted Solar Panel 2
Demise Altitude = 77.640953
Debris Casualty Area = 0.000000
Impact Kinetic Energy = 0.000000

*************************************
name = Spring Loaded Hinge
Demise Altitude = 0.000000
Debris Casualty Area = 1.560307
Impact Kinetic Energy = 0.432898

*************************************
name = Top Monofilament Guide
Demise Altitude = 0.000000
Debris Casualty Area = 0.403544
Impact Kinetic Energy = 0.007449

*************************************
name = Bottom Monofilament Guide
Demise Altitude = 0.000000
Debris Casualty Area = 0.407877
Impact Kinetic Energy = 0.007376

*************************************
name = Sidekiq
Demise Altitude = 77.403542
Debris Casualty Area = 0.000000
Impact Kinetic Energy = 0.000000

*************************************
name = Daughterboard
Demise Altitude = 77.484444
Debris Casualty Area = 0.000000
Impact Kinetic Energy = 0.000000

*************************************
name = Antenna Arm
Demise Altitude = 77.654327
Debris Casualty Area = 0.000000
Impact Kinetic Energy = 0.000000

*************************************
name = RF Antenna
Demise Altitude = 77.808846
Debris Casualty Area = 0.000000
Impact Kinetic Energy = 0.000000
```

```
*************************************
name = Antenna Spring
Demise Altitude = 77.450401
Debris Casualty Area = 0.000000
Impact Kinetic Energy = 0.000000

*************************************
name = GPS Board
Demise Altitude = 77.205978
Debris Casualty Area = 0.000000
Impact Kinetic Energy = 0.000000

*************************************
name = Patch Antenna
Demise Altitude = 76.934601
Debris Casualty Area = 0.000000
Impact Kinetic Energy = 0.000000

*************************************
name = CDH Board
Demise Altitude = 76.823715
Debris Casualty Area = 0.000000
Impact Kinetic Energy = 0.000000

*************************************
name = Raspberry Pi
Demise Altitude = 77.551010
Debris Casualty Area = 0.000000
Impact Kinetic Energy = 0.000000

*************************************
name = Horizontal Magnetorquer
Demise Altitude = 72.878189
Debris Casualty Area = 0.000000
Impact Kinetic Energy = 0.000000

*************************************
name = Vertical Magnetorquer
Demise Altitude = 76.282021
Debris Casualty Area = 0.000000
Impact Kinetic Energy = 0.000000

*************************************
name = Aluminum Shielding Tape
Demise Altitude = 77.987602
Debris Casualty Area = 0.000000
Impact Kinetic Energy = 0.000000

*************************************
name = 3M 1205 Kapton Tape
Demise Altitude = 77.983192
Debris Casualty Area = 0.000000
Impact Kinetic Energy = 0.000000
=============== End of Requirement 4.7-1 ===============
```

```
10 21 2019; 13:27:43PM    Science and Engineering - Apogee/Perigee History for a Given Orbit

**INPUT**

    Perigee Altitude = 450.000000 (km)
    Apogee Altitude = 450.000000 (km)
    Inclination = 97.000000 (deg)
    RAAN = 0.000000 (deg)
    Argument of Perigee = 0.000000 (deg)
    Mean Anomaly = 0.000000 (deg)
    Area-To-Mass Ratio = 0.010330 (m^2/kg)
    Start Year = 2019.900000 (yr)
    Integration Time = 4.000000 (yr)

**OUTPUT**

    Plot
```

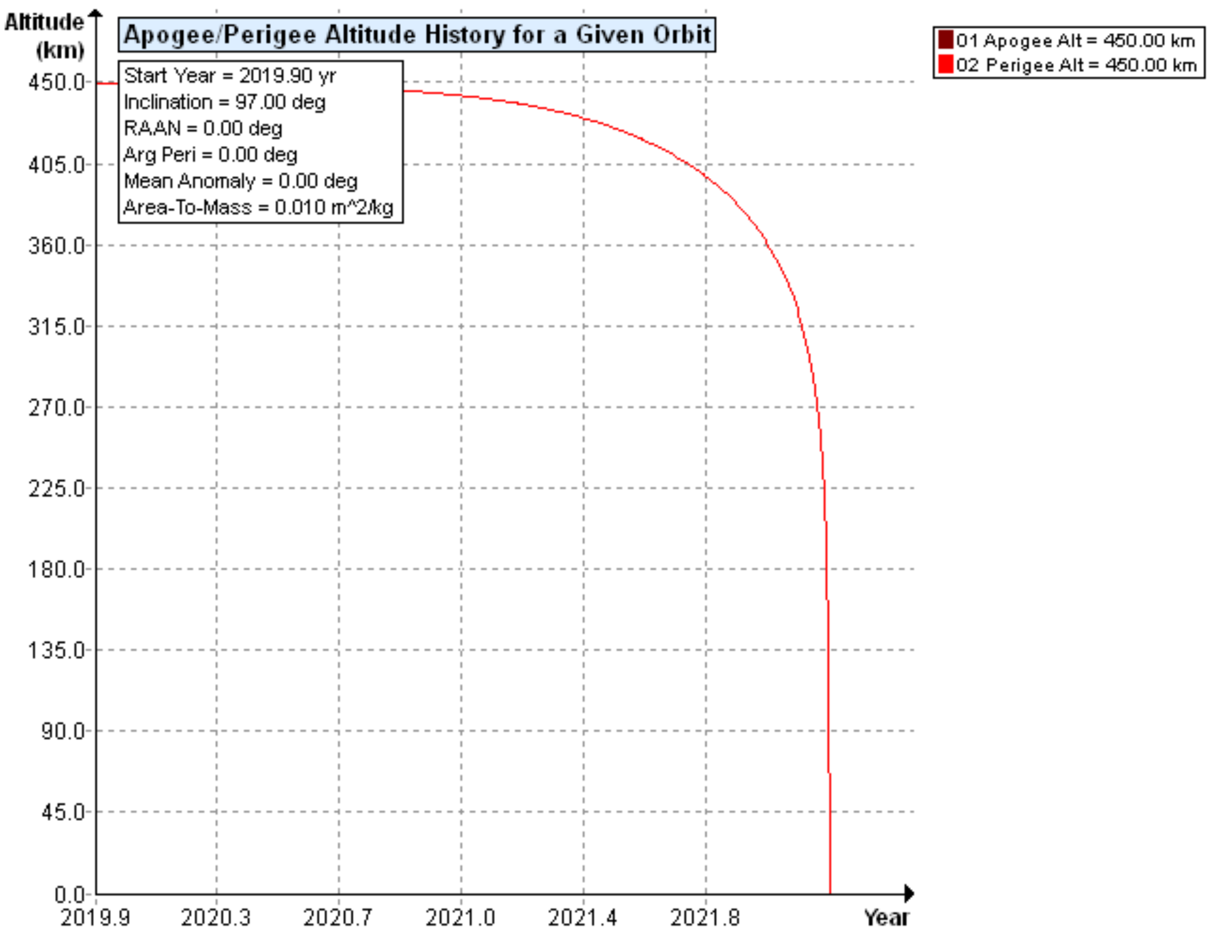

Figure B.1: ARCE-1 Stowed Lifetime

