



ORBITAL DEBRIS ASSESSMENT REPORT (ODAR) FOR THE ORBITAL TEST BED (OTB) SATELLITE

This document supports the General Atomics Electromagnetic Systems (GA-EMS) Orbital Test Bed Satellite FCC license and has been prepared in accordance with:

NASA Technical Standard NASA-STD-8719.14A (inc. change 1, 25-5-2012) Process for Limiting Orbital Debris

DAS Software version used in analysis V 2.1.1



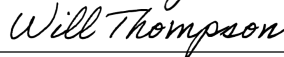
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DOCUMENT REVISION STATUS

Revision Number	Nature of Changes	Edited by	Date
01	Initial issue for comment.	M Brown	Aug '13
02	Addition of Section 7A hazardous materials data. Updated spacecraft design information.	M Brown	Aug '13
03	Updated contacts in 1.1.2, updates to sections 1.1.4, 1.1.7, 2.1.9, 6.1.4, and 6.1.6, figures 2-1 and 2-2 updated, as well as minor grammatical corrections throughout.	T Murphy	Apr '15
04	Updated for inclusion of the drag augmentation device, complete reformatting of the document and content.	T Murphy	Sept '17
05	Updated for heritage of the drag augmentation device. Updated following acquisition of SST-US by GA-EMS, including the OTB satellite and all associated IP.	C Martin	Dec '17

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1 Applicable Documents

AD#	Title	Doc. No.	Issue
AD-1	NASA Technical Standard NASA-STD-8719.14A (inc. Change 1, 25-5-2012) Process for Limiting Orbital Debris	NASA-STD-8719.14A	May 25 th , 2012
AD-2	NASA Debris Assessment Software (DAS)		v. 2.1.1
AD-3	GUIDANCE ON OBTAINING LICENSES FOR SMALL SATELLITES	13-445	March 15 th , 2013
AD-4	Background Information on the Orbital Test Bed Satellite for the FCC	OTB-DOC-000639-02	August 2013

2 Acronyms and Abbreviations

AFRL	Air Force Research Laboratory
CAD	Computer Aided Design
DAS	Debris Assessment Software
DSAC	Deep Space Atomic Clock
EELV	Evolved Expendable Launch Vehicle
EOM	End of Mission
ESPA	EELV Secondary Payload Adapter
FCC	Federal Communications Commission
GA-EMS	General Atomics Electromagnetic Systems
HDRM	Hold Down Release Mechanism
HDRS	Hold Down and Release System
JPL	Jet Propulsion Laboratory
LANL	Los Alamos National Laboratory
LEO	Low Earth Orbit
MSA	Modular Solar Array
N/A	Not Applicable
NASA	National Aeronautics and Space Administration
ODAR	Orbital Debris Assessment Report
OTB	Orbital Test Bed
PDM	Power Distribution Module
RF	Radio Frequency
SERB	Space Experiments Review Board
USAF	United States Air Force

3 PREAMBLE

The Orbital Debris Assessment Report (ODAR) has been prepared by GA-EMS for the Orbital Test Bed (OTB) satellite. It considers in turn each of the requirements for limiting the generation of orbital debris, as specified in the NASA Technical Standard. As such, this document has been prepared in accordance with reference [1] using the following software tool:

- DAS software version 2.1.1 [2].

This document supports GA-EMS' application for an experimental license [3]. Further information on OTB's RF system is provided in reference [4].

4 ODAR SELF ASSESSMENT

Orbital Debris Assessment Report Evaluation: Orbital Test Bed (OTB) Mission.

This provides a summary overview of the compliance against requirements. The details for each requirement are contained within the body of this report. Note: GA-EMS is not responsible for the launch vehicle ODAR.

Reqm't #	Launch Vehicle				Spacecraft			Comments
	Complaint	Not Compliant	Incomplete	Standard Non-Compliant	Compliant or N/A	Not Compliant	Incomplete	
								Note: GA-EMS is not responsible for the launch vehicle ODAR
4.3-1.a	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	x	<input type="checkbox"/>	<input type="checkbox"/>	Compliant - no debris released
4.3-1b	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	x	<input type="checkbox"/>	<input type="checkbox"/>	Compliant - no debris released
4.3-2	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	x	<input type="checkbox"/>	<input type="checkbox"/>	Compliant - no debris released
4.4-1	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	x	<input type="checkbox"/>	<input type="checkbox"/>	Compliant - no credible risk of explosion
4.4-2	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	x	<input type="checkbox"/>	<input type="checkbox"/>	Compliant - end of mission passivation
4.4-3	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	x	<input type="checkbox"/>	<input type="checkbox"/>	N/A - no planned explosions or intentional collisions
4.4-4	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	x	<input type="checkbox"/>	<input type="checkbox"/>	N/A - no planned explosions or intentional collisions
4.5-1	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	x	<input type="checkbox"/>	<input type="checkbox"/>	Compliant - probability of collision 0.00031
4.5-2	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	x	<input type="checkbox"/>	<input type="checkbox"/>	Compliant - probability of collision 0.000506
4.6-1(a)	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	x	<input type="checkbox"/>	<input type="checkbox"/>	Compliant - deorbit 23.76 years from EOM or 25.76 years from launch
4.6-1(b)	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	x	<input type="checkbox"/>	<input type="checkbox"/>	N/A - atmospheric re-entry disposal
4.6-1(c)	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	x	<input type="checkbox"/>	<input type="checkbox"/>	N/A - atmospheric re-entry disposal
4.6-2	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	x	<input type="checkbox"/>	<input type="checkbox"/>	N/A - OTB will be in LEO
4.6-3	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	x	<input type="checkbox"/>	<input type="checkbox"/>	N/A - OTB will be in LEO
4.6-4	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	x	<input type="checkbox"/>	<input type="checkbox"/>	Compliant - significant spacecraft heritage and EOM HDRM heritage
4.7-1	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	x	<input type="checkbox"/>	<input type="checkbox"/>	Compliant - no objects expected to survive re-entry, 1:100000000
4.8-1	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	x	<input type="checkbox"/>	<input type="checkbox"/>	N/A - no tether on OTB

5 PROGRAM MANAGEMENT AND MISSION OVERVIEW

5.1 Mission Owner and Operator

General Atomics Electromagnetic Systems is headquartered in San Diego, at 3550 General Atomics Court, San Diego, CA 92121. GA-EMS is the owner and operator of the OTB spacecraft. Operations will be led out of the GA-EMS Englewood facility at 345 Inverness Drive South, Suite 100, Englewood, Colorado, 80112.

5.2 Responsible Program / Project Team

William Thompson - Project Manager
 Matt Yavorsky - Systems Engineer
 Becky Yoder - Director of Englewood Operations

William.Thompson@ga.com
 Matthew.Yavorsky@ga.com
 Becky.Yoder@ga.com

5.3 Foreign Government or Space Agency Participation

There is no foreign government or space agency participation in the mission.

It is noted that a significant payload hosted by the OTB satellite is the Deep Space Atomic Clock (DSAC) provided by NASA / Jet Propulsion Laboratory (JPL) under sub-contract number 1468935-04 to GA-EMS.

5.4 Mission Schedule Overview

Preliminary Design Review	September 16 th , 2013
Critical Design Review	January 13 th , 2014
Flight Readiness Review	October 24 th , 2017
Proposed Launch Date	June 1 st , 2018

5.5 Brief Description of the Mission

The Orbital Test Bed (OTB) satellite is a GA-EMS owned and operated small LEO satellite that will provide an on-orbit test bed for the demonstration of scientific, research and prototype payloads, subsystems and equipment. A number of hosted payloads are sponsored by external parties:

- 1) Deep Space Atomic Clock (DSAC) – sponsored by the Jet Propulsion Laboratory (JPL) under subcontract No 1468935 (http://www.nasa.gov/mission_pages/tm/clock/).
- 2) iMESA-R – a space weather monitor built by the USAF Academy and sponsored through AFRL Space Experiments Review Board (SERB) (<http://www.usafa.edu/df/dfe/dfer/centers/sparc>).
- 3) Modular Solar Array (MSA) – built by Vanguard and sponsored through AFRL Space Experiments Review Board (SERB).
- 4) Cremains - sponsored by Celestis, Inc.

In addition, the GA-EMS primary payloads are:

- 1) FlexRx – a new spacecraft RF receiver design.
- 2) Radiation Monitor – a new spacecraft radiation monitor device.
- 3) Custom Experimental Solar Panel – a new solar panel technology.

5.6 Launch Vehicle and Launch Site

SpaceX (Falcon Heavy Launch Vehicle), STP-2 (US Air Force). This is the confirmed launch for this mission, on which the OTB satellite is a rideshare partner.

The planned launch site is Space Launch Complex 39A at Cape Canaveral AFS.

5.7 Launch Date and Mission Duration

Launch date from end Q1 2018 onwards, currently manifested for June 2018. Mission duration is 2 years.

