Varuna Technology Demonstration Mission

Orbital Debris Assessment Report (ODAR)

Release 1.0

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This report is prepared in accordance with NASA-STD-8719.14C, APPENDIX A.

March 15, 2022

Revision History

Revision	Date	Description
1.0	03/15/2022	Initial Release

PREPARED BY:

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APPROVAL:

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Analysis performed using DAS version 3.2
Supplemental analysis using Aerospace Corp Atmospheric Heating & Breakup (AHaB) Tool

Self- Assessment

Section	Topic	Status	Comment
4.3-1	Planned debris release passing through LEO – orbital lifetime & object-time product	Not Applicable	
4.3-2	Planned debris release passing near GEO	Not Applicable	
4.4-1	Limiting the risk to other space systems from accidental explosions	Comply	
4.4-2	Design for passivation after completion of mission operations	Comply	
4.4-3	Limiting the long-term risk to other space systems from planned breakup	Not Applicable	
4.4-4	Limiting the short-term risk to other space systems from planned breakup	Not Applicable	
4.5.1	Limiting debris generated by collisions with large objects	Comply	
4.5-2	Limiting debris generated by collisions with small objects	Comply	
4.6-1	Post mission disposal via natural entry, direct entry, or direct retrieval	Comply	
4.6-2	Post mission disposal via storage or Earth escape	Not Applicable	
4.6-3	Post mission disposal for space structures in MEO, Tundra, or Highly Inclined GEO	Not Applicable	
4.6-4	Reliability of post-mission disposal operations	Comply	
4.7-1	Limit the risk of human casualty	Comply	
4.8-1	Special classes of space missions (constellations, rendezvous & proximity, servicing, active debris removal, tethers, CubeSat-class satellites)	Not Applicable	

Assessment Report Format

This ODAR follows NASA-STD-8719.14C, Appendix A.1 and includes the content indicated as a minimum, in each of sections 2 through 8 below. Sections 9 through 14 apply to the launch vehicle ODAR and are not included here.

1 Program Management and Mission Overview

a) Mission Sponsor: Boeing

b) Program Manager: Christian Dommell

c) No foreign government or foreign space agency participation. No NASA responsibilities for this mission

d) Schedule milestones:

- Spacecraft PDR/CDR January 2022
- Shipment of spacecraft: June 2022
- Launch: August 2022

e) Mission Description:

Varuna is a commercial program, intended to demonstrate technologies and perform in-orbit performance testing for a V-band communications system with characteristics consistent with the system recently approved by the FCC *(The Boeing Company Application for Authority to Launch and Operate a Non-Geostationary Satellite Orbit System in the Fixed-Satellite Service, Call Sign, S2993, IBFS File Nos. SAT-LOA-20170301-00028, SAT-AMD-20170929-00137, SAT-AMD-20180131-00013 (Nov. 3, 2022))*

The in-orbit demonstration will allow for verification of assumptions regarding the propagation characteristics of V-band spectrum, will provide an opportunity for manufacturers of terminal equipment and other hardware compatible with Boeing's V-band Non-Geostationary Fixed Satellite Service system to demonstrate and confirm the capabilities of their equipment designs, and allow prospective users of Boeing's broadband communications services (including both commercial and federal government users) an opportunity to evaluate the performance of V-band communications links and ascertain their attributes and acceptability for specific applications

f) Launch Vehicle and Launch Site

The mission is planned to launch on a SpaceX Falcon 9 rideshare mission. The launch site has not yet been finalized.

g) Launch Date and Mission Duration

Launch is planned for August 2022. Planned mission duration is for up to two years.

h) Launch and Deployment Profile

i. Separation from launch vehicle at 280km circular orbit

ii. Perform bus commissioning & initialization

iii. Raise orbit via two Hohmann burns to its operational orbit (1056 km circular orbit at 54^{o} inclination)

iv. Perform payload commissioning & initialization

v. Perform V-band operations for a period of up to two years.

vi. At conclusion of mission, perform deorbit burn to reduce orbit perigee to 300km

vii. Re-entry via natural orbital decay due to atmospheric drag

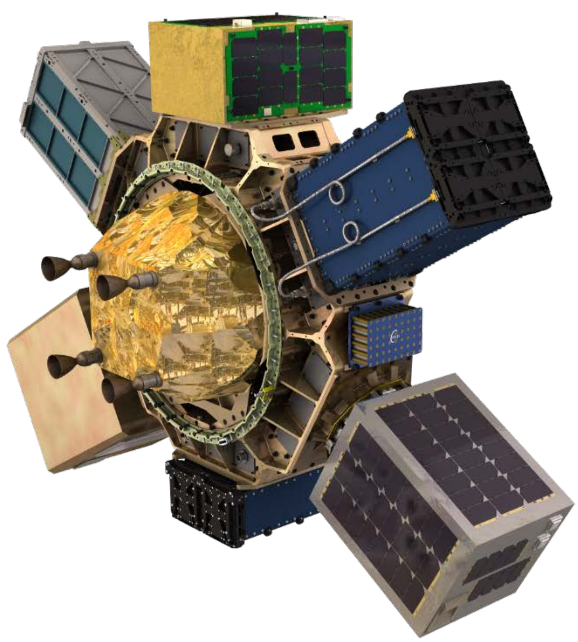
2 Spacecraft Description

a) Physical Description of the spacecraft:

The Varuna spacecraft consists of a Sherpa orbital transfer vehicle with an integral bipropellant propulsion system and solar panel assembly, and spacecraft functions housed in two separate modules hosted on the Sherpa ring. These modules are the command & control system (CCS) and a V-band payload module).

b) Detailed illustration of the spacecraft

Spaceflight Industry's Sherpa-LTC (shown here in its standard configuration) will host the CCS and V-band modules. For the Varuna mission, four of the available Sherpa slots will remain vacant.



