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Systems Engineering Report
BATC Commercial Space Operations

PROJECT TITLE	CAGE CODE	CII N/A
Compact Infrared Radiometer in Space (CIRiS)	13993	PROJECT CODE Civil Space

SUBJECT TITLE

CIRiS – Orbital Debris Assessment – Rev B

PREPARED BY	DEPT NO.	DATE	APPROVED BY	DATE
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SCOPE/TEXT (ATTACH ADDITIONAL SHEETS AS REQUIRED)

This SER documents an assessment of orbital debris generated by the CIRiS mission during launch, operations, and post-mission disposal. This assessment follows the guidelines specified in NASA-STD 8719.14 “Process for Limiting Orbital Debris.” NASA’s Debris Assessment Software (DAS), Version 2.1.1, was used for many of the quantitative calculations. The report is in the format recommended by NASA-STD 8719.14.

Ball performed this study in-house using software and guidelines provided by NASA.

As required, a self-assessment of the ODAR to check compliance with all requirements given by NASA-STD 8719.14 is in Appendix A. Based on this analysis, the CIRiS mission satisfies the NASA guidelines to limit orbital debris.

DISTRIBUTION

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Table 1 shows the compliance of the CIRiS mission with NASA-STD 8719.14. CIRiS satisfies all NASA guidelines to limit orbital debris.

Table 1. Compliance of CIRiS with NASA-STD 8719.14

Guideline	Description	Requirement	CIRiS Performance
4.3-1	Debris released during initialization		
	Area-time product	<0.1 m^2 yr	0
	Object-time product	<100 object yr	0
4.3-2	Debris released during mission operations		
	Area-time product	<0.1 m^2 yr	0
	Object-time product	<100 object yr	0
4.4-1	Accidental explosions during mission		
	Probability of accidental explosion	<0.0001	0
4.4-2	Accidental explosions after mission		
	Limit risk of explosion after mission	Must Do	Pass
4.4-3,4.4-4	Intentional explosions		Pass
4.5-1	Collision with large objects		
	Probability	<0.001	0.0000031
4.5-2	Collision with small objects		
	Probability	<0.01	0.00109
4.6-1	Postmission disposal – LEO		
	Postmission lifetime	<25 yrs	~8 months
4.7-1	Debris survival – uncontrolled reentry		
	Probability of human casualty	< 0.0001	0

The outline of this report follows that suggested in section A.1.5 of NASA-STD 8719.14A. Quantitative probability estimates to compare with requirements were made using the Debris Assessment Software (DAS), Version 2.1.1, available from NASA's Orbital Debris Program Office.

1.0 Program Management and Mission Overview

1.1 Mission Description and Objective

The Compact Infrared Radiometer in Space (CIRiS) is a rebuild of Ball's aircraft and UAV-mounted BESST (Ball Experimental Sea Surface Temperature) thermal infrared radiometer (7.5 to 13.5 um) with improvements to radiometric performance and adaptations for use in the space environment. The upgrades to the components of the previous instrument consists of a more advanced uncooled microbolometer model and a carbon nanotube (CNT) calibration source. Space-based radiometric imaging of the Earth in the thermal infrared band has demonstrated its benefit to scientific research in studies of the hydrologic cycle, urban climate, and extreme storms, while also leading to improvements in ocean/atmosphere interaction models for climate modeling. Land use management will gain the benefit of improved vegetation monitoring and water absorption mapping across agricultural areas and drought-ridden states.

Implementation of an infrared radiometric imager on a CubeSat would potentially provide these benefits at a greatly reduced cost compared to the conventional spacecraft approach. Furthermore, CubeSat constellations could offer an affordable way to increase temporal and spatial earth coverage. Achieving these capabilities will require instrument validation and flight heritage. Therefore, the objectives of this mission are:

1) Raise the Technology Readiness Level (TRL) of the new uncooled detector and carbon nanotube source from TRL 5 to 6.
2) Validate the instrument design in the space environment.
3) Verify that the design achieves a radiometric uncertainty level compliant with the Sustainable Landsat Imager requirements, when calibrating at most once every 50 minutes.
4) Measure the major components of radiometric uncertainty.

No foreign government or space agency involvement will take place in the duration of this mission.