5.8 Launch and Deployment Profile

OTB will be released from the STP-2 Falcon Heavy into its intended mission orbit. The orbit will be a 720km +/-18.5 km altitude LEO circular orbit of 24 degrees inclination. OTB will remain in this orbit until the end of the mission.

5.9 Reason for Selection of Operational Orbit

The selection of the operational orbit is primarily based on the timeframe for launch and the available rideshare launch opportunity, coupled with the desired concept of operations for each of the hosted payloads. The combination of the payload objectives means a circular LEO orbit that is sufficiently above the atmosphere to enable a stable platform for the initial tests to be run, particularly for the JPL sponsored DSAC payload. Additionally the stability of this orbit allows for very few attitude maneuvers over the mission lifetime which allows for longer stable periods for science data collection.

5.10 Interaction or Potential Physical Interference with other Operational Spacecraft

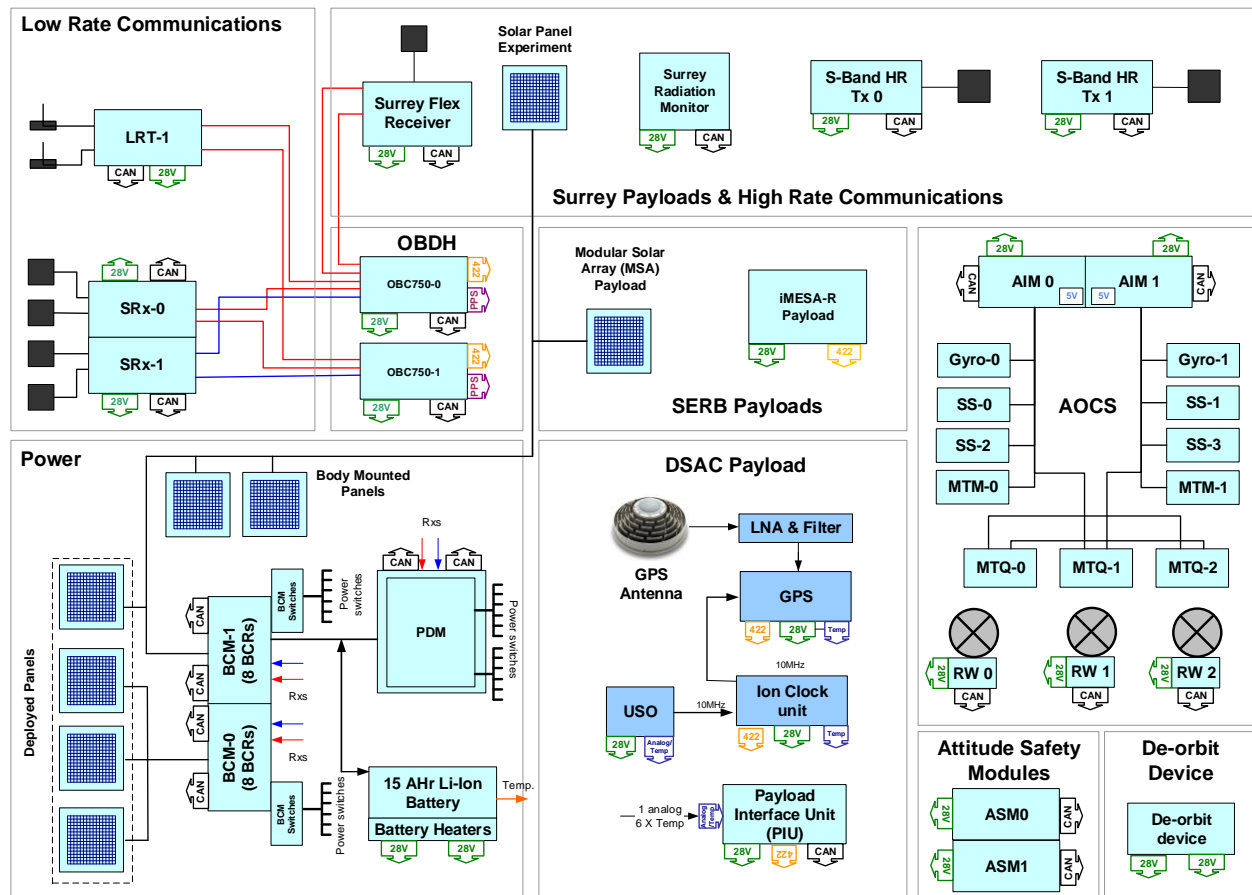
None identified, noting that the low inclination of the orbit places OTB in a different orbit to the ISS, away from the popular sun-synchronous orbits, and the planned large constellations of satellites such as OneWeb.

6 SPACECRAFT DESCRIPTION

6.1 Physical Description of the Spacecraft

The OTB satellite is an evolution of the ESPA compatible SSTL-150 spacecraft, first flown in 2007 for LANL (http://www.sst-us.com/downloads/datasheets/sstl_150-feb-09). OTB is an ESPA class spacecraft with four deployable solar panels. The spacecraft will be operated in a nadir fixed orientation for the mission duration and requires only seasonal attitude maneuvers to adjust for the position of the Sun relative to the orbit.

The avionics suite is based on a heritage set of units with minor updates for mission specific requirements. The OTB platform block diagram is shown in Figure 6-1 and the physical configuration of the OTB satellite including solar arrays, antennae etc. is shown in Figure 6-2 and Figure 6-3.



Acronyms: AOCS - Attitude & Orbit Control System; AIM - Attitude Interface Module; BCM - Battery Charge Module; LNA - Low Noise Amplifier; LRT - Low Rate Transmitter; MTM - Magnetometer; MTQ - Magnetorquer; OBDH - On Board Data Handling; PCM - Power Conditioning Module; RW - Reaction Wheel; SRx - S Band Receiver; SS - Sun sensor USO - Ultra-stable Oscillator.

Figure 6-1: OTB Block Diagram

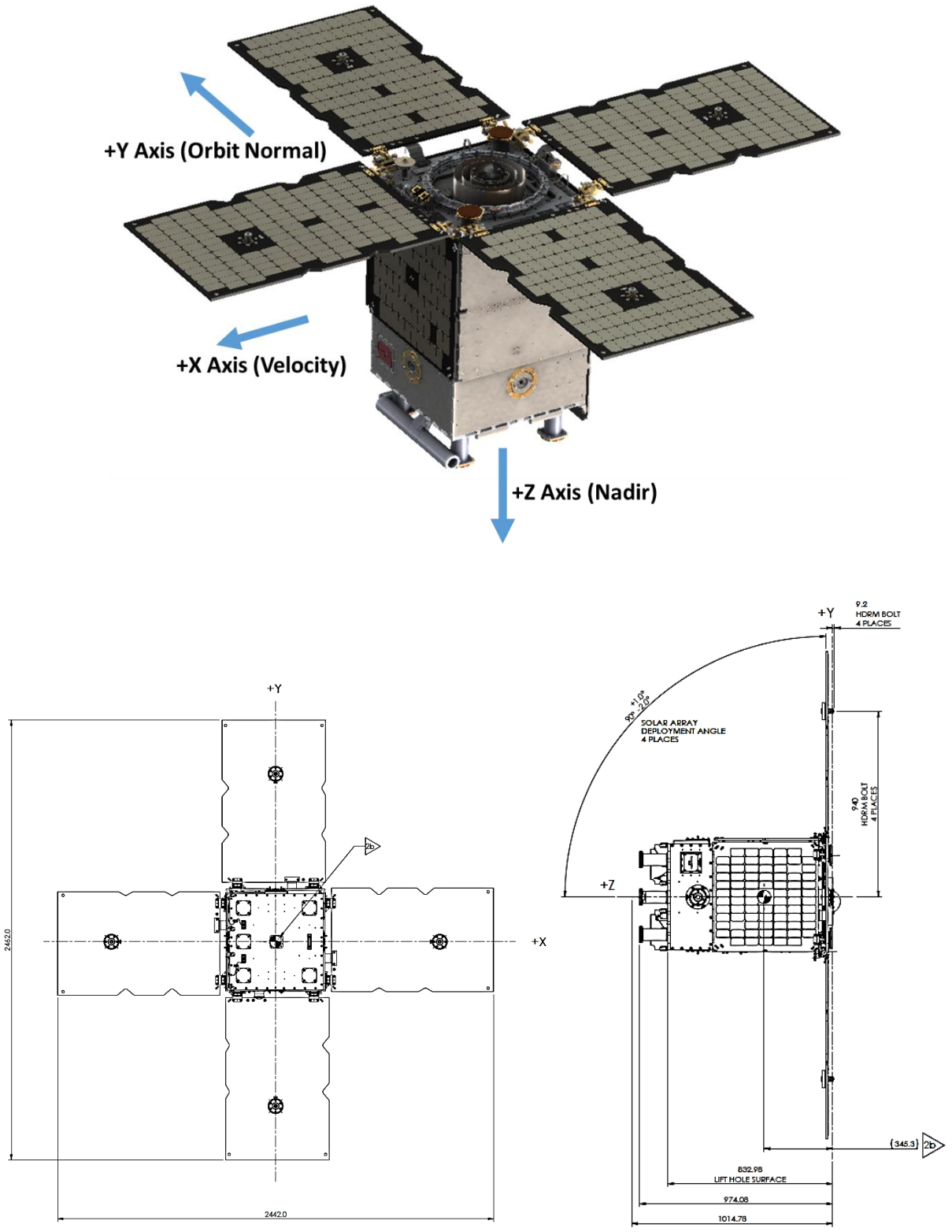


Figure 6-2: OTB Physical Configuration (units in mm)