Satellite dimensions are: 82 cm (Z) 142 cm (X) x 123 cm (Y)

Figure 1: Varuna spacecraft

b) Total spacecraft mass at launch = 180 kg

c) Dry mass of spacecraft at launch = 140 kg

d) Identification of All Fluids On-board

- 1.0 kg of Gaseous Nitrogen (GN2) for pressurization
- 32.9 kg of high-test peroxide (HTP) as oxidizer
- 6.1 kg of isopropyl alcohol (IPA) as fuel

e) Description of Propulsion System

The propulsion system is the “Polaris” chemical propulsion assembly from Benchmark Space Systems, using “Ocelot” downstream hydrocarbon injection thrusters. The propellant is a mix of HTP and IPA, with GN2 used for pressurization. The system provides 88N of thrust with a specific impulse of 300 seconds.

f) Description of Attitude Control System

The Attitude Control System uses MAI (Redwire) Star Trackers with Sensonor STUM277H gyros for attitude and rate determination. Control is provided Sinclair (RL) Reaction Wheels combined with Newspace Magnetorquer Rods. Operational modes are described below.

ADCS Mode	Description
Nominal	The space will be tracking the sun vector on its +X body axis to generate sufficient power to charge up the batteries.
TT&C	During TT&C mode the spacecraft can perform a slew to track the ground station but may not be required based on the antenna placement andattitude of the spacecraft.
Downlink	The spacecraft will perform a slew to track the corresponding ground station as long as line of sight is available. The antenna is located on its +Z body axis.

Table 3: ADCS Modes

g) Description of Range Safety or Pyrotechnic Devices

There are no range safety or pyrotechnic devices on the satellite.

h) Description of Electrical and Power System

Power is generated by the 4 Main Solar Panels (MSP) mounted on the +X body axis of the spacecraft. Each MSP is comprised of 14 cells in series with 3 strings for a total of 42 cells per panel. The MSPs provide 46 W power per panel. 4 keep-alive panels are placed on the Command and Control System (CCS), 3 in the -Z and 1 in the -X body axis to serve as backup power generators in case of an uncontrolled tumble or clocking maneuvers. The 3 panels consist of 12 cells in series while the 4th is an 18 cell in series configuration.

The satellite will have 2 battery packs, one Data & Power Module (DPM) and a set of Direct Energy Packs (DEPs). The DPM battery pack contains a set of 8 Lithium-Ion battery cells in parallel with a capacity of 144 W-hr, enclosed inside its own module and then mounted inside the DPM. The DEP contains a set of 7 Lithium-Ion battery cells in series, with a capacity of 126 W-hr and are also enclosed inside their own aluminum casing. For this mission two DEP's will be used and connected in parallel to provide a total battery pack capacity of 252 W-hr

The battery packs are all equipped with power regulation ICs which regulate the discharge state of individual battery cells. All the power regulation required for operating the bus is done though DPM. The DEP batteries function as the primary source of energy storage while DPM batteries are used as backup. All battery packs are charged through the solar panels. Battery charge/discharge cycle is managed by the Flight Computer.

i) Description of any other stored energy devices

There are no other stored energy devices.

j) Radioactive materials

There are no radioactive materials onboard.

k) Planned proximity operations

There are no planned proximity, rendezvous, or docking operations.

3 Assessment of Debris Released During Normal Operations

a) Identification of Objects Expected to be Released at Any Time

There are no planned releases of objects during this mission.

b) Rationale for Release of Objects

Not applicable.

c) Time of Release of Objects

Not applicable.

d) Release Velocity

Not applicable.

e) Expected Orbital Parameters After Object Release

Not applicable.

f) Calculated Orbital Lifetime of Release Objects

Not applicable.

g) Assessment of Compliance with Requirements 4.3-1 and 4.3-2

Requirement 4.3-1: Planned debris release passing through LEO

Compliance Statement Not applicable

Requirement 4.3-2: Planned debris release passing near GEO

Compliance Statement: Not Applicable

4 Assessment of Spacecraft Intentional Breakups and Potential for Explosions

a) Identification of all potential causes of spacecraft breakup during deployment and mission operation

There are no known or anticipated causes for spacecraft breakup or explosion.

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

The only foreseen risk of explosion would be as a result of battery overheating and the resulting low probability of cell explosion. A Failure Modes and Effects Analysis (FMEA) was performed to demonstrate that multiple combined, mutually exclusive failures would have to occur to result in the potential for accidental explosion of the batteries. Seven independent scenarios were analyzed to consider the risk that battery explosion could occur, with an exceptionally low cumulative probability that explosion will occur. Details are shown below.

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

There are no planned breakups, explosions, or collisions.

d) List of components which shall be passivated at End of Mission (EOM) including method of passivation and amount which cannot be passivated

After the satellite has completed its operational life, the deorbit burn will be executed, to fully deplete the propellant. The battery cells will be discharged completely by disabling the solar array charging circuit which will fully discharge all cells within a few days.

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

This is not applicable, as all items will be passivated.

f) Assessment of spacecraft compliance with Requirements 4.4-1 through 4.4-4

Requirement 4.4-1: Limiting the risk to other space systems from accidental explosions

"For each spacecraft and launch vehicle orbital stage employed for a mission, the program orproject 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)"

Compliance Statement: Comply

- Required Probability: < 0.001
- Expected Probability: ~ 0.000

Supporting Rationale and FMEA Details

- Battery Explosion
  - Effect: All failure modes below might result in battery explosion with the possibility of orbital debris generation. However, in the unlikely event that a battery cell does explosively rupture, the size, mass, and potential energy, of these small batteries is such that while the spacecraft could be expected to vent gases, most debris from the battery rupture should be contained within the spacecraft due to the lack of penetration energy to the multiple enclosures surrounding the batteries.
  - Probability: Extremely Low. It is believed to be less than 0.01% given that multiple independent faults must occur for each failure to cause an explosion. Each battery cell is UL/UN certified with individual over-voltage and over-current protection. Identical batteries have been flown on all Astro Digital spacecraft. Even in extreme cases (such as a launch vehicle hydrazine explosion in proximity to the spacecraft), the batteries showed no signs of damage or degradation.
- Failure Mode 1: Internal short circuit
  - Mitigation: Protoflight level sine burst, sine and random vibration in three axes of bothspacecraft, thermal vacuum cycling of both spacecraft and extensive functional testing followed by maximum system rate-limited charge and discharge cycles were performed to prove that no internal short circuit sensitivity exists. Additional environmental and functional testing of the batteries at the power subsystem vendor facilities were also conducted on the batteries at the component level.