```
10 21 2019; 13:28:24PM    Science and Engineering - Orbit Lifetime/Dwell Time

**INPUT**

    Start Year = 2019.000000 (yr)
    Perigee Altitude = 450.000000 (km)
    Apogee Altitude = 450.000000 (km)
    Inclination = 97.000000 (deg)
    RAAN = 0.000000 (deg)
    Argument of Perigee = 0.000000 (deg)
    Area-To-Mass Ratio = 0.010330 (m^2/kg)

**OUTPUT**

    Orbital Lifetime from Startyr = 3.082820 (yr)
    Time Spent in LEO during Lifetime  = 3.082820 (yr)
    Last year of Propagation = 2022 (yr)
    Returned Error Message: Object reentered
```

Appendix C

DAS Inputs and Outputs - Deployed/Tumbling Configuration

```
10 11 2019; 10:54:06AM    Activity Log Started
10 21 2019; 11:45:14AM    Project Data Saved To File
10 21 2019; 11:45:14AM    Saved Project As C:\Users\user\Sterk\ARCE\DAS10-21\
10 21 2019; 12:56:43PM    Mission Editor Changes Applied
10 21 2019; 13:00:51PM    Processing Requirement 4.5-1: Return Status:  Passed
==============
Run Data
==============
**INPUT**

    Space Structure Name = ARCE-1
    Space Structure Type = Payload
    Perigee Altitude = 450.000000 (km)
    Apogee Altitude = 450.000000 (km)
    Inclination = 97.000000 (deg)
    RAAN = 0.000000 (deg)
    Argument of Perigee = 0.000000 (deg)
    Mean Anomaly = 0.000000 (deg)
    Final Area-To-Mass Ratio = 0.026500 (m^2/kg)
    Start Year = 2019.000000 (yr)
    Initial Mass = 0.928832 (kg)
    Final Mass = 0.928832 (kg)
    Duration = 5.000000 (yr)
    Station-Kept = False
    Abandoned = True
    PMD Perigee Altitude = -1.000000 (km)
    PMD Apogee Altitude = -1.000000 (km)
    PMD Inclination = 0.000000 (deg)
    PMD RAAN = 0.000000 (deg)
    PMD Argument of Perigee = 0.000000 (deg)
    PMD Mean Anomaly = 0.000000 (deg)

**OUTPUT**

    Collision Probability = 0.000000
    Returned Error Message: Normal Processing
    Date Range Error Message: Normal Date Range
    Status = Pass
==============
=============== End of Requirement 4.5-1 ===============
```

```
10 21 2019; 13:01:14PM    Requirement 4.5-2:  Compliant
10 21 2019; 13:01:27PM    Processing Requirement 4.6: Return Status: Passed
==============
Project Data
==============
**INPUT**

    Space Structure Name = ARCE-1
    Space Structure Type = Payload
    Perigee Altitude = 450.000000 (km)
    Apogee Altitude = 450.000000 (km)
    Inclination = 97.000000 (deg)
    RAAN = 0.000000 (deg)
    Argument of Perigee = 0.000000 (deg)
    Mean Anomaly = 0.000000 (deg)
    Area-To-Mass Ratio = 0.026500 (m^2/kg)
    Start Year = 2019.000000 (yr)
    Initial Mass = 0.928832 (kg)
    Final Mass = 0.928832 (kg)
    Duration = 5.000000 (yr)
    Station Kept = False
    Abandoned = True
    PMD Perigee Altitude = -1.000000 (km)
    PMD Apogee Altitude = -1.000000 (km)
    PMD Inclination = 0.000000 (deg)
    PMD RAAN = 0.000000 (deg)
    PMD Argument of Perigee = 0.000000 (deg)
    PMD Mean Anomaly = 0.000000 (deg)