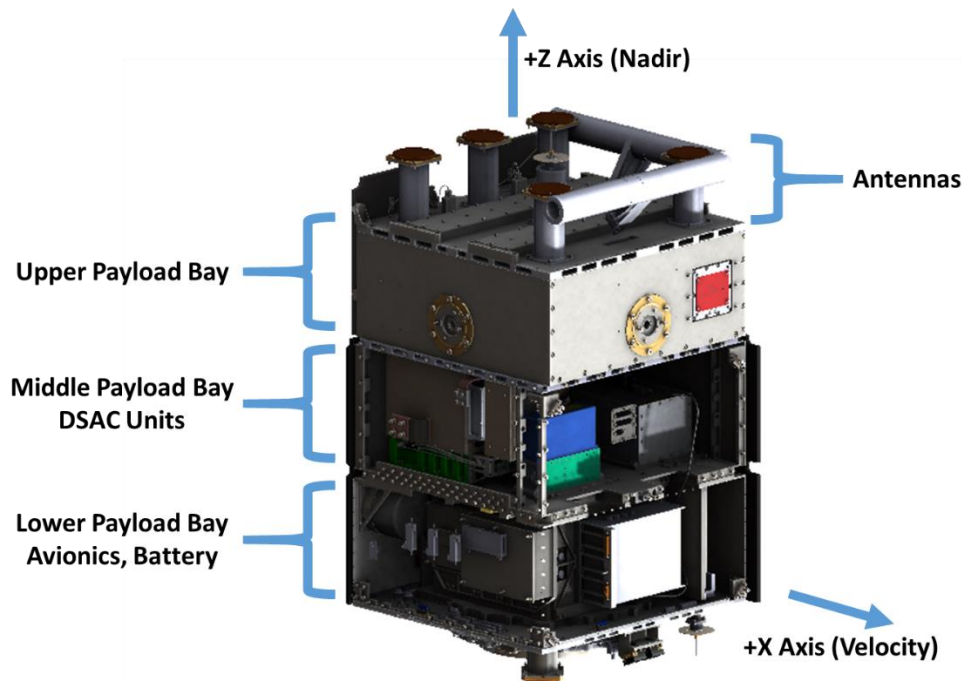


Figure 6-3: Outline of OTB Satellite Configuration (solar panels removed)

6.2 Spacecraft Mass at Launch

The total spacecraft mass of OTB at launch is 138kg.

6.3 Dry Mass of Spacecraft at Launch

The total dry mass of OTB at launch is 138kg.

6.4 Description of Propulsion Systems

There are no propulsion systems within the OTB satellite.

6.5 Fluids

There are no propellant, sealed heat pipes, or pressurization tanks within OTB. Consequently a fluid loading plan / strategy is not required.

OTB will fly the flight proven EnerSys/ABSL 8s10p Lithium-ion battery that employs the SONY 18650HC cell. The contents of this cell are held at 1 bar with all cells having a pressure release device that provides a safe rupture to vent ratio in accordance with recommended NASA safety standards. This battery pack design has flown on over 50 missions including several flown by SSTL.

6.6 Attitude Control

The co-ordinate system of OTB is indicated in Figure 6-2, with the Earth pointing on the Z-axis, the velocity vector along the X-axis and the orbital normal along the Y-axis.

The OTB satellite utilizes three SSTL designed and built heritage reaction wheels (10sp-m-small-satellite-microwheel) for attitude control, together with three SSTL heritage magnetorquers for de-

saturation of the reaction wheels. In addition, sun sensors, gyros and magnetometers also form part of the Attitude & Orbit Control System as shown in the block diagram, Figure 6-1.

6.7 Range Safety or other Pyrotechnic Devices

There are no pyrotechnic devices within the OTB satellite.

6.8 Electrical Generation and Storage System

The OTB bus has four deployable solar panels and four body-mounted panels, of which two are hosted payloads, see Figure 6-2. The power from the solar panels is used to charge a flight proven ABSL 8s10p Lithium-Ion battery manufactured by ABSL (<http://www.enersys.com/>) which provides an unregulated power supply to downstream subsystems. The system and battery have been designed in order to complete the mission even if there is a string failure on the battery or the solar arrays.

Power is supplied from the battery to the Power Distribution Module (PDM) units. The PDM controls the switching of the 28V unregulated battery supply to spacecraft subsystems.

6.9 Other Sources of Stored Energy

The deployable solar panels are deployed using the SSTL hold down and release system (HDRS, see section 7.1). No debris is produced during solar panel deployment.

6.10 Radioactive Materials

There are no radioactive materials onboard the OTB satellite.

7 ASSESSMENT OF SPACECRAFT DEBRIS RELEASED DURING NORMAL OPERATIONS

7.1 Objects Expected to be released from the Spacecraft any time after Launch

There are no intentional releases from OTB; all deployment systems are self-contained entities designed not to release debris into the environment.

The deployment systems are:

1) SSTL Hold Down and Release System

The Hold Down and Release System (HDRS) for the deployable solar panels utilizes captive devices on both sides of the interface (retention of bolt and springs) and as such does not generate debris. This system has been used successfully on previous SSTL spacecraft and as such is TRL9 Flight Proven.

2) Planetary Systems Corporation Separation System ('Lightband')

Planetary Systems Corporation states within their 2000785 Rev C User's Manual for Mark II Lightband, 2nd April 2013 (section 3, point 5): Non-pyrotechnic. *The Lightband generates no debris on or after separation' and is a TRL 9 system.* <http://www.planetarysystemscorp.com/#!/products/mark-ii-motorized-lightband>.

3) Drag Augmentation Device

The drag augmentation device is based on flight proven technologies and components. This system is further explained in section 10.

7.2 Spacecraft Compliance with Requirements 4.3-1 and 4.3-2

Requirement 4.3-1: Debris passing through LEO - released debris with diameters of 1mm or larger:

- a) Requirement 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 (Requirement 56398).

Compliant – no debris released during normal operations.

- b) Requirement 4.3-1b: The total object-time product shall be no larger than 100 object-years per mission (Requirement 56399). The object-time product is the sum of all debris of the total time spent below 2,000 km altitude during the orbital lifetime of each object. (See section 4.3.4.2 for methods to calculate the object-time product.)

Compliant – no debris released during normal operations.

Requirement 4.3-2: Debris passing near GEO: For missions leaving debris in orbits with the potential of traversing GEO (GEO altitude +/- 200 km and +/- 15 degrees latitude), 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 (Requirement 56400). DAS will be used to assess compliance against these requirements.

Compliant – no debris released during normal operations.

8 ASSESSMENT OF SPACECRAFT INTENTIONAL BREAKUPS AND POTENTIAL FOR EXPLOSIONS

8.1 Potential Causes of Spacecraft Breakup during Deployment and Mission Operations

The spacecraft is a heritage design and has undergone rigorous structural acceptance testing during qualification. There are no pressurized systems on board, and no propulsion system.

OTB will fly the flight proven ABSL 8s10p Lithium-ion battery that employs the commercial SONY 18650HC cell. The contents of this cell are held at 1 bar with all cells having a pressure release device that provides a safe rupture to vent ratio in accordance with recommended NASA safety standards.

No credible potential causes of spacecraft breakup during deployment or mission operations are foreseen.

8.2 Summary of Failure Modes and Effects Analyses of all Credible Failure Modes which may lead to an Accidental Explosion

The only device that stores a sufficient amount of energy to cause an accidental explosion is the flight proven, heritage ABSL 8s10p battery. This unit has flown on over 50 spacecraft to date and the SONY 18650HC cell that it employs has accrued more than 50,000 cell years in orbit without any safety events in space. Before launch, the battery is charged and then disconnected from the spacecraft. It is only connected to the spacecraft power system upon separation from the launch vehicle so it presents no credible risk during the launch phase of the mission.

Upon separation and during operations, the battery will be cycled at a benign depth of discharge of less than 15% with an end of charge voltage of 32.8V. The power system is a heritage design and has battery charge and discharge safety functionality that has been proven on numerous other SSTL spacecraft including CFESat, RapidEye, UK-DMC-2, Deimos and exactView-1.