- Combined faults required for realized failure: Environmental testing AND functionalcharge/discharge tests must both be ineffective in discovery of the failure mode.

- Failure Mode 2: Internal thermal rise due to high load discharge rate
  - Mitigation: Battery cells were tested in lab for high load discharge rates in a varietyof flight-like configurations to determine if the feasibility of an out-of-control thermal rise in the cell. Cells were also tested in a hot, thermal vacuum environment (5 cycles at 50$_0$ C, then to -20$_0$C) in order to test the upper limit of the cells capability. Nofailures were observed or identified via satellite telemetry or via external monitoring circuitry.
  - Combined faults required for failure: Spacecraft thermal design must be incorrect and external over-current detection and disconnect function must fail for this failure mode.

- Failure Mode 3: Excessive discharge rate or short-circuit due to external device failure orterminal contact with conductors not at battery voltage levels (due to abrasion or inadequateproximity separation).
  - Mitigation: This failure mode is negated by:
    * Qualification tested short circuit protection on each external circuit,
    * Design of battery packs and insulators such that no contact with nearby boardtraces is possible without being caused by some other mechanical failure,
    * Observation of such other mechanical failures by protoflight level environmental tests (sine burst, random vibration, thermal cycling, and thermal-vacuum tests).
  - Combined faults required for realized failure: An external load must fail/short-circuit AND external over-current detection and disconnect function must all occur to enable this failure mode.

- Failure Mode 4: Inoperable vents
  - Mitigation: Battery venting is not inhibited by the battery holder design or the space- craft design. The battery is capable of venting gases to the external environment
  - Combined faults required for realized failure: The cell manufacturer OR the satellite integrator fails to install proper venting.

- Failure Mode 5: Crushing
  - Mitigation: This mode is negated by spacecraft design. There are no moving parts in the proximity of the batteries.
  - Combined faults required for realized failure: A catastrophic failure must occur

in an external system AND the failure must cause a collision sufficient to crush the batteriesleading to an internal short circuit AND the satellite must be in a naturally sustainedorbit at the time the crushing occurs.

- Failure Mode 6: Low level current leakage or short-circuit through battery pack case or dueto moisture-based degradation of insulators.
  - Mitigation: These modes are negated by:
    - Battery holder/case design made of non-conductive plastic, and
    - Operation in vacuum such that no moisture can affect insulators.
  - Combined faults required for realized failure: Abrasion or piercing failure of circuitboard coating or wire insulators AND dislocation of battery packs AND failure of battery terminal insulators AND failure to detect such failures in environmental tests must occur to result in this failure mode.
- Failure Mode 7: Excess temperatures due to orbital environment and high discharge combined.
  - Mitigation: The spacecraft thermal design will negate this possibility. Thermal rise has been analyzed in combination with space environment temperatures showing that batteries do not exceed normal allowable operating temperatures under a variety of modeled cases, including worst case orbital scenarios. Analysis shows these temperatures to be well below temperatures of concern for explosions.
  - Combined faults required for realized failure: Thermal analysis AND thermal design AND mission simulations in thermal-vacuum chamber testing AND over-current monitoring and control must all fail for this failure mode to occur.

Requirement 4.4-2

"Design of all spacecraft and launch vehicle orbital stages shall include the ability and a plan to either 1) deplete all onboard sources of stored energy and disconnect all energy generation sources when they are no longer required for mission operations or post mission disposal or 2) control to a level which cannot cause an explosion or deflagration large enough to release orbital debris or break up the spacecraft. The design of depletion burns and ventings should minimize the probability of accidental collision with tracked objects in space."

Compliance Statement: Comply

The spacecraft includes the ability to fully disconnect the Lithium Ion cells from the charging current of the solar arrays. Once the satellite reaches its End of Life (EOL), this feature will be used to completely passivate the batteries by removing all energy from them. In the unlikely event that a battery cell does explosively rupture, the small size, mass, and potential energy, of these small batteries is such that while the spacecraft could be expected to vent gases, the debris from the battery rupture should be contained within the spacecraft due to the lack of penetration energy to the multiple enclosures surrounding the batteries.

Requirement 4.4-3: Limiting the long-term risk to other space systems from planned breakup

Compliance Statement: Not Applicable

Requirement 4.4-4: Limiting the short-term risk to other space systems from planned breakup

Compliance Statement: Not Applicable

5 Assessment of Potential for On-Orbit Collisions

a) Calculation of spacecraft probability of collision with space objects larger than 10cm in diameter during the orbital lifetime of the spacecraft.

See attached results from DAS 3.2

b) Calculation of spacecraft probability of collision with space objects, including orbital debris and meteoroids, of sufficient size to prevent post mission disposal.

See attached results from DAS 3.2

c) Assessment of Compliance with Requirement 4.5-1 and 4.5-2

Requirement 4.5-1: Limiting debris generated by collisions with large objects

”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 does not exceed 0.001. For spacecraft and orbital stages passing through the protected region ±200 km and ±15 degrees of geostationary orbit, the probability of accidental collision with space objects larger than 10 cm in diameter shall not exceed 0.001 when integrated over 100 years from time of launch”

Compliance Statement: Comply

A probability of collision analysis was performed using NASA’s DAS 3.2 software for our operational orbit over both the planned 2-year lifetime, as well as the expected duration in elliptical low-perigee orbit prior to reentry.