**OUTPUT**

    Suggested Perigee Altitude = 450.000000 (km)
    Suggested Apogee Altitude = 450.000000 (km)
    Returned Error Message = Reentry during mission (no PMD req.).
    Released Year = 2021 (yr)
    Requirement = 61
    Compliance Status = Pass
==============
=============== End of Requirement 4.6 ===============
10 21 2019; 13:01:27PM    Processing Requirement 4.7-1: Return Status: Passed
**INPUT**
```

See Appendix E for the data input for DAS simulation of Requirement 4.7-1.

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

name = ARCE-1
Demise Altitude = 77.999336
Debris Casualty Area = 0.000000
Impact Kinetic Energy = 0.000000
```

```
************************************
name = Structure Lid
Demise Altitude = 75.156044
Debris Casualty Area = 0.000000
Impact Kinetic Energy = 0.000000

************************************
name = Structure Case
Demise Altitude = 76.299614
Debris Casualty Area = 0.000000
Impact Kinetic Energy = 0.000000

************************************
name = M3 Bolts
Demise Altitude = 77.225639
Debris Casualty Area = 0.000000
Impact Kinetic Energy = 0.000000

************************************
name = M3 Nuts
Demise Altitude = 75.995667
Debris Casualty Area = 0.000000
Impact Kinetic Energy = 0.000000

************************************
name = M3 Lock Washers
Demise Altitude = 76.271591
Debris Casualty Area = 0.000000
Impact Kinetic Energy = 0.000000

************************************
name = Separation Spring Plunger
Demise Altitude = 76.754341
Debris Casualty Area = 0.000000
Impact Kinetic Energy = 0.000000

************************************
name = Separation Legs
Demise Altitude = 0.000000
Debris Casualty Area = 0.769055
Impact Kinetic Energy = 0.088558

************************************
name = Housing Plate
Demise Altitude = 77.654449
Debris Casualty Area = 0.000000
Impact Kinetic Energy = 0.000000

************************************
name = Housing Cap
Demise Altitude = 77.918602
Debris Casualty Area = 0.000000
Impact Kinetic Energy = 0.000000
```

```
************************************
name = 18650 Battery
Demise Altitude = 75.015045
Debris Casualty Area = 0.000000
Impact Kinetic Energy = 0.000000

************************************
name = M2 Bolt
Demise Altitude = 77.427200
Debris Casualty Area = 0.000000
Impact Kinetic Energy = 0.000000

************************************
name = M2 Screw
Demise Altitude = 77.515945
Debris Casualty Area = 0.000000
Impact Kinetic Energy = 0.000000

************************************
name = Structure Spacer
Demise Altitude = 77.983162
Debris Casualty Area = 0.000000
Impact Kinetic Energy = 0.000000

************************************
name = Separation Switch
Demise Altitude = 77.902260
Debris Casualty Area = 0.000000
Impact Kinetic Energy = 0.000000

************************************
name = Servo Arm
Demise Altitude = 77.857788
Debris Casualty Area = 0.000000
Impact Kinetic Energy = 0.000000

************************************
name = Servo Screw
Demise Altitude = 77.515762
Debris Casualty Area = 0.000000
Impact Kinetic Energy = 0.000000

************************************
name = Servo
Demise Altitude = 76.284401
Debris Casualty Area = 0.000000
Impact Kinetic Energy = 0.000000

************************************
name = Face Mounted Solar Panel
Demise Altitude = 77.649307
Debris Casualty Area = 0.000000
Impact Kinetic Energy = 0.000000
```

```
*************************************
name = Hinge Mounted Solar Panel 1
Demise Altitude = 77.585281
Debris Casualty Area = 0.000000
Impact Kinetic Energy = 0.000000

*************************************
name = Hinge Mounted Solar Panel 2
Demise Altitude = 77.640953
Debris Casualty Area = 0.000000
Impact Kinetic Energy = 0.000000

*************************************
name = Spring Loaded Hinge
Demise Altitude = 0.000000
Debris Casualty Area = 1.560307
Impact Kinetic Energy = 0.432898

*************************************
name = Top Monofilament Guide
Demise Altitude = 0.000000
Debris Casualty Area = 0.403544
Impact Kinetic Energy = 0.007449

*************************************
name = Bottom Monofilament Guide
Demise Altitude = 0.000000
Debris Casualty Area = 0.407877
Impact Kinetic Energy = 0.007376

*************************************
name = Sidekiq
Demise Altitude = 77.403542
Debris Casualty Area = 0.000000
Impact Kinetic Energy = 0.000000

*************************************
name = Daughterboard
Demise Altitude = 77.484444
Debris Casualty Area = 0.000000
Impact Kinetic Energy = 0.000000

*************************************
name = Antenna Arm
Demise Altitude = 77.654327
Debris Casualty Area = 0.000000
Impact Kinetic Energy = 0.000000

*************************************
name = RF Antenna
Demise Altitude = 77.808846
Debris Casualty Area = 0.000000
Impact Kinetic Energy = 0.000000
```

```
*************************************
name = Antenna Spring
Demise Altitude = 77.450401
Debris Casualty Area = 0.000000
Impact Kinetic Energy = 0.000000

*************************************
name = GPS Board
Demise Altitude = 77.205978
Debris Casualty Area = 0.000000
Impact Kinetic Energy = 0.000000

*************************************
name = Patch Antenna
Demise Altitude = 76.934601
Debris Casualty Area = 0.000000
Impact Kinetic Energy = 0.000000

*************************************
name = CDH Board
Demise Altitude = 76.823715
Debris Casualty Area = 0.000000
Impact Kinetic Energy = 0.000000

*************************************
name = Raspberry Pi
Demise Altitude = 77.551010
Debris Casualty Area = 0.000000
Impact Kinetic Energy = 0.000000

*************************************
name = Horizontal Magnetorquer
Demise Altitude = 72.878189
Debris Casualty Area = 0.000000
Impact Kinetic Energy = 0.000000

*************************************
name = Vertical Magnetorquer
Demise Altitude = 76.282021
Debris Casualty Area = 0.000000
Impact Kinetic Energy = 0.000000

*************************************
name = Aluminum Shielding Tape
Demise Altitude = 77.987602
Debris Casualty Area = 0.000000
Impact Kinetic Energy = 0.000000

*************************************
name = 3M 1205 Kapton Tape
Demise Altitude = 77.983192
Debris Casualty Area = 0.000000
Impact Kinetic Energy = 0.000000
=============== End of Requirement 4.7-1 ===============
```

```
10 21 2019; 13:02:14PM    Science and Engineering - Apogee/Perigee History for a Given Orbit

**INPUT**

    Perigee Altitude = 450.000000 (km)
    Apogee Altitude = 450.000000 (km)
    Inclination = 97.000000 (deg)
    RAAN = 0.000000 (deg)
    Argument of Perigee = 0.000000 (deg)
    Mean Anomaly = 0.000000 (deg)
    Area-To-Mass Ratio = 0.026500 (m^2/kg)
    Start Year = 2019.900000 (yr)
    Integration Time = 4.000000 (yr)

**OUTPUT**

    Plot
```