There are three possible failure modes for the battery:

- 1) Overcharge of Lithium-ion batteries above the recommended maximum end of charge voltage of 33.6V could result in thermal runaway. To prevent this, the battery voltage is constantly monitored by the power subsystem and charging is halted if this voltage is exceeded. This functionality has been tested and verified using the OTB power subsystem. As a second level of protection, in the event of the failure of this safety circuitry, the ABSL 8s10p cells contain internal protection devices that result in an open circuit shutting down the entire battery. This functionality has been demonstrated via a number of ground tests.
- 2) Short circuit of Lithium-ion batteries can result in very high current draw that leads to heating and could invoke thermal runaway. To prevent this, the spacecraft has fused or switched power lines to all components so that high current draw effects are halted before the battery can be affected. As an additional level of protection, in the event of fuse failure, the ABSL 8s10p cells carry short circuit protection devices that detect a rise in temperature and increase the internal resistance reducing current flow mitigating a rise in temperature.
- 3) Over discharge of the ABSL 8s10p, where the battery is taken below the minimum recommended operating voltage of 20V, has been proven by test to degrade battery performance but not pose a safety risk. Over-discharge tests where ABSL 8s10p cells have been driven to negative voltage have been shown to result in a safe failure with cells effectively becoming resistors. In addition, the power system of the satellite will switch off below 23V to limit the discharge of the battery below this point.

The SONY 18650HC cells in the ABSL 8s10p battery have had thermal runaway testing performed, which showed that in the event of a single cell thermal runaway with other cells in healthy conditions propagation does not occur. As such, even thermal runaway of a single cell (which is protected against through the mechanisms described above) has not been shown to cause an explosion.

In summary, there are no credible failure modes which would cause an accidental explosion and the battery design has been sufficiently tested to insure that thermal runaway propagation does not occur.

8.3 Detailed Plan for any Designed Spacecraft Breakup

There are no intentional breakups – explosions nor intentional collisions – planned.

8.4 List of Components which are Passivated at EOM

At End of Mission (EOM), all units except the power system and the RF receivers will be turned off. The battery will continue to charge and discharge at a very low depth of discharge to the nominal end of charge level set via telecommand. The design of the heritage power system is such that the battery cannot be disconnected from the power system at EOM.

Reaction wheels are stopped in a controlled manner as part of EOM operations and switched off.

An end of charge voltage of 31V will be selected (the minimum possible) that will result in the battery being at a state of charge < 50% and minimize the energy available for any failure event. Ground and in-orbit life test data indicate an expected graceful degradation of the battery with effective battery capacity reducing over time, leading to a benign state through the absence of useful capacity. With the end of charge voltage set to 31 V any additional charging capacity will be dissipated from the radiator surface.

8.5 Rationale for Items which cannot be Passivated due to their Design

Please see response to section 8.4 on the battery. The battery cannot be completely passivated (discharged to 0% state of charge and disconnected from the power system) due to heritage system design and power system which have successfully flown on numerous SSTL missions.

8.6 Spacecraft Compliance with Requirements 4.4-1 through 4.4-4

Requirement 4.4-1: Limiting the risk to other space systems from accidental explosions during deployment and mission operations while in orbit about Earth or the Moon: For each spacecraft and launch vehicle orbital stage employed for a mission, the program or project shall demonstrate, via failure mode and effects analyses or equivalent analyses, that the integrated probability of explosion for all credible failure modes of each spacecraft and launch vehicle is less than 0.001 (excluding small particle impacts) (Requirement 56449).

Compliant – GA-EMS see no credible risk of spacecraft explosion (caused by the spacecraft itself without external impact) during launch, nominal operations and the time between EOM and Earth re-entry (Refer to section 8.1).

Requirement 4.4-2: Design for passivation after completion of mission operations while in orbit about Earth or the Moon: Design of all spacecraft and launch vehicle orbital stages shall include the ability and a plan to deplete all on-board 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 (Requirement 56450)

Compliant.

Requirement 4.4-3: Limiting the long-term risk to other space systems from planned breakups: 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 (Requirement 56453). For example, if the debris fragments greater than 10cm decay in the maximum allowed 1 year, a maximum of 100 such fragments can be generated by the breakup.
- b) Not generate debris larger than 1 mm that remains in Earth orbit longer than one year (Requirement 56454).

Not applicable – OTB will not undertake any planned explosions or intentional collisions.

Requirement 4.4-4: Limiting the short-term risk to other space systems from planned breakups: 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 10^{-6} (Requirement 56455).

Not applicable – OTB will not undertake any planned explosions or intentional collisions.

9 ASSESSMENT OF SPACECRAFT POTENTIAL FOR ON-ORBIT COLLISIONS

9.1 Probability of Collision with Space Objects > 10 cm in diameter

The NASA DAS software [2] was used to assess compliance of the OTB spacecraft with Requirement 4.5-1. For this analysis, the average area-to-mass ratio was used. This represents the spacecraft following the deployment of the drag augmentation devices and in tumble. In order to calculate this the maximum cross-sectional area was identified, and with the two orthogonal areas, the average cross-sectional area was calculated using the accepted NASA formula. (Note that the maximum cross-sectional area, with the drag augmentation device deployed, is not orthogonal to the plane of the deployed solar panels.) The resulting area-to-mass ratio is calculated to be 0.0329m²/kg. The mission duration of 2 years was listed as this is the controlled mission lifetime. The DAS software takes into account the full orbital lifetime until deorbit.

The probability of collision with large objects was calculated to be 0.00031 during the orbital lifetime (Figure 9-1), which is compliant with the requirement. Additional analysis was performed to confirm that the deployment of the drag augmentation device does not increase the probability of collision to a level greater than that if no device was used.

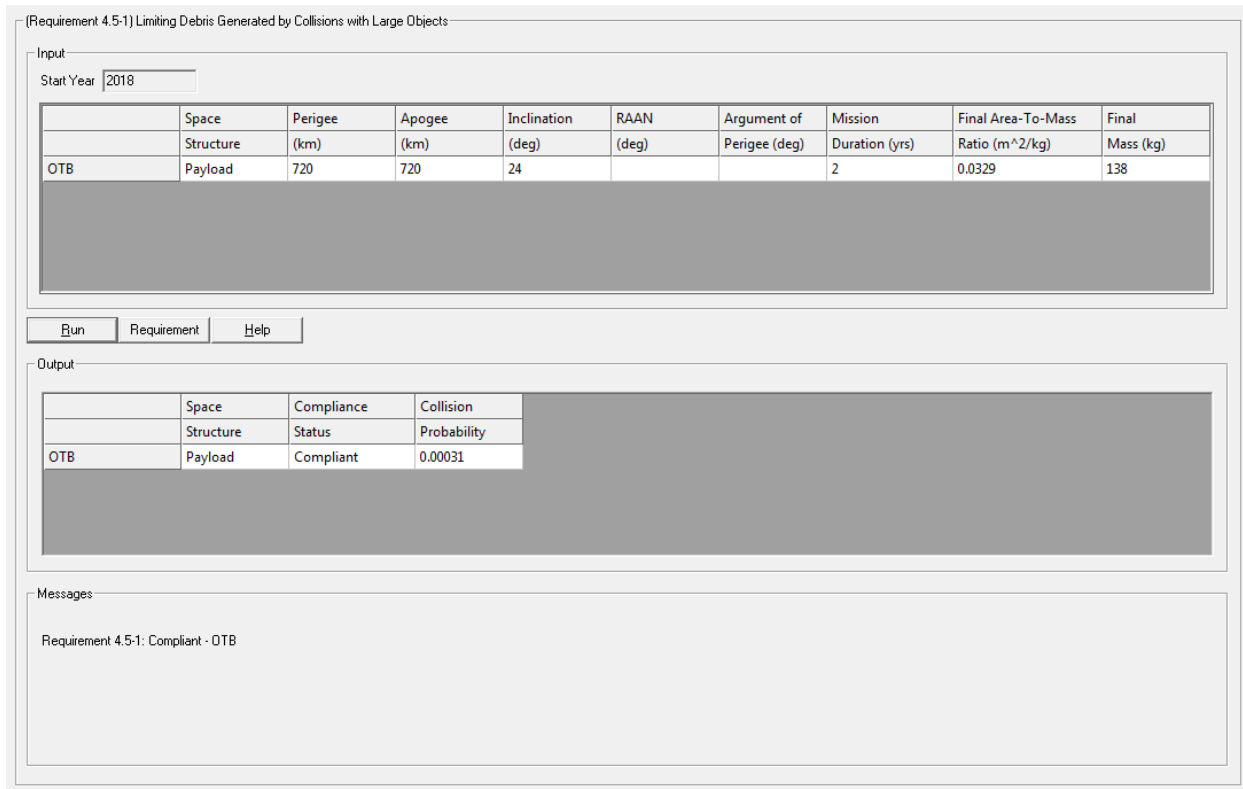


Figure 9-1: OTB DAS output for Collisions with Large Objects

9.2 Probability of Collision with Space Objects of sufficient size to prevent Post-Mission Disposal

The units listed in Table 9-1 are critical to completing post-mission disposal activities. Each unit is listed with its individual Probability of Penetration value, as calculated by DAS [2]. The OTB spacecraft will enter the EOM phase of operations in the nominal, nadir-pointing attitude, and it will remain nadir-

pointing until the deorbit device is deployed. The critical surface of the units will therefore be in the plane of the direction of motion.