The calculated probability of collision is:

- 3.0070×10^{-5} during the operational phase of the mission, at 1056 km circular orbit

- 5.2085×10^{-6} during the re-entry phase of the mission, starting at an elliptical orbit of 300 km perigee x 1056 km apogee.

Requirement 4.5-2: Limiting debris generated by collisions with small objects

"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 toprevent compliance with the applicable post mission disposal maneuver requirements does not exceed 0.01"

Compliance Statement: Comply

A probability of collision analysis was performed using NASA's DAS 3.2 software for our operational orbit over the planned 2-year lifetime. The analysis shows the system is compliant.

d) Description and assessment of efficacy of any planned debris avoidance capability intended to help in meeting requirement 4.5-1.

The satellite meets the requirements of requirement 4.5-1 without need of debris avoidance maneuvering capability. In the event that unplanned maneuvering becomes necessary, the propulsion system is capable of being used for such a purpose, with 6 kg of propellant margin in the design.

6 Assessment of Post-Mission Disposal Plans and Procedure

a) Description of Spacecraft Disposal Option Selected

The Varuna spacecraft will use natural reentry as the method of disposal. To facilitate reentry and demise within the required timeline, the satellite perigee will be lowered to 300km, placing the satellite into a 300km x 1056km elliptical orbit. A simple Hohmann transfer burn will be executed to achieve the disposal orbit. Estimated ΔV for this maneuver is 199 m/sec. Analysis using DAS 3.2 shows this achieves reentry and demise in approximately 2 years.

b) Components required to accomplish the disposal maneuver

Nominal deorbit sequence used the following components

- Flight Computer
- GPS
- TT&C radio (1 of 2)
- Polaris propulsion system
- Star Tracker

- Gyro
- RWA & RWA Control Boards
- Distributed Energy Pack/Main Solar Panel
- Power & Battery Boards

For contingency scenarios, deorbit could be conducted without GPS (using ground ranging and propagated ephemeris), either Star Tracker or Gyro (using a single sensor for attitude knowledge), and without one of the 3 RWAs.

c) Calculation of area-to-mass ratio after post-mission disposal

- Spacecraft Mass: 140 Kg (CBE + MGA)
- Cross-sectional Area: 1.246 m^2 (average RAM)
- Area to mass ratio: 0.0091 m^2/kg

d) If appropriate, preliminary plan for controlled reentry

Not applicable

e) Assessment of Compliance with Requirement 4.6-1 Through 4.6-4

Requirement 4.6-1: Post mission disposal via natural entry, direct entry, or direct retrieval

"A spacecraft or orbital stage with a perigee altitude below 2,000 km shall be disposed of by one of the following three methods:

- Atmospheric reentry option: Leave the space structure in an orbit in which natural forceswill lead to atmospheric reentry within 25 years after the completion of mission; or maneuver the space structure into a controlled de-orbit trajectory as soon as practical after completionof mission

- Storage orbit option: Maneuver the space structure into an orbit with perigee altitude above2000 km and ensure its apogee altitude will be below 19,700 km, both for a minimum of100 years

- Direct retrieval: Retrieve the space structure and remove it from orbit within 10 years after completion of mission

Compliance Statement: **Comply**

The orbit lifetime was assessed using the DAS Orbit Evolution Analysis tool. As seen below, the estimated to time for reentry is slightly over 2 years, well below the 25 year requirement.

Requirement 4.6-2: Post mission disposal via storage or Earth escape

Compliance Statement: Not Applicable

Requirement 4.6-3: Post mission disposal for space structures in MEO, Tundra, or Highly Inclined GEO

Compliance Statement: Not Applicable

Requirement 4.6-4

Compliance Statement: Comply

Reliability calculation based on the set of hardware required for a nominal deorbit scenario is 0.926

Component	Reliability
Flight Computer	0.991949
GPS	0.997070
TT&C radio	0.999447
Polaris propulsion	0.984252
Star Tracker	0.999997
Gyro	
Reaction Wheel (RWA)	0.976991
RW Power Board (RWPDB)	0.997969
DEP/Main Solar Panel	0.999997
Power Board A	0.999910
High Voltage Power Board	
Battery Boards	0.976431
Mission	**0.926**

7 Assessment of Reentry Hazards

a) Detailed description of spacecraft components

See output run from DAS 3.2 software, attached below.

b) Summary of objects expected to survive a controlled reentry using DAS 3.2

The following components are shown as being expected to survive the uncontrolled reentry using DAS 3.2

Component	Total DCS	KE
RW rotor	1.5	128.07
OCELOT ENGINE ASSEMBLIES	2.14	152.9
DMLS PRESSURANT TANK POLARIS 100417 CONFIG	1.18	365.12
FLUID COMPONENTS TOP HALF	1.14	423.32
FLUID COMPONENTS BOTTOM HALF	1.13	512.53

c) Calculation of risk of human casualty

DAS 3.2 calculates the risk of human casualty as being 1:7800. Due to this result, a higher-fidelity modeling run was conducted by the Aerospace Corporation, using their AHaB (Atmospheric Heating and Breakup) tool, developed under Aerospace IR&D. This analysis was performed for Varuna and LCT1, so results from both are included in the attachment.

Attached results indicate that three of the five components (RW rotor, top & bottom fluid components) will in fact demise prior to re-entry, each at above 50km altitude. The only two components which do not fully demise are the Ocelot engines and the titanium pressurant tanks.