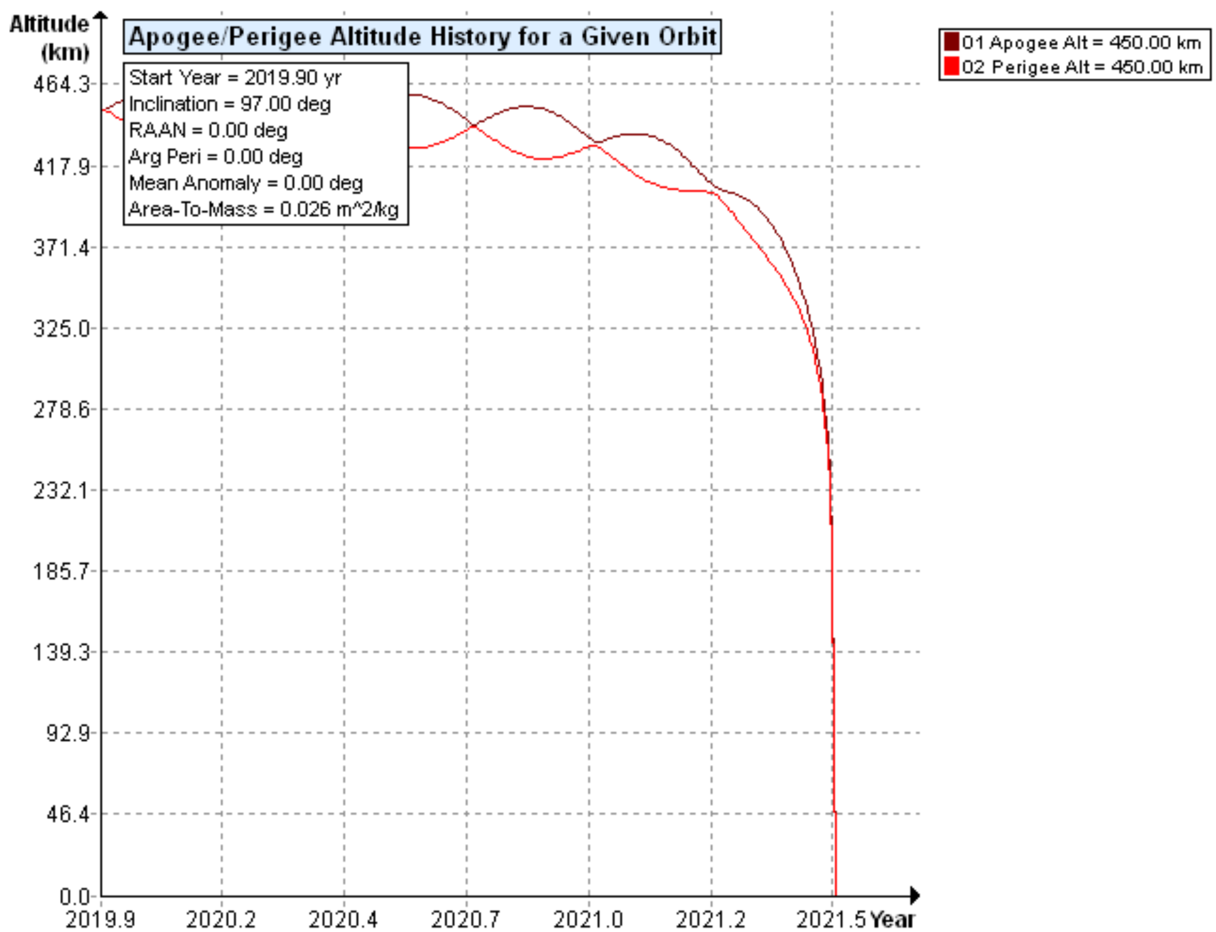

Figure C.1: ARCE-1 Deployed/Tumbling Lifetime

```
10 21 2019; 13:04:52PM    Science and Engineering - Orbit Lifetime/Dwell Time

**INPUT**

    Start Year = 2019.000000 (yr)
    Perigee Altitude = 450.000000 (km)
    Apogee Altitude = 450.000000 (km)
    Inclination = 97.000000 (deg)
    RAAN = 0.000000 (deg)
    Argument of Perigee = 0.000000 (deg)
    Area-To-Mass Ratio = 0.026500 (m^2/kg)

**OUTPUT**

    Orbital Lifetime from Startyr = 2.360027 (yr)
    Time Spent in LEO during Lifetime  = 2.360027 (yr)
    Last year of Propagation = 2021 (yr)
    Returned Error Message: Object reentered
```