1.2 Program Schedule

CIRiS internal program kick-off took place in January of 2016 and is now in the integration and test stage. Anticipated launch vehicle and launch site are currently unknown, though Ball Aerospace has chosen a proven institution in the Utah State University Space Dynamics Laboratory (SDL) to perform mission operations and coordinate spacecraft launch. The CubeSat Launch Initiative (CSLI) has indicated that launch will be no earlier than October 1, 2018. CIRiS is integrated onto a commercial 6U CubeSat bus and will be deployed into Low Earth Orbit (LEO) from the International Space Station

(ISS) or from a venture class launch. As such, orbit altitude will vary between 400-600 km, with a desired orbit and inclination of 500 km and 98 degrees. Selection of this flight altitude enables scenes of both summer and winter seasons, and overlaps with instruments on Landsat 8 and the ISS to enable cross calibration. The CIRiS mission is aiming for an orbit as close to circular as possible to simplify data correlation through the orbit. This low altitude ensures the spacecraft will enter the Earth's atmosphere within 25 years in accordance to NASA-STD 8719.14 requirement 4.6-1. Calculated lifetime in orbit with CIRiS's drag profile and mass is nearly 250 days (approximately 8 months).

There will be no intended interaction or potential physical interference with other operational spacecraft.

1.3 Responsible Program Manager

The Principle Investigator from Ball Aerospace and Technologies Corp. is David P. Osterman. The Program Manager is Reuben Rohrschneider. Co-Investigator is Sandra Collins and collaborator is William Good.

2.0 Spacecraft Description

2.1 Hardware

2.1.1 Physical Description of Main Structure

A top-level configuration of the fully deployed CIRiS spacecraft during mission operations can be seen in Figure 1.

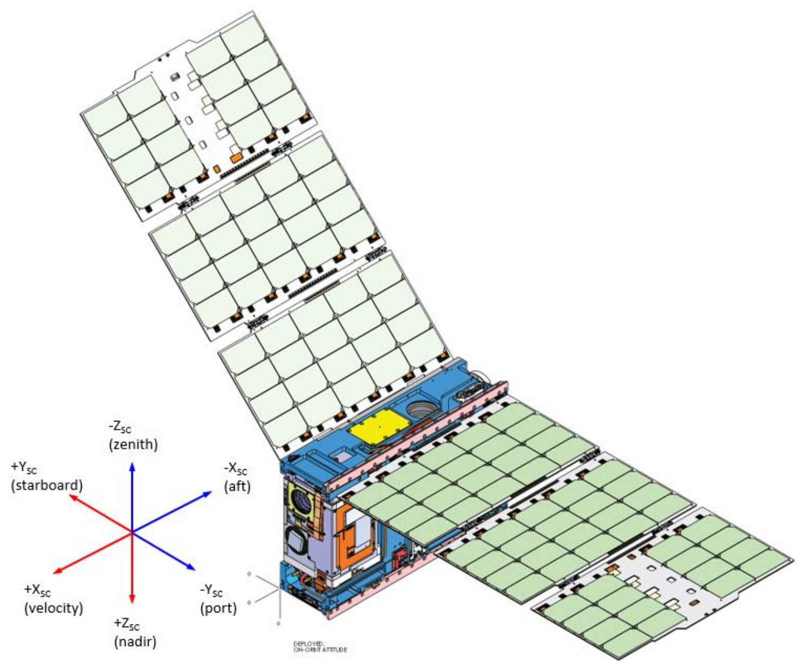

Figure 1. Top Level, Configuration, On-Orbit Deployed

The Blue Canyon Technologies XB1 spacecraft was selected for the CIRiS mission as the spacecraft bus. The structure accommodates the weight and size requirements of the CIRiS main instrument, a contingent maximum mass of 1.5 kg and envelope of 18x19x9 cm^3, using the 6U sized chassis. An exploded view of the internal components is shown in Figure 2.