Excerpt from Aerospace report:

Time (EI+)	Key Events	Demise
1071 sec	88.2 km	CCS & 2-way QuadPack
1100 sec	85.6 km	R2A & 4-way QuadPack
1208 sec	70.6 km	24-inch J-channel spacer ring
1221 sec	68.0 km	CAB hex plate
1255 sec	59.9 km	Aft CAB Bulkhead

Notes
- Property estimated, or dimension derived from mass
- Survives and poses risk
- Risk negligible or KE < 15 J

Object Description	Shape	Count	Material Type	Diam/Width (m)	Length (m)	Wall/Core Thickness (m)	Face Sheet Thickness (m)	Height or Min Diam (m)	Unit Mass (kg)	Total Mass (kg)	Separation Altitude (km)	Demise Altitude (km)	Debris Area (m^2)	Total Debris Area (m^2)	Total Casualty Area (m^2)
STRUCTURE AND EQUIPMENT															
Upper half of 24-in separation system	Ring	1	Al 6061-T6	0.610	0.031	0.011			1.80	1.80		84.2	0.000	0.000	0.000
24-inch J-channel spacer ring	Ring	1	Al 6061-T6	0.667	0.083	0.011			5.26	5.26		70.7	0.000	0.000	0.000
Solar panel wing	Plate	6	Al 6061-T6	0.546	0.549	0.003		0.060	2.35	14.10		96.0	0.000	0.000	0.000
CAB hex plate	Ring	2	Al 6061-T6	0.822	0.070	0.021			10.00	20.00		68.0	0.000	0.000	0.000
CAB interior wall	Plate	6	Al 6061-T6	0.118	0.318	0.008			0.83	4.98	68.0	67.8	0.000	0.000	0.000
CAB corner brace	Box	6	Al 6061-T6	0.151	0.178	0.004		0.151	1.10	6.60		88.2	0.000	0.000	0.000
Port 4 avionics adapter plate	Plate	1	Al 6061-T6	0.294	0.311	0.005			1.15	1.15		71.9	0.000	0.000	0.000
R2A-Core	Box	1	Al 6061-T6	0.265	0.265	0.005		0.090	3.20	3.20		85.6	0.000	0.000	0.000
NSL black box std	Box	1	Al (generic)	0.054	0.089	0.006		0.047	0.29	0.29		83.0	0.000	0.000	0.000
Camera bracket	Plate	2	Al 6061-T6	0.146	0.178	0.006			0.62	1.24		85.6	0.000	0.000	0.000
IMPERX camera	Box	2	Al 6061-T6	0.037	0.072	0.004		0.037	0.12	0.23		88.2	0.000	0.000	0.000
Camera lens assembly	Cylinder	2	SS 304	0.034	0.047	0.003			0.13	0.27	85.6	73.3	0.000	0.000	0.000
Battery thermal isolator	Plate	2	G10/FR4	0.102	0.145	0.009			0.26	0.52	70.6	68.6	0.000	0.000	0.000
Battery module	Box	2	Al 6061-T6	0.100	0.139	0.018		0.100	2.65	5.30	68.6	58.1	0.000	0.000	0.000
QuadPack adapter plate	Plate	4	Al 6061-T6	0.297	0.311	0.007			1.73	6.91		68.8	0.000	0.000	0.000
Empty 2-way QuadPack	Box	2	Al 6061-T6	0.250	0.440	0.004		0.250	6.30	12.60		88.2	0.000	0.000	0.000
Empty 4-way QuadPack	Box	1	Al 6061-T6	0.250	0.440	0.005		0.250	7.50	7.50		85.6	0.000	0.000	0.000
QuadPack mass model	Box	1	Al 6061-T6	0.250	0.528	0.017		0.250	26.30	26.30	68.0	64.4	0.000	0.000	0.000
RPG base ring	Ring	1	Al 6061-T6	0.626	0.038	0.026			5.08	5.08	68.0	54.8	0.000	0.000	0.000
RPG leg	Box	6	Al 6061-T6	0.051	0.196	0.006		0.051	0.63	3.78	54.8	54.2	0.000	0.000	0.000
RPG triangle plate	Plate	1	Al 6061-T6	0.346	0.400	0.012		0.076	4.47	4.47		69.2	0.000	0.000	0.000
RPG MLB adapter plate	Plate	3	Al 6061-T6	0.255	0.322	0.027			2.43	7.29	54.2	53.2	0.000	0.000	0.000
Lower 8-in separation system	Ring	3	Al 6061-T6	0.118	0.045	0.039			1.19	3.57		53.9	0.000	0.000	0.000
CCS enclosure	Box	1	Al 6061-T6	0.190	0.382	0.004		0.272	4.81	4.81		88.2	0.000	0.000	0.000
Torque rod	Cylinder	3	Iron	0.020	0.300	0.004			0.45	1.35	88.2	67.0	0.000	0.000	0.000
AD avionics	Box	4	Al 6061-T6	0.120	0.150	0.016		0.100	3.00	12.00	88.2	66.1	0.000	0.000	0.000
RWA enclosure	Box	3	Al 6061-T6	0.140	0.150	0.003		0.042	0.57	1.71	88.2	80.6	0.000	0.000	0.000
RWA rotor	Ring	3	SS 410	0.135	0.037	0.003			0.40	1.20	80.6	69.7	0.000	0.000	0.000
PROPULSION															
100504_AFT CAB BULKHEAD	Disk	1	Al 7076-T6	0.572		0.025			3.32	3.32	70.6	59.9	0.000	0.000	0.000
100602_DMLS PRESSURANT TANK_POLARIS 100417 CONFIG	Cylinder	2	Ti-6Al-4V	0.085	0.327	0.003			0.98	1.96	59.9	0.0	0.028	0.056	1.176
100535_OX TANK ASSEMBLIES	Cylinder	3	Al 6061-T6	0.204	0.340	0.004			4.75	14.25		64.1	0.000	0.000	0.000
FLUID COMPONENTS, TOP HALF	Cylinder	1	SS 316	0.025	0.416	0.0125			3.27	3.27		62.3	0.000	0.000	0.000
100733_FUEL TANK ASSEMBLY	Cylinder	1	Al 6061-T6	0.204	0.340	0.004			4.75	4.75		88.2	0.000	0.000	0.000
100719_A LEG, THRUST DECK	Beam	3	Al 7076-T6	0.015	0.243	0.004		0.015	0.22	0.66		89.6	0.000	0.000	0.000
FLUID COMPONENTS, BOTTOM HALF	Cylinder	1	SS 316	0.025	0.387	0.0125			3.60	3.60		74.0	0.000	0.000	0.000
100716_THRUST BULKHEAD, POLARIS	Ring	1	Al 7076-T6	0.446	0.013	0.021			1.03	1.03		82.8	0.000	0.000	0.000
100688_OCELOT ENGINE ASSEMBLIES	Cylinder	4	Niobium-C103	0.086	0.202				0.51	2.04	82.8	0.0	0.017	0.069	2.141
Totals		88								154.34				0.1	3.32