Appendix D

DAS Inputs and Outputs - Deployed/Nominal Configuration

```
10 21 2019; 13:07:16PM    Activity Log Started
10 21 2019; 13:07:26PM    Project Data Saved To File
10 21 2019; 13:07:59PM    Project Data Saved To File
10 21 2019; 13:07:59PM    Saved Project As C:\Users\user\Sterk\ARCE\DAS10-21DN\
10 21 2019; 13:08:22PM    Mission Editor Changes Applied
10 21 2019; 13:12:17PM    Processing Requirement 4.5-1: Return Status: Passed
==============
Run Data
==============
**INPUT**

    Space Structure Name = ARCE-1
    Space Structure Type = Payload
    Perigee Altitude = 450.000000 (km)
    Apogee Altitude = 450.000000 (km)
    Inclination = 97.000000 (deg)
    RAAN = 0.000000 (deg)
    Argument of Perigee = 0.000000 (deg)
    Mean Anomaly = 0.000000 (deg)
    Final Area-To-Mass Ratio = 0.023600 (m^2/kg)
    Start Year = 2019.000000 (yr)
    Initial Mass = 0.928832 (kg)
    Final Mass = 0.928832 (kg)
    Duration = 5.000000 (yr)
    Station-Kept = False
    Abandoned = True
    PMD Perigee Altitude = -1.000000 (km)
    PMD Apogee Altitude = -1.000000 (km)
    PMD Inclination = 0.000000 (deg)
    PMD RAAN = 0.000000 (deg)
    PMD Argument of Perigee = 0.000000 (deg)
    PMD Mean Anomaly = 0.000000 (deg)

**OUTPUT**

    Collision Probability = 0.000000
    Returned Error Message: Normal Processing
    Date Range Error Message: Normal Date Range
    Status = Pass
==============
=============== End of Requirement 4.5-1 ===============
```

```
10 21 2019; 13:12:46PM    Requirement 4.5-2:  Compliant
10 21 2019; 13:12:50PM    Processing Requirement 4.6: Return Status: Passed
==============
Project Data
==============
**INPUT**

    Space Structure Name = ARCE-1
    Space Structure Type = Payload
    Perigee Altitude = 450.000000 (km)
    Apogee Altitude = 450.000000 (km)
    Inclination = 97.000000 (deg)
    RAAN = 0.000000 (deg)
    Argument of Perigee = 0.000000 (deg)
    Mean Anomaly = 0.000000 (deg)
    Area-To-Mass Ratio = 0.023600 (m^2/kg)
    Start Year = 2019.000000 (yr)
    Initial Mass = 0.928832 (kg)
    Final Mass = 0.928832 (kg)
    Duration = 5.000000 (yr)
    Station Kept = False
    Abandoned = True
    PMD Perigee Altitude = -1.000000 (km)
    PMD Apogee Altitude = -1.000000 (km)
    PMD Inclination = 0.000000 (deg)
    PMD RAAN = 0.000000 (deg)
    PMD Argument of Perigee = 0.000000 (deg)
    PMD Mean Anomaly = 0.000000 (deg)

**OUTPUT**

    Suggested Perigee Altitude = 450.000000 (km)
    Suggested Apogee Altitude = 450.000000 (km)
    Returned Error Message = Reentry during mission (no PMD req.).
    Released Year = 2021 (yr)
    Requirement = 61
    Compliance Status = Pass
==============
=============== End of Requirement 4.6 ===============
10 21 2019; 13:12:50PM    Processing Requirement 4.7-1: Return Status: Passed
**INPUT**
```

See Appendix E for the data input for DAS simulation of Requirement 4.7-1.

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

name = ARCE-1
Demise Altitude = 77.999336
Debris Casualty Area = 0.000000
Impact Kinetic Energy = 0.000000
```

```
*************************************
name = Structure Lid
Demise Altitude = 75.156044
Debris Casualty Area = 0.000000
Impact Kinetic Energy = 0.000000

*************************************
name = Structure Case
Demise Altitude = 76.299614
Debris Casualty Area = 0.000000
Impact Kinetic Energy = 0.000000

*************************************
name = M3 Bolts
Demise Altitude = 77.225639
Debris Casualty Area = 0.000000
Impact Kinetic Energy = 0.000000

*************************************
name = M3 Nuts
Demise Altitude = 75.995667
Debris Casualty Area = 0.000000
Impact Kinetic Energy = 0.000000

*************************************
name = M3 Lock Washers
Demise Altitude = 76.271591
Debris Casualty Area = 0.000000
Impact Kinetic Energy = 0.000000

*************************************
name = Separation Spring Plunger
Demise Altitude = 76.754341
Debris Casualty Area = 0.000000
Impact Kinetic Energy = 0.000000

*************************************
name = Separation Legs
Demise Altitude = 0.000000
Debris Casualty Area = 0.769055
Impact Kinetic Energy = 0.088558

*************************************
name = Housing Plate
Demise Altitude = 77.654449
Debris Casualty Area = 0.000000
Impact Kinetic Energy = 0.000000

*************************************
name = Housing Cap
Demise Altitude = 77.918602
Debris Casualty Area = 0.000000
Impact Kinetic Energy = 0.000000
```

```
*************************************
name = 18650 Battery
Demise Altitude = 75.015045
Debris Casualty Area = 0.000000
Impact Kinetic Energy = 0.000000

*************************************
name = M2 Bolt
Demise Altitude = 77.427200
Debris Casualty Area = 0.000000
Impact Kinetic Energy = 0.000000

*************************************
name = M2 Screw
Demise Altitude = 77.515945
Debris Casualty Area = 0.000000
Impact Kinetic Energy = 0.000000

*************************************
name = Structure Spacer
Demise Altitude = 77.983162
Debris Casualty Area = 0.000000
Impact Kinetic Energy = 0.000000

*************************************
name = Separation Switch
Demise Altitude = 77.902260
Debris Casualty Area = 0.000000
Impact Kinetic Energy = 0.000000

*************************************
name = Servo Arm
Demise Altitude = 77.857788
Debris Casualty Area = 0.000000
Impact Kinetic Energy = 0.000000