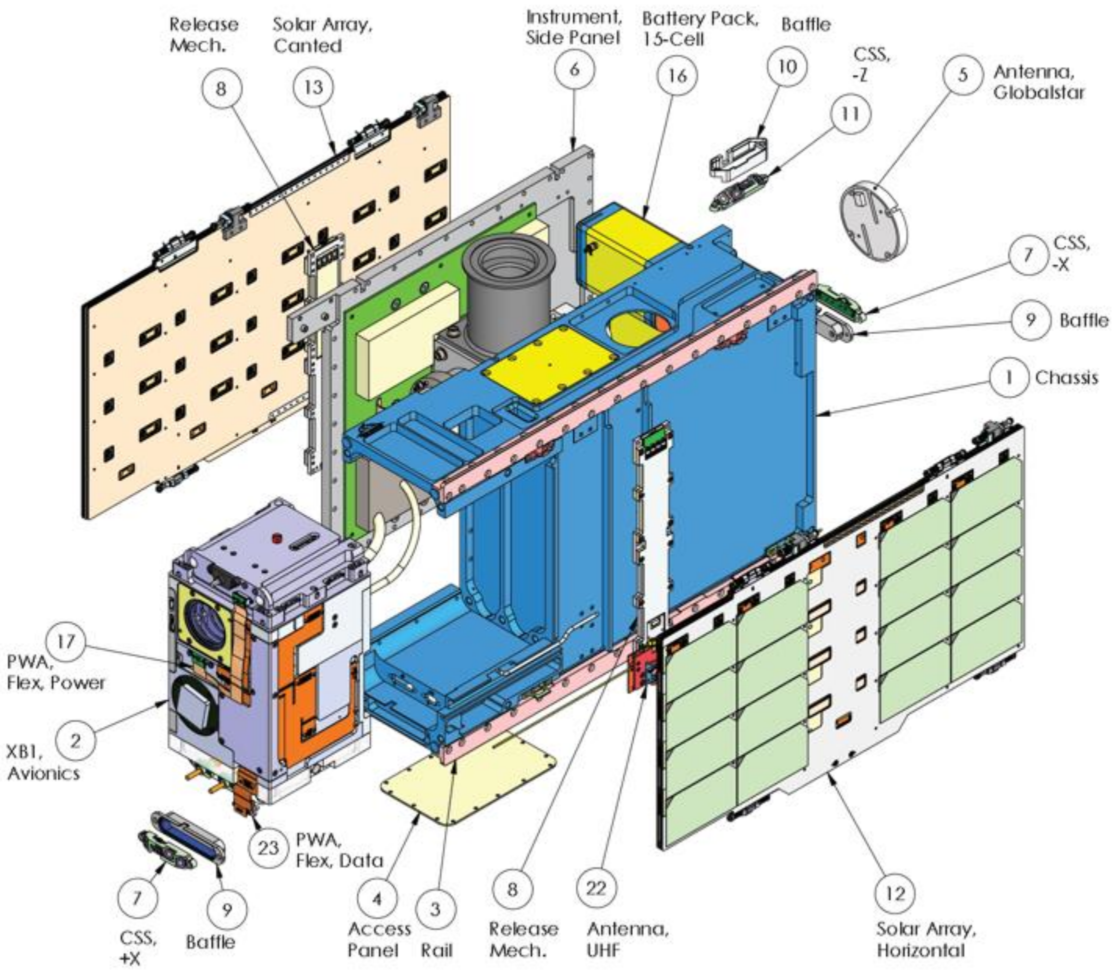

Figure 2. CIRiS top Level assembly, exploded view

The integration view and the CIRiS instrument itself are shown in Figures 3 and 4 respectively.