During the EOM phase, the flight computer will receive the deorbit command from the ground through the S-band patch antennas and the receiver. The onboard computer will then command the deorbit device to deploy, which will begin to deorbit the spacecraft. For these actions to occur, the power system must also be active.

An extra level of protection to the critical units is provided by our standard dual-redundant design approach. Each of the units listed in Table 9-1, aside from the deorbit device, are redundant. In the unlikely event of a unit being damaged during the operational phase, the deorbit device could still be deployed by the redundant components. See section 10 for further discussion.

Table 9-1: Critical Units/Surfaces

Critical Surface	Probability of Penetration
Drag Augmentation HDRM	0.000000
OBC	0.000067
PDM	0.000014
Battery	0.000010
RF Tray	0.000012
Antennas	0.000405
TOTAL PROBABILITY OF PENETRATION	0.000508

The total probability of post-mission disposal failure is 0.000508, which is compliant with the requirement.

9.3 Spacecraft Compliance with Requirements 4.5-1 and 4.5-2

Requirement 4.5-1: Limiting debris generated by collisions with large objects when operating in Earth orbit: For each spacecraft and launch vehicle orbital stage in or passing through LEO, the program or project shall demonstrate that, during the orbital lifetime of each spacecraft and orbital stage, the probability of accidental collision with space objects larger than 10 cm in diameter is less than 0.001 (Requirement 56506).

Compliant – the probability of collision with large objects was calculated by DAS [2] to be 0.00031 during the orbital lifetime, which is compliant with the requirement, Figure 9-1.

Requirement 4.5-2: Limiting debris generated by collisions with small objects when operating in Earth or lunar orbit: For each spacecraft, the program or project shall demonstrate that, during the mission of the spacecraft, the probability of accidental collision with orbital debris and meteoroids sufficient to prevent compliance with the applicable post mission disposal requirements is less than 0.01 (Requirement 56507).

Compliant – the probability of accidental collision with orbital debris and meteoroids sufficient to interfere with post-mission disposal was calculated by DAS [2] to be 0.000508, which is compliant with the requirement, Table 9-1.

10 ASSESSMENT OF SPACECRAFT POSTMISSION DISPOSAL PLANS AND PROCEDURES

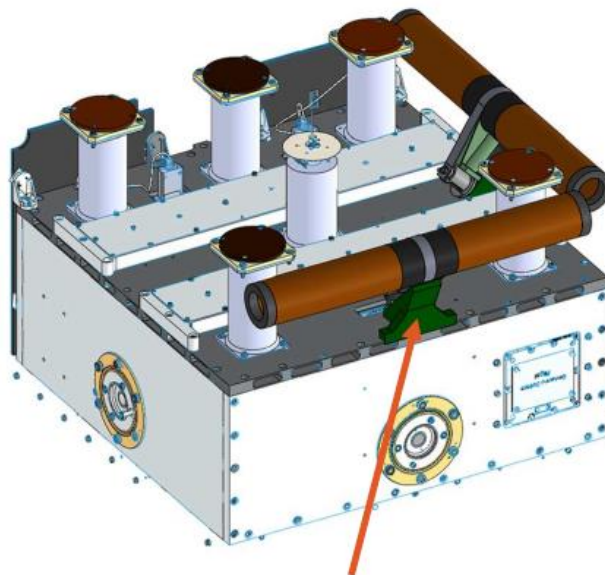
10.1 Spacecraft Disposal

The spacecraft will deorbit naturally by atmospheric re-entry following the deployment of a drag augmentation device. This device has been designed in order to increase the average cross-sectional area of the satellite at the end-of-mission (EOM) to deorbit OTB while utilizing simple mechanical principles and the “KISS” philosophy – focusing on the simplicity and robustness of the device.

OTB will carry a drag augmentation device that is based on the following on-orbit demonstrated technologies:

- Carbon fiber slit-tube booms – successfully demonstrated on orbit through the Roll Out Solar Array (ROSA) mission and also a sub-orbital launch of a NASA Terrier Improved Malemute sounding rocket.
- Aerospace rated Kapton materials featuring rip-stop features – typical for thermal blankets on satellites and common in the industry.
- Industry standard Frangibolt release mechanisms – since 1994, the Frangibolt has been qualified and used on numerous space applications.

The drag augmentation device will be stowed on the Earth facing facet of the spacecraft, shown in Figure 10-1, for launch as well as the expected mission duration of 2 years. At EOM, the device will be activated by sending an Arm and Fire command set. Deployment of the drag augmentation device only requires that the Frangibolt releases; the rolled carbon fiber slit-tube’s stored mechanical energy ensures deployment upon release. With the drag augmentation device deployed the spacecraft can then be passivated for final disposal. The spacecraft does not need to be controlled through re-entry as the system has been designed to deorbit within the required period in a random tumbling orientation.



Mounts, unique for each plane

Figure 10-1: Stowed Drag Augmentation Device

Drag Augmentation Device

The drag augmentation device uses composite slit-tube booms manufactured by ROCCOR, benefitting from their extensive experience with this technology. This boom technology is combined with the industry standard TiNi Frangibolt release mechanism and heritage Dunmore materials to effectively increase the drag cross-sectional area of OTB at EOM. The stowed configuration of the drag augmentation device is shown in Figure 10-2.

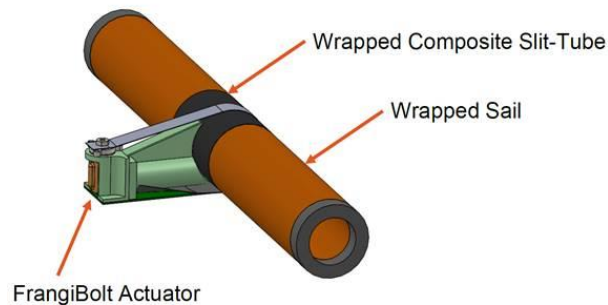


Figure 10-2: Stowed Drag Augmentation Device (detailed view)

Frangibolts operate through the expansion of a shape memory alloy that increases the preload of a specially designed titanium bolt to the point of fracture at a designed fracture point. The Frangibolt is implemented so that both sides of the restraint bolt are retained by the system, the threaded section in the base of the drag augmentation device and the head of the bolt remains connected to a hold-down strap that is also connected to the base of the drag augmentation device. At no time is there a potential for the fractured bolt to be released as debris.

Upon activation, the Frangibolt will release the constrained wrapped composite slit tube allowing its stored energy to unroll the entire wrapped composite material, without need for any active or electrically-powered components, or mechanical springs; in other words allowing it to unroll naturally. There are no further mechanical or electrical elements to the device, and no additional commands required to fully deploy the drag augmentation device (as illustrated by Figure 10-3). The deployed state of the system is shown in Figure 10-4. Each deployed device will be 0.45 m wide and 3.8 m long.

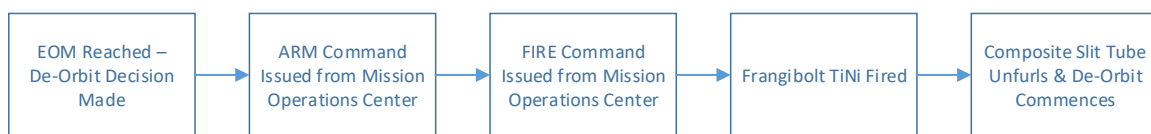


Figure 10-3: Drag Augmentation Device Activation Diagram

The design is based upon proven technologies and components (shown in Table 10-1) and the development and testing of the device is subject to the same rigor as every other subsystem on the satellite. The utilization of these technologies for a drag augmentation device represents a simple and robust method to help address the growing concern of EOM disposal.