*************************************
name = Servo Screw
Demise Altitude = 77.515762
Debris Casualty Area = 0.000000
Impact Kinetic Energy = 0.000000

*************************************
name = Servo
Demise Altitude = 76.284401
Debris Casualty Area = 0.000000
Impact Kinetic Energy = 0.000000

*************************************
name = Face Mounted Solar Panel
Demise Altitude = 77.649307
Debris Casualty Area = 0.000000
Impact Kinetic Energy = 0.000000
```

```
************************************
name = Hinge Mounted Solar Panel 1
Demise Altitude = 77.585281
Debris Casualty Area = 0.000000
Impact Kinetic Energy = 0.000000

************************************
name = Hinge Mounted Solar Panel 2
Demise Altitude = 77.640953
Debris Casualty Area = 0.000000
Impact Kinetic Energy = 0.000000

************************************
name = Spring Loaded Hinge
Demise Altitude = 0.000000
Debris Casualty Area = 1.560307
Impact Kinetic Energy = 0.432898

************************************
name = Top Monofilament Guide
Demise Altitude = 0.000000
Debris Casualty Area = 0.403544
Impact Kinetic Energy = 0.007449

************************************
name = Bottom Monofilament Guide
Demise Altitude = 0.000000
Debris Casualty Area = 0.407877
Impact Kinetic Energy = 0.007376

************************************
name = Sidekiq
Demise Altitude = 77.403542
Debris Casualty Area = 0.000000
Impact Kinetic Energy = 0.000000

************************************
name = Daughterboard
Demise Altitude = 77.484444
Debris Casualty Area = 0.000000
Impact Kinetic Energy = 0.000000

************************************
name = Antenna Arm
Demise Altitude = 77.654327
Debris Casualty Area = 0.000000
Impact Kinetic Energy = 0.000000

************************************
name = RF Antenna
Demise Altitude = 77.808846
Debris Casualty Area = 0.000000
Impact Kinetic Energy = 0.000000
```

```
*************************************
name = Antenna Spring
Demise Altitude = 77.450401
Debris Casualty Area = 0.000000
Impact Kinetic Energy = 0.000000

*************************************
name = GPS Board
Demise Altitude = 77.205978
Debris Casualty Area = 0.000000
Impact Kinetic Energy = 0.000000

*************************************
name = Patch Antenna
Demise Altitude = 76.934601
Debris Casualty Area = 0.000000
Impact Kinetic Energy = 0.000000

*************************************
name = CDH Board
Demise Altitude = 76.823715
Debris Casualty Area = 0.000000
Impact Kinetic Energy = 0.000000

*************************************
name = Raspberry Pi
Demise Altitude = 77.551010
Debris Casualty Area = 0.000000
Impact Kinetic Energy = 0.000000

*************************************
name = Horizontal Magnetorquer
Demise Altitude = 72.878189
Debris Casualty Area = 0.000000
Impact Kinetic Energy = 0.000000

*************************************
name = Vertical Magnetorquer
Demise Altitude = 76.282021
Debris Casualty Area = 0.000000
Impact Kinetic Energy = 0.000000

*************************************
name = Aluminum Shielding Tape
Demise Altitude = 77.987602
Debris Casualty Area = 0.000000
Impact Kinetic Energy = 0.000000

*************************************
name = 3M 1205 Kapton Tape
Demise Altitude = 77.983192
Debris Casualty Area = 0.000000
Impact Kinetic Energy = 0.000000
=============== End of Requirement 4.7-1 ===============
```

```
10 21 2019; 13:13:57PM    Science and Engineering - Apogee/Perigee History for a Given Orbit

**INPUT**

    Perigee Altitude = 450.000000 (km)
    Apogee Altitude = 450.000000 (km)
    Inclination = 97.000000 (deg)
    RAAN = 0.000000 (deg)
    Argument of Perigee = 0.000000 (deg)
    Mean Anomaly = 0.000000 (deg)
    Area-To-Mass Ratio = 0.023600 (m^2/kg)
    Start Year = 2019.900000 (yr)
    Integration Time = 4.000000 (yr)