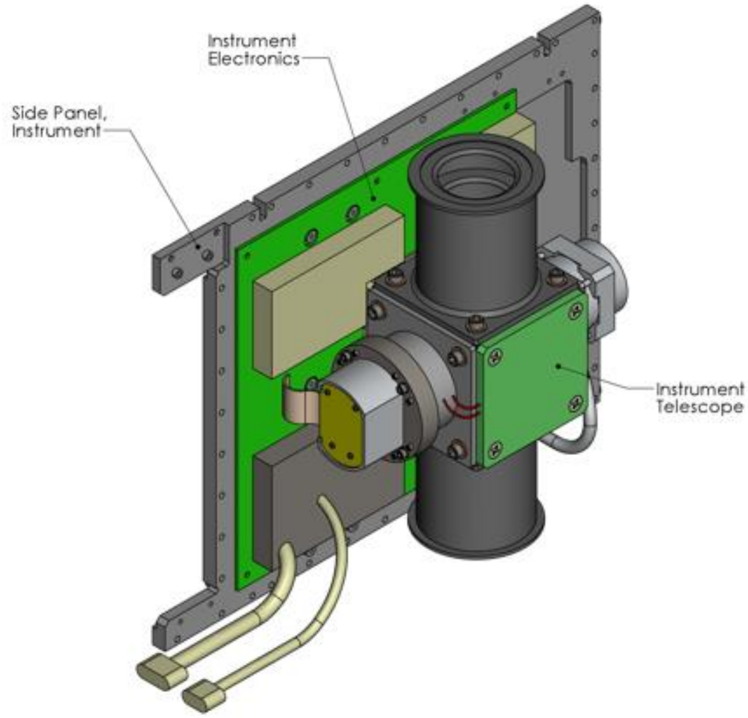

Figure 3. CIRiS Integration View

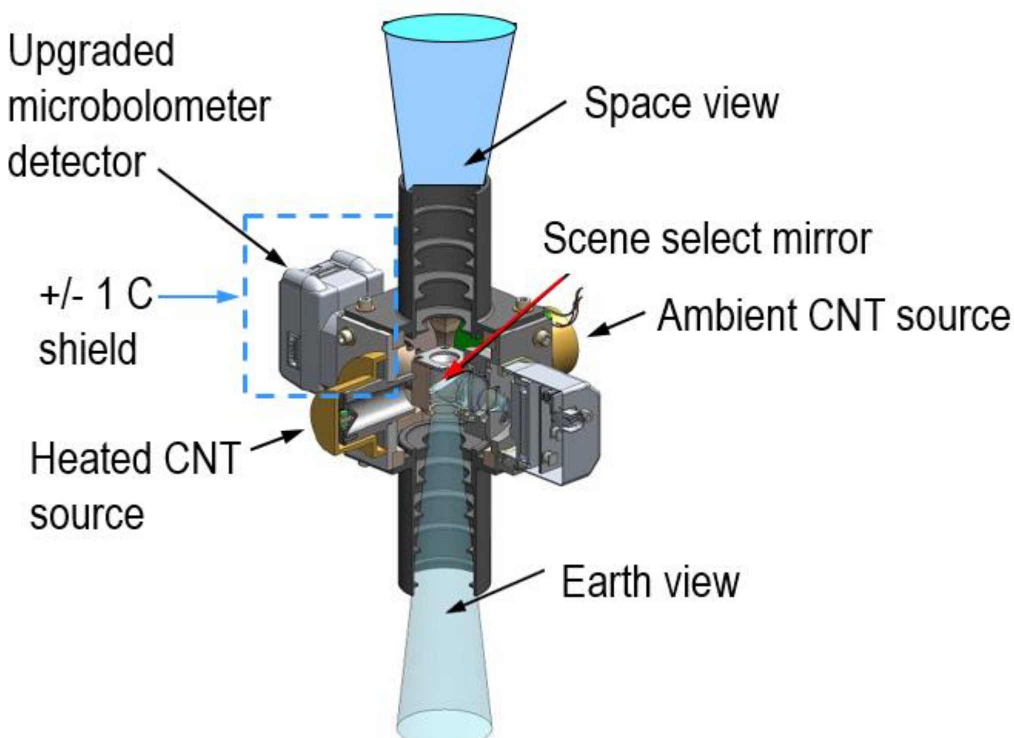

Figure 4. CIRiS Instrument

The total spacecraft mass at launch is estimated to be 10.7 kg and the mass breakdown can be seen in Table 2.