88.6 kg were part of analyzed configuration but not part of Sherpa-LTC2

RWA rotors

Titanium tanks

Fluid comps, top

Fluid comps, bottom

Ocelot engines

These non-fully-demising components have a combined area of 3.32 m^2

Object Description	Shape	Count	Material Type	Diameter (m)	Length (m)	Wall Thickness (m)	Height (m)	Unit Mass (kg)	Total Mass (kg)	Debris Area (m2)	Total Debris Area (m2)	Total Casualty Area (m2)
100602_DMLS PRESSURANT TANK_POLARIS 100417 CONFIG	Cylinder	2	Ti-6 AL-4V	0.085	0.327	0.003		0.98	1.96	0.028	0.056	1.176
100688_OCELOT ENGINE ASSEMBLIES	Cylinder	4	Niobium-C103	0.086	0.202			0.51	2.04	0.017	0.069	2.141
Totals		6										3.32

When this area is applied to the calculated 1.76 x 10^{-5} casualty per unit area, this provides a casualty rate of 1:17,100. Overall analysis results are attached below.

d) Assessment of Compliance with Requirement 4.7-1

Requirement 4.7-1: Limit the risk of human casualty

"The potential for human casualty is assumed for any object with an impacting kinetic energy in excess of 15 joules:

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

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

c. For controlled reentry, the product of the probability of failure to execute the reentry burn and the risk of human casualty assuming uncontrolled reentry shall be less than 0.0001 (1:10,000).

d. For long-term reentry of space structures in MEO, Tundra orbits, highly inclined GEO, and other orbits: Surviving debris shall have less than 7 m2 total debris casualty area or 0.0001 (1 in 10,000) risk of human casualty.

Compliance Statement: Comply

The applicable requirement for Varuna is 4.7-1.a. Analysis shows the risk of human casualty from reentry is 1:17,100, compared to the 1:10,000 requirement

8 Assessment for Special Classes of Missions

This section is not applicable to Varuna, as it does not meet any of the conditions for special classes of missions:

- Varuna is a single spacecraft, not a large constellation
- There are no rendezvous or proximity operations planned
- There is no satellite servicing planned
- There is no active debris removal
- There are no tethers on the satellite
- Varuna is not a small satellite, as defined in NASA-STD-8719.14C

Requirement 4.8-1. Special classes of space missions: Special classes of space missions, including large constellations; rendezvous, proximity operations, and satellite servicing; safety of active debris removal operations; tethers; and small satellites