**OUTPUT**

    Plot
```

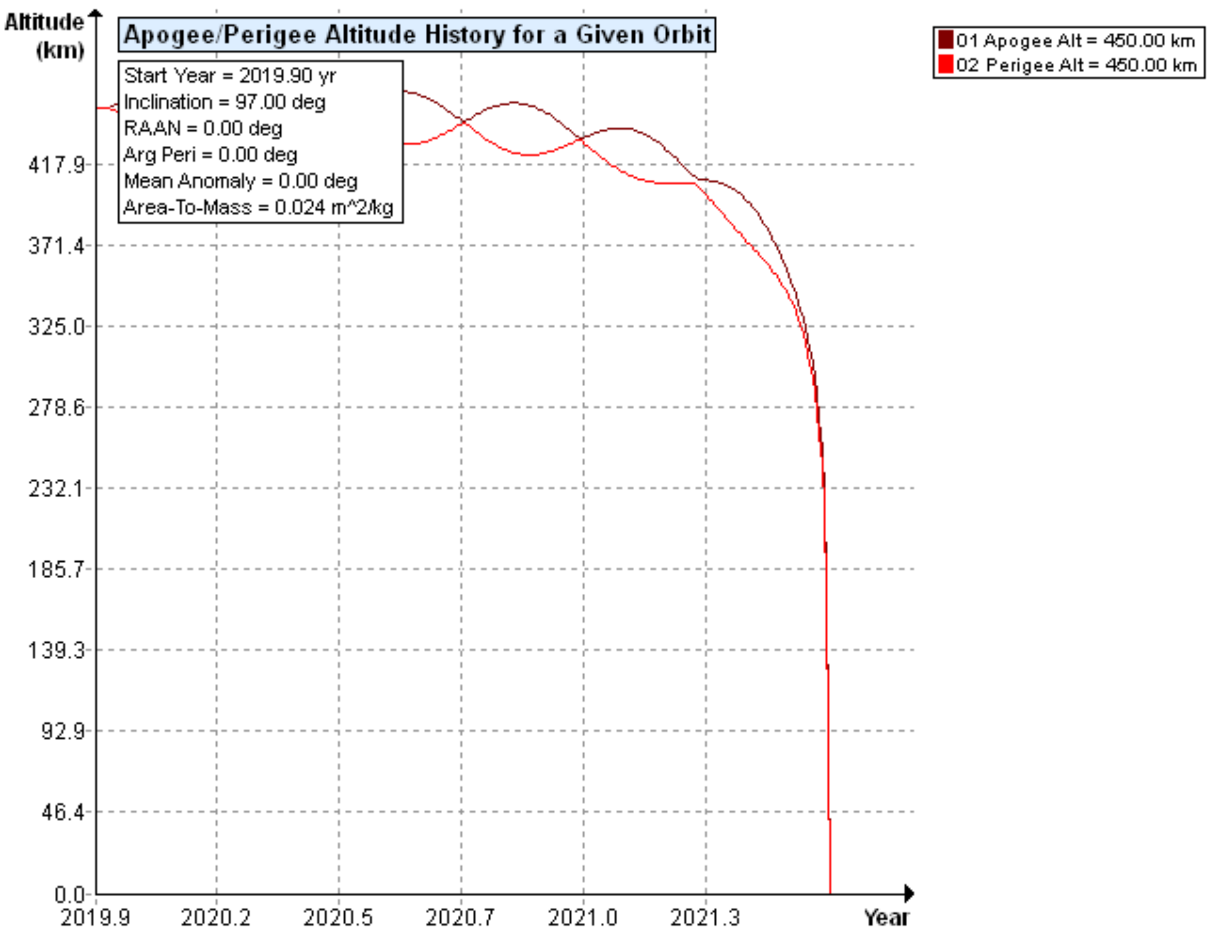

Figure D.1: ARCE-1 Deployed/Nominal Lifetime

```
10 21 2019; 13:14:48PM    Science and Engineering - Orbit Lifetime/Dwell Time

**INPUT**

    Start Year = 2019.000000 (yr)
    Perigee Altitude = 450.000000 (km)
    Apogee Altitude = 450.000000 (km)
    Inclination = 97.000000 (deg)
    RAAN = 0.000000 (deg)
    Argument of Perigee = 0.000000 (deg)
    Area-To-Mass Ratio = 0.023600 (m^2/kg)

**OUTPUT**

    Orbital Lifetime from Startyr = 2.442163 (yr)
    Time Spent in LEO during Lifetime  = 2.442163 (yr)
    Last year of Propagation = 2021 (yr)
    Returned Error Message: Object reentered
```

Appendix E

DAS Inputs: Components and Materials

```
Item Number = 1
name = ARCE-1
quantity = 1
parent = 0
materialID = 8
type = Box
Aero Mass = 0.928832
Thermal Mass = 0.928832
Diameter/Width = 0.100000
Length = 0.110000
Height = 0.052000

name = Structure Lid
quantity = 1
parent = 1
materialID = 8
type = Box
Aero Mass = 0.070000
Thermal Mass = 0.070000
Diameter/Width = 0.032500
Length = 0.100000
Height = 0.010000

name = Structure Case
quantity = 1
parent = 1
materialID = 8
type = Box
Aero Mass = 0.122000
Thermal Mass = 0.122000
Diameter/Width = 0.100000
Length = 0.110000
Height = 0.052000

name = M3 Bolts
quantity = 4
parent = 1
materialID = 54
type = Box
Aero Mass = 0.002000
Thermal Mass = 0.002000
Diameter/Width = 0.005500
Length = 0.058000
Height = 0.005500
```

```
name = M3 Nuts
quantity = 4
parent = 1
materialID = 54
type = Box
Aero Mass = 0.000380
Thermal Mass = 0.000380
Diameter/Width = 0.005500
Length = 0.006350
Height = 0.002400

name = M3 Lock Washers
quantity = 4
parent = 1
materialID = 54
type = Flat Plate
Aero Mass = 0.000475
Thermal Mass = 0.000475
Diameter/Width = 0.008500
Length = 0.008500

name = Separation Spring Plunger
quantity = 2
parent = 1
materialID = 54
type = Cylinder
Aero Mass = 0.000720
Thermal Mass = 0.000720
Diameter/Width = 0.004000
Length = 0.012000

name = Separation Legs
quantity = 2
parent = 1
materialID = 54
type = Box
Aero Mass = 0.001920
Thermal Mass = 0.001920
Diameter/Width = 0.025000
Length = 0.026500
Height = 0.005500

name = Housing Plate
quantity = 1
parent = 1
materialID = 9
type = Box
Aero Mass = 0.013900
Thermal Mass = 0.013900
Diameter/Width = 0.082950
Length = 0.096100
Height = 0.007350
```

```
name = Housing Cap
quantity = 1
parent = 1
materialID = 76
type = Box
Aero Mass = 0.021000
Thermal Mass = 0.021000
Diameter/Width = 0.087350
Length = 0.092950
Height = 0.026600

name = 18650 Battery
quantity = 4
parent = 1
materialID = 8
type = Cylinder
Aero Mass = 0.044700
Thermal Mass = 0.044700
Diameter/Width = 0.018500
Length = 0.069000

name = M2 Bolt
quantity = 6
parent = 1
materialID = 54
type = Cylinder
Aero Mass = 0.000255
Thermal Mass = 0.000255
Diameter/Width = 0.004000
Length = 0.009000

name = M2 Screw
quantity = 4
parent = 1
materialID = 54
type = Cylinder
Aero Mass = 0.000198
Thermal Mass = 0.000198
Diameter/Width = 0.004000
Length = 0.008000

name = Structure Spacer
quantity = 28
parent = 1
materialID = 76
type = Box
Aero Mass = 0.000050
Thermal Mass = 0.000050
Diameter/Width = 0.006350
Length = 0.006350
Height = 0.001700
```