Table 2. CIRiS Mass Summary

FN	Qty.	Document No.	Type	Description	Mass	Contingency	Mass, Ext. w/ Cont.	Notes
	[-]				[g]	[%]	[g]	
-	1	26ASM2148	ASM	CIRiS, Top Level Assembly	**9801.8**	-	**10727.2**	Total
1	1	26PRT2155	PRT	CIRiS, Chassis	2164.9	5%	2273.2	CAD
6	1	26PRT2179	PRT	CIRiS, Instrument Panel	892.3	5%	936.9	CAD
3	2	20PRT2163	PRT	Rail, PSC, -1	75.1	5%	157.8	CAD
4	1	20PRT2175	PRT	Panel, Access	26.2	5%	27.5	CAD
8	2	15ASM1791	ASM	Release Mechanism	78.1	5%	163.9	CAD
2	1	6ASM1750	ASM	XB1, Top Level Assembly	2242.5	5%	2354.6	CAD
5	1	6PRT1483	PRT	Antenna, Globalstar	57.5	5%	60.4	CAD
12	1	15ASM1808	ASM	Solar Array, Horizontal	581.9	5%	611.0	CAD
13	1	15ASM1809	ASM	Solar Array, Canted	581.9	5%	611.0	CAD
9	2	3PRT2159	PRT	CSS, Baffle, Bathtub	5.1	5%	10.7	CAD
7	2	3ASM2025	ASM	CSS, Linear, Digital	8.5	5%	17.8	CAD
10	1	21PRT1945	PRT	CSS, Baffle, Bathtub	3.5	5%	3.6	CAD
11	1	3ASM2015	ASM	CSS, Linear, Digital, Canted	8.9	5%	9.3	CAD
14	4	15PRT2335	PRT	Hinge, Retainer Clip, -1	2.0	5%	8.5	CAD
15	4	15PRT2336	PRT	Hinge, Retainer Clip, -2	1.5	5%	6.2	CAD
22	2	15ASM2495	ASM	Antenna, UHF	13.3	5%	28.0	CAD
23	1	6WA2150	ASM	Harness, Flex	21.5	5%	22.6	CAD
17	1	22WA2102	ASM	Harness, Flex	3.9	5%	4.1	CAD
-	1	-	ASM	Harness, Misc	151.4	5%	158.9	CAD
-	1	-	ASM	CIRiS, Instrument	1500.0	5%	1575.0	Estimate
16	1	26ASM2583	ASM	CIRiS, Battery Pack Assembly	1291.0	5%	1355.6	CAD
-	1	-	-	Fastener Hardware	90.9	5%	95.4	CAD
-	1	-	-	Consumables	196.0	20%	235.2	Estimate

2.1.2 Description of On-Board Propellants

The CIRiS spacecraft contains neither pressure vessels nor a propulsion system for use during on-orbit operations.

2.1.3 Description of Electrical Generation and Storage System

Electrical generation is performed using SolAero solar cells with 26.62 cm^2 cell area and 29.5% efficiency. The deployed array is shown in Figure 1. Collected energy is stored in the 15-cell Lithium-ion pack (3S3P) with 14 Ahr capacity. Average payload orbit power is 30 W during operations and 16 W during charge and communication orbits.

2.1.4 Description of Control Systems

Precision pointing of CIRiS is done using star trackers, reaction wheels, torque rods, an IMU, magnetometer, sun sensors, and GPS. Normal attitude with respect to the velocity vector is demonstrated in Figure 1.

2.1.5 Description of Range Safety Systems

The CIRiS spacecraft is not equipped with range safety systems.

2.1.6 Description of Radioactive Materials On-Board

The CIRiS spacecraft does not contain radioactive materials on-board.

2.1.7 Description of Additional Sources of Stored Energy

The CIRiS spacecraft contains three reaction wheels to provide attitude control torques. Their maximum momentum capability is 0.045 Nms and will not be enough to be a source of dangerous stored energy.

3.0 Assessment of Spacecraft Debris Released During Normal Operations

NASA-STD 8719.14 requirement 4.3-1a states:

“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.”

NASA-STD 8719.14 requirement 4.3-1b states:

“The total object-time product shall be no larger than 100 object-years per mission. 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.”

NASA-STD 8719.14 requirement 4.3-2 states:

“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.”

3.1 Debris Released During Staging, Payload Separation, or Payload Deployment

CIRiS will not release any debris during staging or payload deployment.

3.2 Debris Released During Mission Operations

CIRiS will not release any debris during mission operations.

4.0 Assessment of Spacecraft Intentional Breakups and Potential for Explosions

NASA-STD 8719.14 requirement 4.4-1 states:

“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).”

NASA-STD 8719.14 requirement 4.4-2 states:

“Design of all spacecraft and launch vehicle orbital stages shall include the ability and a plan to deplete all onboard sources of stored energy and disconnect all energy generation sources when they are no longer required for mission operations or postmission disposal or control to a level which can not cause an explosion or deflagration large enough to release orbital debris or break up the spacecraft.”

NASA-STD 8719.14 requirement 4.4-3 states:

“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. 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.”