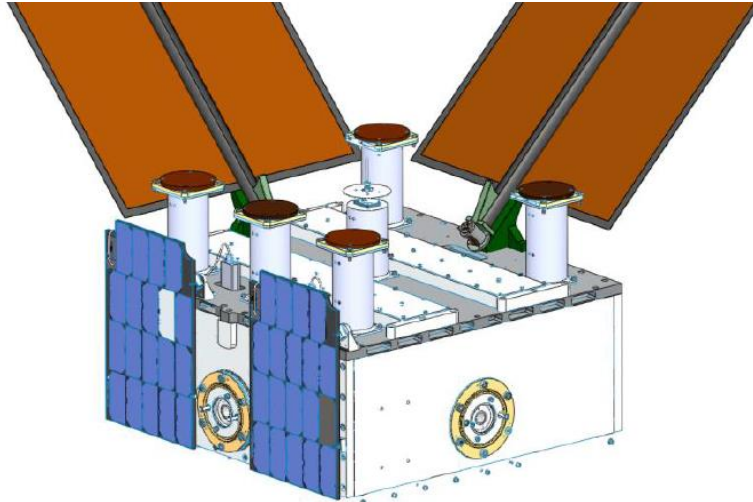


Figure 10-4: Deployed State of Drag Augmentation Device

Table 10-1: Drag Augmentation Device Technology TRL

Key Technology	Maturity
Composite Slit-Tube Boom	TRL-9
Mylar or Kapton Sail (Dunmore)	TRL-9
Hold Down Release Mechanism, HDRM (TiNi Frangibolt)	TRL-9

Composite slit-tube boom technology is used in a wide variety of on-orbit applications, both current and planned. Examples include small satellite de-orbit devices (RODEO), radar booms, antenna booms, solar array booms. In comparison to the uses listed here, the application in the OTB deorbit device is very simple, being shorter, with no hinges, and not supporting the mass of a full solar array or antenna.

The Roll-Out DeOrbiting (RODEO) device boom was self-deploying, meaning the stored strain energy of the packaged boom provided the necessary deployment force; as per the device being implemented on OTB. RODEO was ultimately successfully demonstrated through a flight experiment conducted as part of the Colorado Space Grant Consortium's (COSGC) RocketSat-8 program (<http://es mats.eu/amspapers/pastpapers/pdfs/2014/turse.pdf>). During the flight experiment the deployment was slower than expected but continued in short bursts until reaching full deployment. It was determined, and verified through on-ground tests, that this was caused by moisture saturation in the composite boom, plasticizing the resin and reducing the stiffness and stored strain energy of the boom. The effect is completely reversible and the boom would deploy as expected after drying out—the multiple starts and stops observed in the flight experiment indicated that as the outer layers of the boom dried out, the boom was gradually able to reach full deployment. Moisture absorption will not be an issue for the OTB satellite mission since the boom will have ample time to completely dry out in the hard vacuum of space prior to deployment at end-of-mission life.

System Reliability

The drag augmentation system has been designed to incorporate multiple redundancies as well as high reliability components, proven in orbit, in order to ensure the effective disposal of the spacecraft at EOM. This redundancy is incorporated at three levels:

- Activation
- Release
- Performance

Activation redundancy is achieved through the spacecraft platform design, including the electrical power system and switch architecture. The deployment of the drag augmentation device is controlled by the power system through a system of series switches. This allows for Arm and Fire commanded switches to ensure that the deployment only takes place when commanded at EOM. These Arm and Fire switches are also configured so that each pair has a redundant circuit in the event of a failure of one of the sets. The commanding of these switches also contains a built in redundancy in that the commands come directly from the onboard computer (OBC), but in the event of a critical system failure with the OBC the switches can still be commanded simply through the RF system via emergency, low-level commanding.

The redundancy inherent in the platform system design for the subsystems required to activate the drag augmentation device is illustrated in Figure 10-5. There are no single point failures present in the platform elements required for activation, with at least one-layer of redundancy. This is our standard design approach, used on numerous missions, which have demonstrated 100% mission success over the last 15 years.

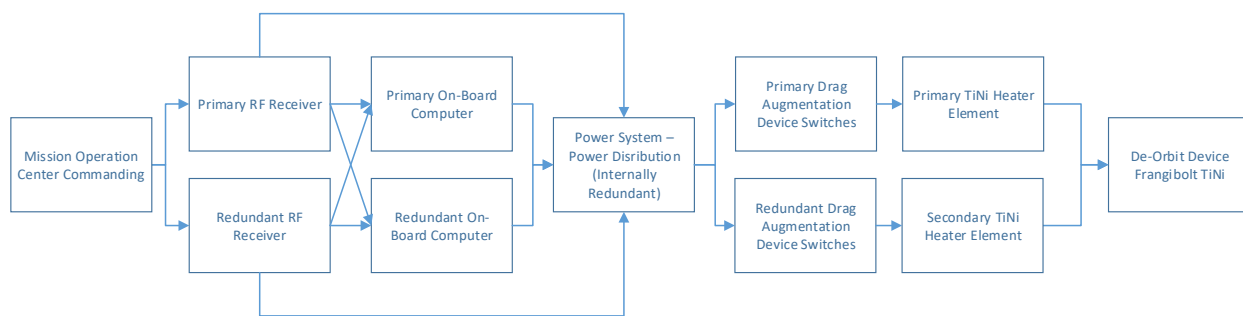


Figure 10-5: Drag Augmentation Redundancy Diagram

Release redundancy is inherit to the TiNi Frangibolts through the use of primary and secondary heater circuits. In the event that the primary heating element is damaged or is unable to release the Frangibolt the secondary heating circuit can be used. This ensures that the Frangibolt successfully deploys.

The drag augmentation system has also been designed to have inherit performance redundancy by being designed to deorbit the system well within the required timeline, as described below. This additional margin provides further confidence for uncertainty in atmospheric models.

Figure 10-6 shows the lifetime plot for the OTB satellite after deployment of the drag augmentation device at end of mission. Assuming a launch date of 2018, with a 2 year mission lifetime, OTB will deorbit within 25.76 years from launch (less than the required 30 years for total on-orbit time). Note that the calculation assumes random tumble of the OTB satellite after deployment.

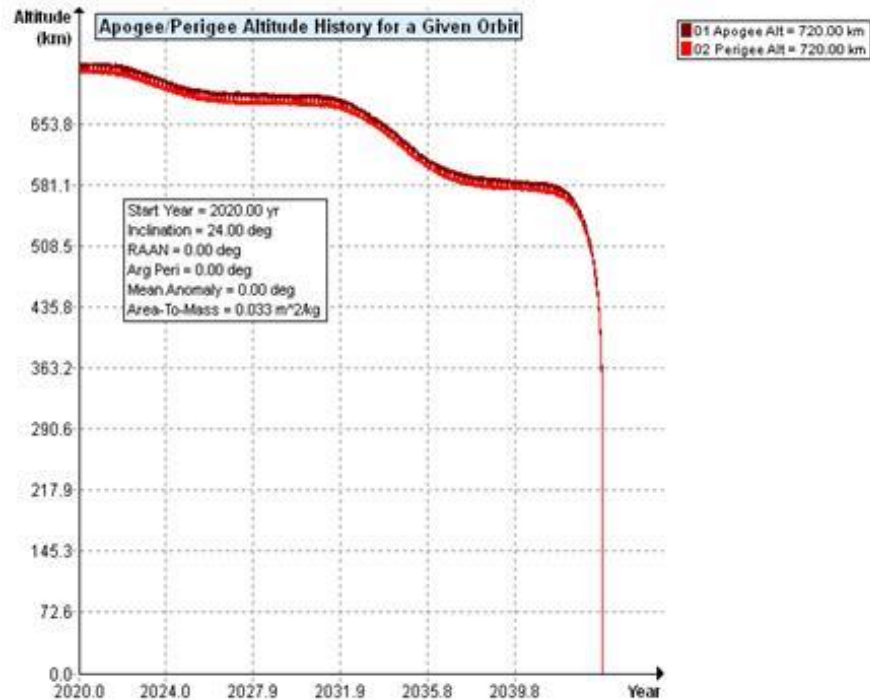


Figure 10-6: Orbital Apogee/Perigee Altitude

10.2 Systems or Components required to accomplish Post-Mission Disposal

Section 10.1 outlines the required components for successful post mission disposal. Section 8.4 details those devices passivated at EOM.

Note that the end-of-mission operational plan is to deploy the de-orbit device and then passivate the satellite. The commands to passivate can be received by the satellite when it is in any orientation, due to the placement of the receive antennas. This antenna placement is a requirement for spacecraft early operations, when initially separated from the launch vehicle in a tumbling state.

10.3 Spacecraft Maneuvers required to accomplish Post-Mission Disposal

No maneuvers are required for the proper deployment of the drag augmentation device.

10.4 Area-to-Mass Ratio after Post-Mission Disposal

Spacecraft Mass: 138 kg
 Cross-sectional Area: 4.545 m²
 Area to mass ratio: 0.0329 m²/kg

The probability of collision with large objects was calculated by DAS [2] to be 0.00031 during the orbital lifetime, please see section 9.1 for further analysis.

10.5 Spacecraft Compliance with Requirements 4.6-1 through 4.6-4

Requirement 4.6-1: Disposal for space structures in or passing through LEO: A spacecraft or orbital stage with a perigee altitude below 2,000 km shall be disposed of by one of the following three methods: (Requirement 56557)

- a) Atmospheric reentry option:

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

The OTB satellite reentry is compliant using reentry option “a”.