```
name = Separation Switch
quantity = 5
parent = 1
materialID = 76
type = Box
Aero Mass = 0.002000
Thermal Mass = 0.002000
Diameter/Width = 0.020000
Length = 0.020650
Height = 0.006450

name = Servo Arm
quantity = 1
parent = 1
materialID = 8
type = Box
Aero Mass = 0.000300
Thermal Mass = 0.000300
Diameter/Width = 0.014000
Length = 0.015000
Height = 0.003400

name = Servo Screw
quantity = 1
parent = 1
materialID = 54
type = Cylinder
Aero Mass = 0.000200
Thermal Mass = 0.000200
Diameter/Width = 0.004000
Length = 0.008000

name = Servo
quantity = 1
parent = 1
materialID = 5
type = Box
Aero Mass = 0.012000
Thermal Mass = 0.012000
Diameter/Width = 0.022300
Length = 0.030300
Height = 0.012000

name = Face Mounted Solar Panel
quantity = 2
parent = 1
materialID = 23
type = Flat Plate
Aero Mass = 0.016340
Thermal Mass = 0.016340
Diameter/Width = 0.074000
Length = 0.098000
```

```
name = Hinge Mounted Solar Panel 1
quantity = 2
parent = 1
materialID = 23
type = Flat Plate
Aero Mass = 0.020700
Thermal Mass = 0.020700
Diameter/Width = 0.084000
Length = 0.098000

name = Hinge Mounted Solar Panel 2
quantity = 2
parent = 1
materialID = 23
type = Flat Plate
Aero Mass = 0.015700
Thermal Mass = 0.015700
Diameter/Width = 0.066500
Length = 0.098000

name = Spring Loaded Hinge
quantity = 4
parent = 1
materialID = 54
type = Flat Plate
Aero Mass = 0.004000
Thermal Mass = 0.004000
Diameter/Width = 0.019000
Length = 0.031750

name = Top Monofilament Guide
quantity = 1
parent = 1
materialID = 59
type = Box
Aero Mass = 0.001000
Thermal Mass = 0.001000
Diameter/Width = 0.037850
Length = 0.044500
Height = 0.018000

name = Bottom Monofilament Guide
quantity = 1
parent = 1
materialID = 59
type = Box
Aero Mass = 0.001120
Thermal Mass = 0.001120
Diameter/Width = 0.035800
Length = 0.043430
Height = 0.033000
```

```
name = Sidekiq
quantity = 1
parent = 1
materialID = 23
type = Flat Plate
Aero Mass = 0.008000
Thermal Mass = 0.008000
Diameter/Width = 0.030000
Length = 0.050950

name = Daughterboard
quantity = 1
parent = 1
materialID = 23
type = Box
Aero Mass = 0.016000
Thermal Mass = 0.016000
Diameter/Width = 0.034000
Length = 0.084000
Height = 0.010000

name = Antenna Arm
quantity = 2
parent = 1
materialID = 8
type = Flat Plate
Aero Mass = 0.001780
Thermal Mass = 0.001780
Diameter/Width = 0.010150
Length = 0.076800

name = RF Antenna
quantity = 2
parent = 1
materialID = 19
type = Flat Plate
Aero Mass = 0.000400
Thermal Mass = 0.000400
Diameter/Width = 0.007500
Length = 0.025000

name = Antenna Spring
quantity = 2
parent = 1
materialID = 54
type = Cylinder
Aero Mass = 0.000800
Thermal Mass = 0.000800
Diameter/Width = 0.009000
Length = 0.025400
```

```
name = GPS Board
quantity = 2
parent = 1
materialID = 23
type = Flat Plate
Aero Mass = 0.020000
Thermal Mass = 0.020000
Diameter/Width = 0.046000
Length = 0.071000

name = Patch Antenna
quantity = 2
parent = 1
materialID = 23
type = Box
Aero Mass = 0.006000
Thermal Mass = 0.006000
Diameter/Width = 0.017500
Length = 0.017500
Height = 0.011000

name = CDH Board
quantity = 1
parent = 1
materialID = 23
type = Flat Plate
Aero Mass = 0.060000
Thermal Mass = 0.060000
Diameter/Width = 0.089000
Length = 0.095900

name = Raspberry Pi
quantity = 1
parent = 1
materialID = 23
type = Flat Plate
Aero Mass = 0.008000
Thermal Mass = 0.008000
Diameter/Width = 0.031000
Length = 0.068000

name = Horizontal Magnetorquer
quantity = 2
parent = 1
materialID = 46
type = Cylinder
Aero Mass = 0.032000
Thermal Mass = 0.032000
Diameter/Width = 0.008000
Length = 0.090000
```

```
name = Vertical Magnetorquer
quantity = 1
parent = 1
materialID = 19
type = Cylinder
Aero Mass = 0.140000
Thermal Mass = 0.140000
Diameter/Width = 0.097000
Length = 0.097000

name = Aluminum Shielding Tape
quantity = 1
parent = 1
materialID = 5
type = Flat Plate
Aero Mass = 0.001650
Thermal Mass = 0.001650
Diameter/Width = 0.060000
Length = 0.400000

name = 3M 1205 Kapton Tape
quantity = 1
parent = 1
materialID = 76
type = Flat Plate
Aero Mass = 0.001000
Thermal Mass = 0.001000
Diameter/Width = 0.008000
Length = 0.180000
```