NASA-STD 8719.14 requirement 4.4-4 states:
“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}.”

4.1 Intentional Breakups

CIRiS will not undergo intentional breakup or fragmentation.

4.2 Potential for Explosions

No on-board systems are susceptible to the potential of explosions. No dangerous fluids or pressurized systems will be used during the life of the satellite.

5.0 Assessment of Spacecraft Potential for On-Orbit Collisions

NASA-STD 8719.14 requirement 4.5-1 states:
“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”

NASA-STD 8719.14 requirement 4.5-2 states:
“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 postmission disposal requirements is less than 0.01”

5.1 Assessment of Collisions with Large Debris During Mission Operations

Large debris are defined by the DAS software as those larger than 10 cm. This is about the limit of objects which can be tracked and catalogued by the United States Space Command. In LEO, the threshold size for cataloguing is approximately 10 to 20 cm in diameter. The probability of collision of CIRiS with large debris was estimated using the DAS software. The following inputs to DAS were used:

- Apogee and perigee altitude = 450 km
- Inclination = 98 degrees
- Spacecraft area-to-mass = 0.098 m^2/kg
- Mass = 10.7 kg
- Mission duration = 0.667 years

The DAS software indicates that for man-made debris larger than 10 cm in diameter, the probability of collision is 0.0000031. This meets the requirement of probability less than 0.001.

5.2 Assessment of Collisions with Small Debris During Mission Operations

Small debris are defined by the NASA Standard 8719.14 as those smaller than 10 cm. This is much smaller than those of sufficient size to be tracked and catalogued by the United States Space Command. The probability for collision of CIRiS with small debris was estimated using the DAS software.

Requirement 4.5-2 applies only to subsystems that are vital to completing postmission disposal. Only critical components that will be at risk of instrument failure after an impact were analyzed. This includes the spacecraft bus, the exposed views of the CIRiS instrument, the batteries, and the antennas. The DAS software was used to acquire the data below:

Table 3. Small Debris Collision Model

Spacecraft	Compliance	Probability of PMD Failure	Critical Surface	Probability of Penetration
CIRiS	Compliant	0.00109	XB1, Avionics Bus	0.000245
			CIRiS Instrument	0.000594
			UHF Antenna	0.000047
			Battery Pack	0.000123

The DAS software indicates that for man-made debris and meteoroids smaller than 10 cm in diameter, the probability of collision with a critical surface is 0.00109. This meets the requirement of probability less than 0.01.

6.0 Assessment of Spacecraft Postmission Disposal Plans and Procedures

NASA-STD 8719.14 requirement 4.6-1 states:
“A spacecraft or orbital stage with a perigee altitude below 2,000 km shall be disposed of by one of the following three methods:

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 de-orbit 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.”

NASA-STD 8719.14 requirement 4.6-2 states:
“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.”

NASA-STD 8719.14 requirement 4.6-3 states:
“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.

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.”

NASA-STD 8719.14 requirement 4.6-4 states:
“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:

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."

6.1 Planned Option for Postmission Disposal

Un-controlled deorbit is currently planned for the postmission disposal of CIRiS. This will meet guideline 4.6-1, as natural forces will lead to atmospheric reentry in approximately 8 months, well within the 25-year requirement.

6.2 Description of Disposal Procedures and Systems

There is no hardware or concept of operations for performing an un-controlled deorbit. Orbital decay will occur throughout the mission life of the spacecraft until CIRiS begins to burn up in the atmosphere approximately 8 months after deployment.

7.0 Assessment of Spacecraft Reentry Hazards

NASA-STD 8719.14 requirement 4.7-1 states:
"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).

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 reentries, the product of the probability of failure of the reentry burn (from Requirement 4.6-4.b) and the risk of human casualty assuming uncontrolled reentry shall not exceed 0.0001 (1:10,000)."

Current plans are for the CIRIS spacecraft to be disposed of by uncontrolled reentry by the natural forces of orbital decay. The remainder of this section contains a preliminary evaluation of the hazard posed by uncontrolled reentry of the CIRiS spacecraft and compliance with NASA-STD 8719.14 requirement 4.7-1a.