Compliance Statement: Not Applicable

Appendix

```
Processing Requirement 4.3-1:     Return Status :  Not Run
=====================
No Project Data Available
=====================
=============== End of Requirement 4.3-1 ===============
Processing Requirement 4.3-2: Return Status : Passed
=====================
No Project Data Available
=====================
=============== End of Requirement 4.3-2 ===============
Processing Requirement 4.5-1:     Return Status :  Passed

==============
Run Data
==============

**INPUT**

      Space Structure Name = SherpaWet
      Space Structure Type = Payload
      Perigee Altitude = 1056.000 (km)
      Apogee Altitude = 1056.000 (km)
      Inclination = 54.000 (deg)
      RAAN = 0.000 (deg)
      Argument of Perigee = 0.000 (deg)
      Mean Anomaly = 0.000 (deg)
      Final Area-To-Mass Ratio = 0.0091 (m^2/kg)
      Start Year = 2023.600 (yr)
      Initial Mass = 180.000 (kg)
      Final Mass = 135.000 (kg)
      Duration = 5.000 (yr)
      Station-Kept = False
      PMD Perigee Altitude = 300.000 (km)
      PMD Apogee Altitude = 1056.000 (km)
      PMD Inclination = 54.000 (deg)
      PMD RAAN = 0.000 (deg)
      PMD Argument of Perigee = 0.000 (deg)
      PMD Mean Anomaly = 0.000 (deg)

**OUTPUT**

      Collision Probability = 3.0107E-05
      Returned Message: Normal Processing
      Date Range Message: Normal Date Range
      Status = Pass

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

**INPUT**

      Space Structure Name = SherpaDry
```

```
      Space Structure Type = Payload
      Perigee Altitude = 300.000 (km)
      Apogee Altitude = 1056.000 (km)
      Inclination = 54.000 (deg)
      RAAN = 0.000 (deg)
      Argument of Perigee = 0.000 (deg)
      Mean Anomaly = 0.000 (deg)
      Final Area-To-Mass Ratio = 0.0091 (m^2/kg)
      Start Year = 2023.600 (yr)
      Initial Mass = 135.000 (kg)
      Final Mass = 135.000 (kg)
      Duration = 5.000 (yr)
      Station-Kept = False
      Abandoned = True

**OUTPUT**

      Collision Probability = 5.2085E-06
      Returned Message: Normal Processing
      Date Range Message: Normal Date Range
      Status = Pass

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

=============== End of Requirement 4.5-1 ===============
Requirement 4.5-2:  Compliant
=============== End of Requirement 4.5-2 ===============
Processing Requirement 4.6   Return Status :  Passed
==============
Project Data
==============
**INPUT**
      Space Structure Name = Varuna
      Space Structure Type = Payload
      Perigee Altitude = 1056.000000 (km)
      Apogee Altitude = 1056.000000 (km)
      Inclination = 54.000000 (deg)
      RAAN = 0.000000 (deg)
      Argument of Perigee = 0.000000 (deg)
      Mean Anomaly = 0.000000 (deg)
      Area-To-Mass Ratio = 0.009100 (m^2/kg)
      Start Year = 2023.600000 (yr)
      Initial Mass = 180.000000 (kg)
      Final Mass = 135.000000 (kg)
      Duration = 5.000000 (yr)
      Station Kept = False
      Abandoned = False
      Long-Term Reentry = False
**OUTPUT**
      Suggested Perigee Altitude = 300.000000 (km)
      Suggested Apogee Altitude = 1056.000000 (km)
      Returned Error Message = Passes LEO reentry orbit criteria.
      Released Year = 2033 (yr)
      Requirement = 61
```

```
      Compliance Status = Pass
==============
=============== End of Requirement 4.6 ===============
*********Processing Requirement 4.7-1
      Return Status :  Passed
***********INPUT****
 Item Number = 1
name = Varuna
quantity = 1
parent = 0
materialID = 5
type = Cylinder
Aero Mass = 135.000000
Thermal Mass = 135.000000
Diameter/Width = 0.813000
name = LT upper 24-in separation sytem
quantity = 1
parent = 1
materialID = 5
type = Box
Aero Mass = 1.800000
Thermal Mass = 1.800000
Diameter/Width = 0.610000
Length = 0.610000
Height = 0.031000
name = 24inch Jchannel spacer ring
quantity = 1
parent = 1
materialID = 8
type = Box
Aero Mass = 5.260000
Thermal Mass = 5.260000
Diameter/Width = 0.666750
Length = 0.666750
Height = 0.082550
name = solar panel wing
quantity = 4
parent = 1
materialID = 8
type = Box
Aero Mass = 2.500000
Thermal Mass = 2.500000
Diameter/Width = 0.546350
Length = 0.548500
Height = 0.060000
name = LT Hex Plate1
quantity = 2
parent = 1
materialID = 8
type = Box
Aero Mass = 10.000000
Thermal Mass = 10.000000
Diameter/Width = 0.100000
Length = 0.822000
```

Height = 0.050000
name = LT Interior Wall
quantity = 6
parent = 1
materialID = 8
type = Flat Plate
Aero Mass = 0.830000
Thermal Mass = 0.830000
Diameter/Width = 0.118000
Length = 0.318000
name = LT Corner Brace
quantity = 6
parent = 1
materialID = 8
type = Box
Aero Mass = 1.100000
Thermal Mass = 1.100000
Diameter/Width = 0.151000
Length = 0.178000
Height = 0.151000
name = Port 4 adapter plate
quantity = 1
parent = 1
materialID = 8
type = Flat Plate
Aero Mass = 1.800000
Thermal Mass = 1.800000
Diameter/Width = 0.311000
Length = 0.350000
name = LT QuadPack adapter plate
quantity = 4
parent = 1
materialID = 8
type = Flat Plate
Aero Mass = 1.800000
Thermal Mass = 1.800000
Diameter/Width = 0.297000
Length = 0.311000
name = V-band radio payload
quantity = 1
parent = 1
materialID = 8
type = Box
Aero Mass = 5.200000
Thermal Mass = 5.200000
Diameter/Width = 0.393000
Length = 0.791000
Height = 0.196000
name = ISIPOD 3U dispenser
quantity = 1
parent = 1
materialID = 5
type = Box
Aero Mass = 2.000000