Requirements 4-6-1(b) and 4-6-1(c) are not applicable.

Requirement 4.6-2: Disposal for space structures near GEO: A spacecraft or orbital stage in an orbit near GEO shall be maneuvered at EOM to a disposal orbit above GEO with a predicted minimum perigee of GEO +200 km (35,986 km) or below GEO with an apogee of GEO - 200 km (35,586 km) for a period of at least 100 years after disposal (Requirement 56563).

Not applicable. OTB will be in LEO.

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

- a. A spacecraft or orbital stage 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 (Requirement 56565).
- b. A spacecraft or orbital stage shall not use nearly circular disposal orbits near regions of high value operational space structures, such as between 19,200 km and 20,700 km (Requirement 56566).

Not applicable. OTB will be in LEO.

Requirement 4.6-4: Reliability of post mission disposal operations in Earth orbit: NASA space programs and projects shall ensure that all post mission disposal operations to meet Requirements 4.6-1, 4.6-2, and/or 4.6-3 are designed for a probability of success as follows: (Requirement 56567)

- a) Be no less than 0.90 at EOM.
- b) For controlled reentry, the probability of success at the time of reentry burn must be sufficiently high so as not to cause a violation of Requirement 4.7-1 pertaining to limiting the risk of human casualty.

SSTL has a long heritage of successful missions, 49 spacecraft launched to date with over 500 years collectively on orbit, in part due to the multiple points of redundancy built into every mission design with a design life of 5 years or more. The drag augmentation device, Frangibolt based, has a minimum reliability of 0.99999 – this is the supplier published reliability for the TiNi Frangibolt and is the industry standard with 20 years of space heritage. The OTB satellite is an “SSTL-150 ESPA” which is listed in the NASA Rapid III catalogue; it has a Ps of 92%. (Noting that SSTL have not had a mission failure on-orbit in over 15 years, and none with this class of satellite.) This gives us confidence that OTB will be able to complete its 2 year mission and successfully deploy the drag augmentation devices at EOM, with a $P_s = 0.91999$.

4.6.4b N/A – OTB does not have a controlled re-entry.

11 ASSESSMENT OF SPACECRAFT REENTRY HAZARDS

11.1 Spacecraft Components by Size, Mass, Material, Shape, and Original Location

Table 11-1 summarizes the major components of the spacecraft, which were input into the DAS software [2]. According to the DAS user's guide, the main structure of a spacecraft is assumed to break apart at an altitude of 78 km, exposing the first level of "child" objects to atmospheric forces. All of the objects in the table below are of this first level, and make up the mass of the spacecraft which enters the atmosphere.

Table 11-1: Modelled Components of the Spacecraft

No. (refer to figures)	Object Name	Qty	Material	Shape	Mass (kg)	Dimensions (m) Box: W x L x H Plate: W x L Cylinder: Diameter x L
1	OTB	1	Aluminum	Box	138	0.574 x 0.859 x 0.574
2	Deployed Solar Panel	4	Aluminum	Flat Plate	2.22	0.580 x 0.934
3	Body Solar Panel	3	Aluminum	Flat Plate	1.04	0.55 x 0.55
4	DSAC Ion Clock	1	Aluminum	Box	16.1	0.260 x 0.285 x 0.229
5	DSAC USO	1	Aluminum	Box	1.52	0.2 x 0.24 x 0.11
6	DSAC GPS Receiver	1	Aluminum	Box	3.6	0.18 x 0.25 x 0.12
7	DSAC GPS Antenna	1	Aluminum	Cylinder	0.7	0.242 x 0.090
8	Top Bay Structural Panels	4	Aluminum	Flat Plate	1.8	0.230 x 0.580
9	iMESA-R (SERB Payload)	1	Aluminum	Box	1.14	0.105 x 0.118 x 0.035
10	Stack Structural Panels	4	Aluminum	Flat Plate	1.08	0.232 x 0.358
11	Radiator Panels	1	Aluminum	Flat Plate	2.99	0.580 x 0.700
12	Earth Facing Panel	1	Aluminum	Flat Plate	2.54	0.543 x 0.543
13	DSAC Bay Structure Panels	2	Aluminum	Flat Plate	1.16	0.236 x 0.543
14	Antennas	7	Aluminum	Box	0.25	0.082 x 0.082 x 0.067
15	AOCS Actuators	3	Aluminum	Box	0.5	0.2 x 0.2 x 0.2
16	Battery	1	Aluminum	Box	4.00	0.159 x 0.221 x 0.068
17	AOCS Sensors	8	Aluminum	Box	0.35	0.15 x 0.15 x 0.15
18	Harness	1	Copper	Flat Plate	10.00	0.2 x 0.4
19	Nanotray	2	Aluminum	Box	3.00	0.135 x 0.190 x 0.055
20	Top Bay Floor Plate	1	Aluminum	Flat Plate	3.86	0.547 x 0.547
21	AIM (Custom Tray)	1	Al 7075-T6	Box	7.679	0.515 x 0.547 x 0.037
22	S-Band Tx/Rx	1	Aluminum	Box	2.576	0.286 x 0.314 x 0.047
23	OBC 750 0/1	1	Aluminum	Box	1.994	0.286 x 0.314 x 0.032
24	F7 PDM	1	Aluminum	Box	1.741	0.286 x 0.314 x 0.041
25	BCM 80 1	1	Aluminum	Box	2.553	0.286 x 0.314 x 0.035
26	BCM 80 0 (Custom Tray)	1	Al 7075-T6	Box	6.850	0.420 x 0.421 x 0.060
27	MLB	1	Aluminum	Box	2.219	0.381 x 0.381 x 0.053
28	HDRM	4	Aluminum	Cylinder	0.960	0.120 x 0.093
29	Spacer Ring	1	Aluminum	Box	0.973	0.381 x 0.381 x 0.019
30	MSA	2	Aluminum	Flat Plate	0.185	0.200 x 0.310
31	ASM	1	Aluminum	Box	0.885	0.515 x 0.547 x 0.037
32	10-SP Wheel	3	Aluminum	Cylinder	1.022	0.100 x 0.100
33	SFF	1	Aluminum	Flat Plate	1.832	0.515 x 0.555
34	HRTx	2	Aluminum	Box	1.8	0.146 x 0.191 x 0.11

No. (refer to figures)	Object Name	Qty	Material	Shape	Mass (kg)	Dimensions (m) Box: W x L x H Plate: W x L Cylinder: Diameter x L
35	GPS Antenna Plate	1	Aluminum	Flat Plate	1.485	0.284 x 0.312
36	FlexRx	1	Aluminum	Box	0.320	0.164 x 0.191 x 0.11
37	RadMon	1	Aluminum	Box	0.700	0.068 x 0.100 x 0.063
38	Monopole antenna	2	Aluminum	Cylinder	0.250	0.060 x 0.150
39	Shear Panel	2	Aluminum	Flat Plate	1.160	0.284 x 0.546
40	Screen	2	Aluminum	Flat Plate	0.200	0.264 x 0.555
41	Shear Panel +Y	1	Aluminum	Flat Plate	2.961	0.515 x 0.522
42	Deorbit Sail	2	Aluminum	Flat Plate	1.0	0.450 x 3.800

Please refer to Figure 11-1 and Figure 11-2 for indication of the object positions on the OTB satellite (objects 36 & 37 not shown are contained behind object 8).

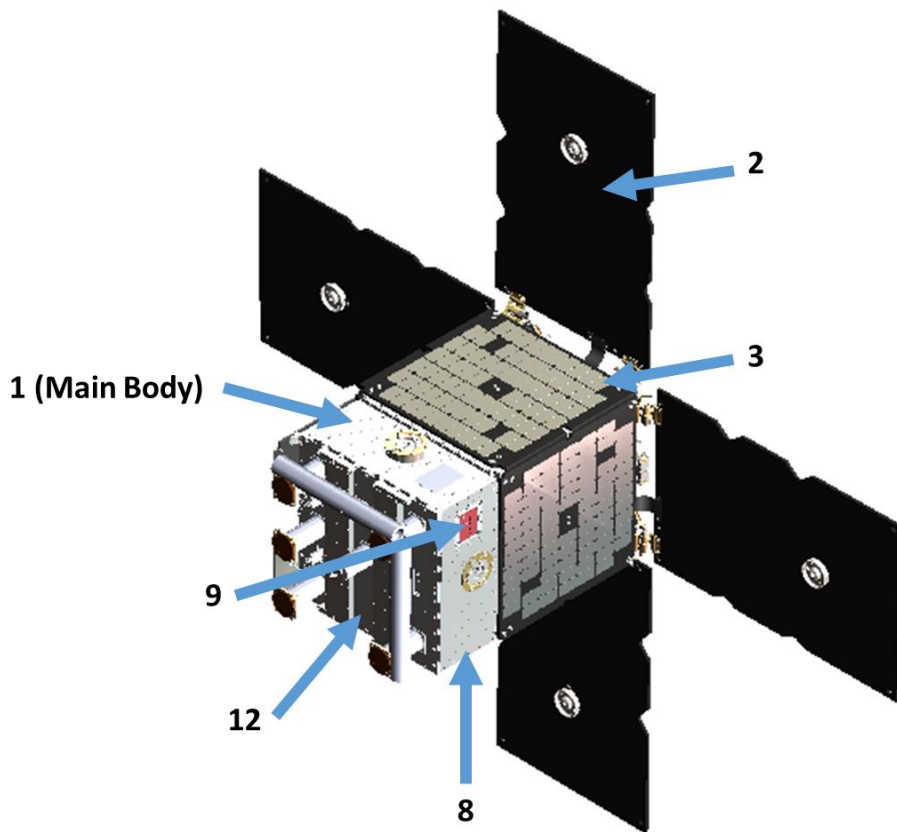


Figure 11-1: CAD Representation of the Satellite (with callouts of objects used in DAS simulation)