7.1 Calculation of Probability of Human Casualty from Debris Surviving Uncontrolled Reentry

To calculate the risk of human casualty, the arrangement of each space structure element needs to be defined to assess its reentry survival potential. As stated in NASA-STD 9719.14 and based on empirical and theoretical values, the outermost structure (*i.e.* the "parent" object) is assumed to break apart at an altitude of 78 km. The first level of “child” objects is exposed at this point. The objects are then subjected to the various forces of the reentry model. If a child object is destroyed (“demises”) due to the reentry forces, it does not affect the final casualty area calculation. The following data was created from the DAS software:

Table 4. Reentry Survival Model for CIRiS

Component	**Demise (km)**	**Casualty Area (m^2)**	**Kinetic Energy (J)**
Parent			
CIRiS Main Structure	67.7	0	0
Solar Array	59.4	0	0
Children			
XB1, Avionics Bus	56.3	0	0
CIRiS Instrument	62.4	0	0
Battery Pack	66.8	0	0
UHF Antenna	67.0	0	0

The DAS software indicates that for uncontrolled reentry of the CIRiS spacecraft, all components of CIRiS will reach its demise before reaching the surface of the Earth. Therefore, there will be no casualty area from the breakup of components. This meets the requirement that the risk of human casualty from surviving debris shall not exceed 0.0001.

7.2 Assessment of Spacecraft Hazardous Materials

The CIRiS spacecraft does not contain hazardous materials.

Appendix A. Requirement Compliance Self-Assessment

Orbital Debris Assessment Report Evaluation: ___CIRiS___ Mission

(based upon ODAR __A__ version, dated ___August 9th__ , 2017)

Reqm't #	Launch Vehicle				Spacecraft			Comments
	Compliant	Not Compliant	Incomplete	Standard Non Compliant	Compliant or N/A	Not Compliant	Incomplete	
4.3-1.a	☐	☐	☐	☐	■	☐	☐	CIRiS will not release any debris during staging or mission operations.
4.3-1.b	☐	☐	☐	☐	■	☐	☐	CIRiS will not release any debris during staging or mission operations.
4.3-2	☐	☐	☐	☐	■	☐	☐	CIRiS will not release any debris during staging or mission operations.
4.4-1	☐	☐	☐	☐	■	☐	☐	No on-board systems are susceptible to the potential of explosions. No dangerous fluids or pressurized systems will be used during the life of the satellite.
4.4-2	☐	☐	☐	☐	■	☐	☐	No on-board systems are susceptible to the potential of explosions. No dangerous fluids or pressurized systems will be used during the life of the satellite.
4.4-3	☐	☐	☐	☐	■	☐	☐	CIRiS will not undergo intentional breakup, fragmentation, or a planned explosion.
4.4-4	☐	☐	☐	☐	■	☐	☐	CIRiS will not undergo intentional breakup, fragmentation, or a planned explosion.
4.5-1	☐	☐	☐	☐	■	☐	☐	Probability of collision is 0.0000031.
4.5-2	☐	☐	☐	☐	■	☐	☐	Probability of collision is 0.00109.
4.6-1(a)	☐	☐	☐	☐	■	☐	☐	CIRiS will reach EOL from orbital decay at approximately 8 months, well below the 25 year limit.
4.6-1(b)	☐	☐	☐	☐	■	☐	☐	Spacecraft will not need to be placed into a storage orbit.
4.6-1(c)	☐	☐	☐	☐	■	☐	☐	Spacecraft will not need to be directly retrieved.

Reqm't #	Launch V				Spacecraft			Comments
	Compliant	Not Compliant	Incomplete	Standard Non Compliant	Compliant	Not Compliant	Incomplete or N/A	
4.6-2	☐	☐	☐	☐	■	☐	☐	A disposal orbit around GEO is unnecessary for a LEO satellite.
4.6-3	☐	☐	☐	☐	■	☐	☐	Does not apply to CIRiS.
4.6-4	☐	☐	☐	☐	■	☐	☐	Probability is above 0.9 at EOM (probability is 1.0, CIRiS will burn up in the atmosphere before ever needing to be placed in storage)
4.7-1	☐	☐	☐	☐	■	☐	☐	All components burn up before reaching the Earth's surface.
4.8-1					☐	☐	☐	

Additional Comments: Required Self-Assessment.

Reviewed by: Alex Orellana on: 9 / 6 / 2017

Figure 5. ODAR Review Check sheet