Attachment 5
Cygnus Debris Assessment Report

Purpose: This memorandum is an attachment to the Orbital ATK FCC experimental radio license application for the OA-8 Cygnus spacecraft.

Scope: This memorandum provides a technical analysis in support of the FCC Office of Engineering and Technology (OET) e-File system application. The data is provided to satisfy § 5.64 Requirements. The data is submitted in support of the following application:

Description	Number
FRN:	0016225740
STA File Number:	0960-EX-ST-2017

Mission Overview: Orbital ATK will launch and operate the OA-8 Cygnus spacecraft as part of the NASA Cargo Resupply Services (CRS) program. The launch vehicle will be an Antares out of Pad 0A at Wallops Flight Facility. The Cygnus mission will include launch, orbit raising maneuvers, approach and berthing with the International Space Station (ISS), unberthing and departure from the ISS, orbit maneuvering, and destructive reentry into the Earth's atmosphere. Destructive re-entry is anticipated to be up to 14 days after separation from the ISS.

Analysis

1 [78 FR 25162, APR. 29, 2013] § 5.64 (B)

Requirement:
Except where the satellite system has already been authorized by the FCC, applicants for an experimental authorization involving a satellite system must submit a description of the design and operational strategies the satellite system will use to mitigate orbital debris, including the following information:
Note:
Orbital ATK has previously prepared and submitted to NASA, pursuant to contractual requirements, a "Cygnus Reentry Analysis for OA-4+ Missions" (6354-ER6104).

§ 5.64 (b)(1)
Requirement:
A statement that the space station operator has assessed and limited the amount of debris released in a planned manner during normal operations, and has assessed and limited the probability of the space station becoming a source of debris by collisions with small debris or meteoroids that could cause loss of control and prevent post-mission disposal;
Assessment:
No planned explosions or intentional collisions are performed for Cygnus.
The Cygnus has a Probability of No Penetrations (PNP) of 0.9996 from Micrometeoroids and Orbital Debris (MMOD) while berthed to the ISS for up to 90 days. Typically Cygnus arrives at the ISS within 3 days after launch and de-orbits within eight days after departing the ISS. Any increase in MMOD risk (beyond that calculated for the ISS berthed phase) will be negligible given that: (a) the time period on-orbit before and after visiting the ISS is very short; and (b)

although the berthed Cygnus receives limited shadowing of the incoming MMOD flux by the ISS, this does not have a significant effect on MMOD PnP, compared to free flight, since the Cygnus sensitive surfaces remain exposed to the flux.

For the Cygnus vehicle itself, there is no planned object or debris release from Cygnus during the mission, with exception of NanoRacks.
For the OA-8 mission, and possible future missions, Cygnus will carry an external NanoRacks CubeSat Satellite Deployer (NRCSD), which will disperse up to10 “CubeSat” microsats following departure from ISS. Each NRCSD, with integrated CubeSats, is provided to OA by NASA. The microsats release point will be either below the ISS (~395 km) or above the ISS (~450 – 500 km). In each case the orbit will be circular. Regulatory requirements including reentry debris assessment on the cubesats are the responsibility of NanoRacks and the respective providers, and are not covered in this document.

1.1 § 5.64 (b)(2)

Requirement:

A statement that the space station operator has assessed and limited the probability of accidental explosions during and after completion of mission operations. This statement must include a demonstration that debris generation will not result from the conversion of energy sources on board the spacecraft into energy that fragments the spacecraft. Energy sources include chemical, pressure, and kinetic energy. This demonstration shall address whether stored energy will be removed at the spacecraft's end of life, by depleting residual fuel and leaving all fuel line valves open, venting any pressurized system, leaving all batteries in a permanent discharge state, and removing any remaining source of stored energy, or through other equivalent procedures specifically disclosed in the application;

Assessment:

Because the Cygnus spacecraft operates in the vicinity of the ISS, Orbital ATK follows a stringent set of safety requirements. As a fundamental design requirement, Cygnus is two-fault tolerant to catastrophic hazards, including accidental explosions that could endanger the ISS and the Crew. Fault tolerance has been verified through detailed Orbital ATK FMEA and hazard assessments, and has been accepted by the NASA ISS Safety Review Panel (SRP) for previous Cygnus missions.
The only identified possible cause of an on-orbit explosion of the Cygnus propulsion subsystem is overpressure of the fuel and oxidizer tanks due to failure of a pressure regulator. The expected probability of a resulting explosion event during Cygnus on-orbit operations is 0.0003, which meets NASA quantitative criteria for limiting the risk of accidental explosions.

The Cygnus planned reentry is performed at the end of the Cygnus mission, and into the South Pacific in an uninhabited area. In light of the planned destructive re-entry, additional measures for removal of stored energy are not necessary to achieve the goal of preventing on-orbit debris generation.