Thermal Mass = 2.000000
Diameter/Width = 0.180000
Length = 0.414000
Height = 0.130000
name = torque rod
quantity = 3
parent = 1
materialID = 38
type = Cylinder
Aero Mass = 0.450000
Thermal Mass = 0.450000
Diameter/Width = 0.020000
Length = 0.300000
name = CCS Avionics
quantity = 1
parent = 1
materialID = 8
type = Box
Aero Mass = 22.000000
Thermal Mass = 22.000000
Diameter/Width = 0.393000
Length = 0.791000
Height = 0.196000
name = RWA enclosure
quantity = 3
parent = 1
materialID = 5
type = Box
Aero Mass = 0.570000
Thermal Mass = 0.570000
Diameter/Width = 0.140000
Length = 0.150000
Height = 0.042000
name = RWA rotor
quantity = 3
parent = 1
materialID = 62
type = Box
Aero Mass = 0.400000
Thermal Mass = 0.400000
Diameter/Width = 0.135000
Length = 0.135000
Height = 0.037000
name = 100535_OX TANK ASSEMBLIES
quantity = 3
parent = 1
materialID = 8
type = Cylinder
Aero Mass = 4.770000
Thermal Mass = 4.770000
Diameter/Width = 0.384000
Length = 0.402000
name = 100733_FUEL TANK ASSEMBLY
quantity = 1

```
parent = 1
materialID = 8
type = Cylinder
Aero Mass = 4.750000
Thermal Mass = 4.750000
Diameter/Width = 0.315000
Length = 0.402000
name = 100688_OCELOT ENGINE ASSEMBLIES
quantity = 4
parent = 1
materialID = 47
type = Cylinder
Aero Mass = 0.510000
Thermal Mass = 0.510000
Diameter/Width = 0.086000
Length = 0.202000
name = 100504_AFT CAB BULKHEAD
quantity = 1
parent = 1
materialID = 8
type = Flat Plate
Aero Mass = 3.320000
Thermal Mass = 3.320000
Diameter/Width = 0.572000
Length = 0.572000
name = 100602_DMLS PRESSURANT TANK_POLARIS 100417 CONFIG
quantity = 2
parent = 1
materialID = 65
type = Cylinder
Aero Mass = 0.980000
Thermal Mass = 0.980000
Diameter/Width = 0.085000
Length = 0.327000
name = FLUID COMPONENTS TOP HALF
quantity = 1
parent = 1
materialID = 59
type = Cylinder
Aero Mass = 3.270000
Thermal Mass = 3.270000
Diameter/Width = 0.529000
Length = 0.416000
name = FLUID COMPONENTS BOTTOM HALF
quantity = 1
parent = 1
materialID = 59
type = Cylinder
Aero Mass = 3.600000
Thermal Mass = 3.600000
Diameter/Width = 0.554000
Length = 0.387000
name = 100719_A LEEG THRUSTER DECK
quantity = 3
```

```
parent = 1
materialID = 9
type = Box
Aero Mass = 0.220000
Thermal Mass = 0.220000
Diameter/Width = 0.020000
Length = 0.243000
Height = 0.020000
name = 100719_THRUST BULKHEAD POLARIS
quantity = 1
parent = 1
materialID = 9
type = Cylinder
Aero Mass = 1.030000
Thermal Mass = 1.030000
Diameter/Width = 0.440000
Length = 0.400000
*************OUTPUT****
Item Number = 1
name = Varuna
Demise Altitude = 77.998672
Debris Casualty Area = 0.000000
Impact Kinetic Energy = 0.000000
************************************
name = LT upper 24-in separation sytem
Demise Altitude = 74.830826
Debris Casualty Area = 0.000000
Impact Kinetic Energy = 0.000000
************************************
name = 24inch Jchannel spacer ring
Demise Altitude = 69.901184
Debris Casualty Area = 0.000000
Impact Kinetic Energy = 0.000000
************************************
name = solar panel wing
Demise Altitude = 74.166298
Debris Casualty Area = 0.000000
Impact Kinetic Energy = 0.000000
************************************
name = LT Hex Plate1
Demise Altitude = 62.985775
Debris Casualty Area = 0.000000
Impact Kinetic Energy = 0.000000
************************************
name = LT Interior Wall
Demise Altitude = 74.074715
Debris Casualty Area = 0.000000
Impact Kinetic Energy = 0.000000
************************************
name = LT Corner Brace
Demise Altitude = 74.920013
Debris Casualty Area = 0.000000
Impact Kinetic Energy = 0.000000
************************************
```

```
name = Port 4 adapter plate
Demise Altitude = 72.878723
Debris Casualty Area = 0.000000
Impact Kinetic Energy = 0.000000
*************************************
name = LT QuadPack adapter plate
Demise Altitude = 72.151550
Debris Casualty Area = 0.000000
Impact Kinetic Energy = 0.000000
*************************************
name = V-band radio payload
Demise Altitude = 74.330971
Debris Casualty Area = 0.000000
Impact Kinetic Energy = 0.000000
*************************************
name = ISIPOD 3U dispenser
Demise Altitude = 74.761436
Debris Casualty Area = 0.000000
Impact Kinetic Energy = 0.000000
*************************************
name = torque rod
Demise Altitude = 66.525436
Debris Casualty Area = 0.000000
Impact Kinetic Energy = 0.000000
*************************************
name = CCS Avionics
Demise Altitude = 61.803627
Debris Casualty Area = 0.000000
Impact Kinetic Energy = 0.000000
*************************************
name = RWA enclosure
Demise Altitude = 74.349312
Debris Casualty Area = 0.000000
Impact Kinetic Energy = 0.000000
*************************************
name = RWA rotor
Demise Altitude = 0.000000
Debris Casualty Area = 1.502729
Impact Kinetic Energy = 128.181412
*************************************
name = 100535_OX TANK ASSEMBLIES
Demise Altitude = 74.393532
Debris Casualty Area = 0.000000
Impact Kinetic Energy = 0.000000
*************************************
name = 100733_FUEL TANK ASSEMBLY
Demise Altitude = 73.517059
Debris Casualty Area = 0.000000
Impact Kinetic Energy = 0.000000
*************************************
name = 100688_OCELOT ENGINE ASSEMBLIES
Demise Altitude = 0.000000
Debris Casualty Area = 2.142142
Impact Kinetic Energy = 152.901245
```

```
*************************************
name = 100504_AFT CAB BULKHEAD
Demise Altitude = 71.690750
Debris Casualty Area = 0.000000
Impact Kinetic Energy = 0.000000
*************************************
name = 100602_DMLS PRESSURANT TANK_POLARIS 100417 CONFIG
Demise Altitude = 0.000000
Debris Casualty Area = 1.175714
Impact Kinetic Energy = 365.181641
*************************************
name = FLUID COMPONENTS TOP HALF
Demise Altitude = 0.000000
Debris Casualty Area = 1.142996
Impact Kinetic Energy = 423.333771
*************************************
name = FLUID COMPONENTS BOTTOM HALF
Demise Altitude = 0.000000
Debris Casualty Area = 1.130036
Impact Kinetic Energy = 512.517761
*************************************
name = 100719_A LEEG THRUSTER DECK
Demise Altitude = 76.097595
Debris Casualty Area = 0.000000
Impact Kinetic Energy = 0.000000
*************************************
name = 100719_THRUST BULKHEAD POLARIS
Demise Altitude = 77.333839
Debris Casualty Area = 0.000000
Impact Kinetic Energy = 0.000000
*************************************
=============== End of Requirement 4.7-1 ===============
03 09 2022; 12:32:43PM Project Data Saved To File
```