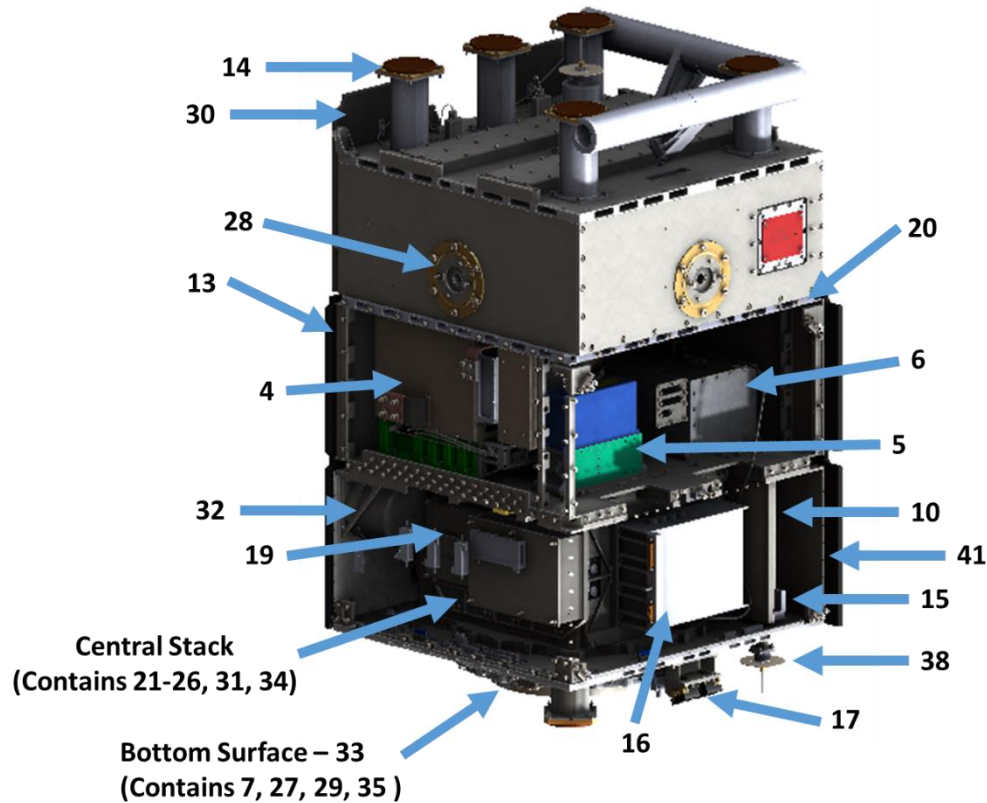


Figure 11-2: Cutaway View of OTB (with callouts of objects used in DAS simulation)
Solar panels and some of the closing panels are removed for clarity (objects 11, 18, 39, & 40 not shown)

11.2 Objects expected to survive an Uncontrolled Re-entry

No objects from OTB are expected to survive uncontrolled re-entry, as calculated using the DAS software [2].

11.3 Probability of Human Casualty

Using DAS [2] calculated results in the above table; total probability of human casualty is 1:100000000, or 0.00000001 (10^{-8}) which is compliant to the requirement, Figure 11-3.

11.4 Spacecraft Compliance with Requirement 4.7-1

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

- a) For uncontrolled reentry, the risk of human casualty from surviving debris shall not exceed 0.0001 (1:10,000) (Requirement 56626).

Using the DAS software [2], OTB is compliant to requirement 4.7-1, as the probability for human casualty does not exceed 1:10000 or 0.0001, Figure 11-3.

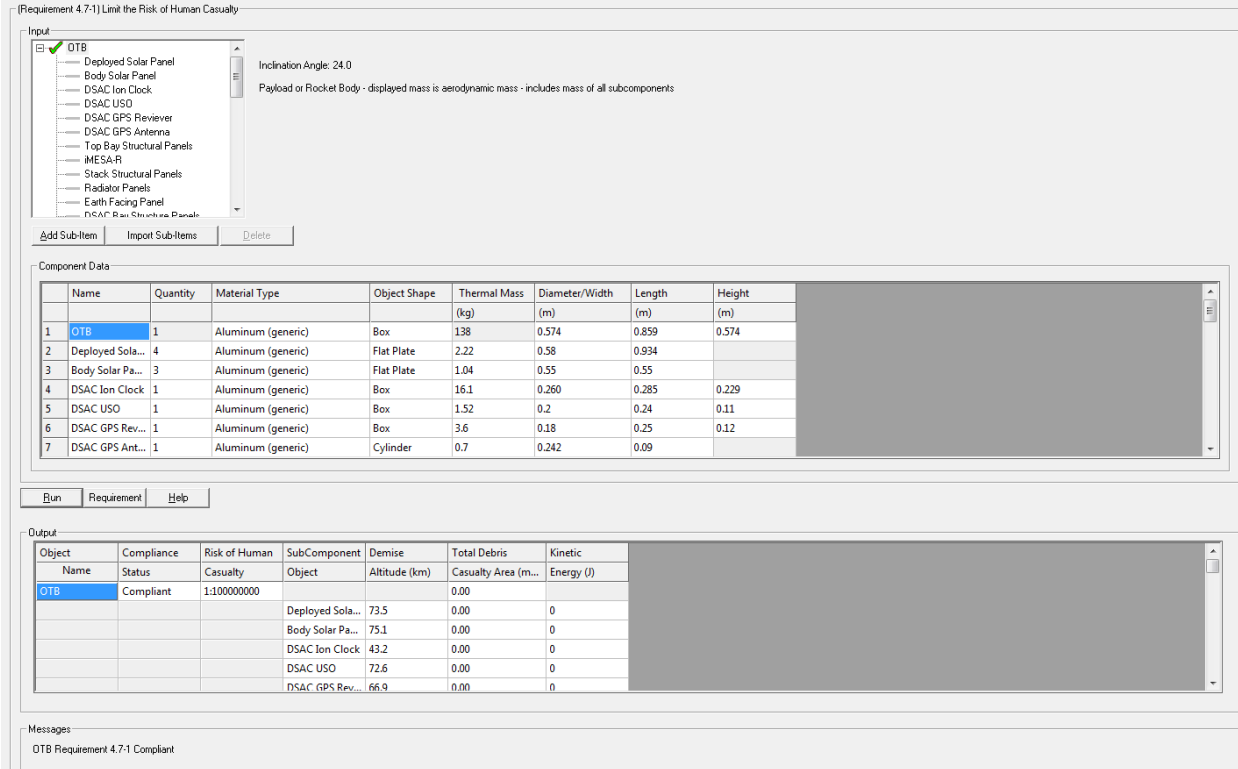


Figure 11-3: DAS Output for Requirement 4.7-1

12 ASSESSMENT OF SPACECRAFT HAZARDOUS MATERIALS

12.1 Hazardous Materials contained on the Spacecraft

Lithium exists within the flight proven ABSL 8s10p lithium-ion battery which employs the commercial SONY 18650HC cell. The quantity and state of the lithium is shown in Table 12-1.

Trace amounts of mercury exist within the Deep Space Atomic Clock Ion Clock unit which is part of the DSAC experiment. The quantity and state of the mercury is shown in Table 12-1.

Table 12-1: Hazardous Materials Data

Material Description	Material Hazard Presented	Material at Launch	Material During Operations	Material at EOM	Material at Passivation	Material Surviving Re-entry
Lithium	Ignition when in contact with water, corrosive	Solid, 24g, Ambient	Solid, 24g, Ambient	Solid, 24g, Ambient	Solid, 24g, Ambient	None
Mercury	Toxic in liquid and gas form	Gas, 100µg, 10e-8 Torr	Gas, 100µg, 10e-8 Torr	Gas, 100µg, 10e-8 Torr	Gas, 100µg, 10e-8 Torr	None