1.2 § 5.64 (b)(3)

Requirement:

A statement that the space station operator has assessed and limited the probability of the space station becoming a source of debris by collisions with large debris or other operational space stations. Where a space station will be launched into a low-Earth orbit that is identical, or very similar, to an orbit used by other space stations, the statement must include an analysis of the potential risk of collision and a description of what measures the space station operator plans to take to avoid in-orbit collisions. If the space station operator is relying on coordination with another system, the statement shall indicate what steps have been taken to contact, and ascertain the likelihood of successful coordination of physical operations with, the other system. The statement must disclose the accuracy - if any - with which orbital parameters of non-geostationary satellite orbit space stations will be maintained, including apogee, perigee, inclination, and the right ascension of the ascending node(s). In the event that a system is not able to maintain orbital tolerances, i.e., it lacks a propulsion system for orbital maintenance, a statement disclosing that fact shall be included in the debris mitigation disclosure. Such systems shall also indicate the anticipated evolution over time of the orbit of the proposed satellite or satellites. Where a space station operator requests the assignment of a geostationary-Earth orbit location, it shall assess whether there are any known satellites located at, or reasonably expected to be located at, the requested orbital location, or assigned in the vicinity of that location, such that the station keeping volumes of the respective satellites might overlap. If so, the statement shall identify those parties and describe the measures that will be taken to prevent collisions;

Assessment:

During free-flight operations, conjunction screening before and after Cygnus phasing Delta-V burns is performed by NASA (with support from JSPOC). Phasing burns are adjusted if a conjunction is noted to clear the conjunction.

Orbital ATK has assessed and limited the probability of unintended contact with the ISS. Cygnus's approach to the ISS is closely coordinated between ISS operations staff and Orbital ATK operations staff. The approach involves successive maneuvers of Cygnus to a series of way-points below ISS, with well-developed contingency plans for aborting the approach if that should become necessary. Each maneuver is designed and verified to be fail-safe, i.e. any failure will leave Cygnus in a trajectory that does not intersect with the ISS. Once Cygnus is in the immediate vicinity of the ISS, the ISS crew grapples the Cygnus capsule and berths it to ISS. Cygnus Flight Software, including new upgrades, is tested and accepted prior to each mission with the NASA customer, including this phase of flight. The flight software is built on previous mission testing and on-orbit experience, going back to the Cygnus Demonstration mission.

When the spacecraft is berthed at the ISS, it will be part of the ISS conjunction assessment and collision avoidance maneuver process.
Post departure from ISS, Cygnus will perform additional mission operations prior to de-orbit, specifically the deployment of up to 10 cubesats. These operations will be completed in 2 days, allowing Cygnus to be de-orbited within 14 days of ISS departure.

1.3 5.64 (b)(4)

Requirement:

A statement detailing the post-mission disposal plans for the space station at end of life, including the quantity of fuel - if any - that will be reserved for post-mission disposal maneuvers. For geostationary-Earth orbit space stations, the statement shall disclose the altitude selected *for a post-mission disposal orbit and the calculations that are used in deriving the disposal altitude. The statement shall also include a casualty risk assessment if planned post-mission disposal involves atmospheric re-entry of the space station. An assessment shall include a statement as to the likelihood that portions of the spacecraft will survive re-entry and reach the surface of the Earth, and the probability of human casualty as a result.*

Assessment:

A controlled reentry is performed by Cygnus. The Cygnus spacecraft is single failure tolerant to conducting the controlled reentry operations. In addition, Orbital ATK will reserve sufficient fuel for reentry operations.

The declared reentry zone for Cygnus controlled reentry is defined by the following boundary coordinates:

500000 S 1300000 W (50.0°S, 130.0°W)
303000 S 1300000 W (30.5°S, 130.0°W)
303000 S 1600000 W (30.5°S, 160.0°W)
500000 S 1600000 W (50.0°S, 160.0°W)

The closest inhabited area to this reentry zone is the French Polynesian island of Rapa, which is located at 27.6°S, 144.6°W. Population is approximately 500, and distance from the northern reentry zone boundary (at 30.5°S) is approximately 410 km. The closest highly populated city is Papeete, French Polynesia, with an urban population of approximately 130,000 and located approximately 1800 km north of the reentry zone boundary.

Cygnus debris field area based on monte carlo analysis of possible trajectories and dispersions shows the predicted debris area provides very large margin against possible debris impacts outside of the declared reentry zone.

Cygnus will have a controlled re-entry that will occur over an unpopulated ocean area. Given compliance with the re-entry trajectory constraints defined above, the population density beneath the trajectory is extremely small and assumed to be 0.

For any uncontrolled re-entry resulting from a combination of Cygnus vehicle anomalies, the Casualty risk is calculated as:

$E_C = (1\text{-}Ps) \times (\sum A_{ci} \times D_{pi})$, where

$(\sum A_{ci} \times D_{pi})$ = the Human Risk factor described in 6354-ER6104, Table 7.3-1; and

Ps = Cygnus probability of mission success

Based on the Reliability Analysis prepared for the Enhanced Cygnus missions, and documented in greater detail in 6341-ER22201, Rev 01, mission probability of success is predicted as 0.9306 for a 100 day total (90 days berthed) mission duration. For purposes of the reentry calculation, however, a separate calculation is performed to include only those Cygnus functions required to successfully perform the reentry. De-orbit and reentry is controlled from the ground and, therefore, the Orbital ATK MMC-D ground station is also included in the calculation. Based on these assumptions, the predicted probability of success for a successful reentry is 0.9858.

The calculation of casualty risk is then:

$E_c = (1 - 0.9858) \times (8.0E\text{-}4)$
$= 11.3E\text{-}6$

For each Cygnus mission, Orbital ATK provides advance notifications to the appropriate regulatory agencies which in turn issue advisories for air traffic (NOTAMs) and sea traffic (NOTMARs) in the affected area. These agencies include: the New Zealand Civil Aviation Authority (CAA) and Direccion General de Aeronautica Civil de Chile (DGAC), for NOTAM postings; and the US National Geospatial Intelligence Agency (NGA) for NOTMARs.