Cygnus NG-21 Debris Assessment Report

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1 Purpose

This memorandum is an attachment to the Northrop Grumman Systems Corporation (NGSC) FCC Special Temporary Authorization (STA) application for the Cygnus NG-21 spacecraft.

2 Scope

This memorandum provides a technical analysis in support of the FCC Office of Engineering and Technology (OET) e-File system application for NGSC. This analysis satisfies requirements in the Title 47 of the Code of Federal Regulations, Chapter I, Subchapter A, Part 5 (Experimental Radio Service), § 5.64(b) (Special provisions for satellite systems), as amended and published in 85 FR 42449 on August 25, 2020.

The analysis supports the following FCC File Number:

Description	Number
FCC File Number	0881-EX-ST-2024

3 Mission Overview

NGSC will launch and operate the Cygnus NG-21 spacecraft as part of the NASA Commercial Resupply Services 2 (CRS2) program. The launch vehicle will be a Falcon 9 out of Cape Canaveral. The Cygnus mission will include launch, orbit-raising maneuvers, approach to and berthing with the International Space Station (ISS), un-berthing and departure from the ISS, orbit maneuvering, and destructive re-entry into the Earth's atmosphere.

4 Assessment of 47 CFR 5 § 5.64

4.1 § 5.64 (b)

Requirement

(b) 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:

Assessment

At the time of this assessment by NGSC, the Cygnus NG-21 spacecraft satellite had yet to receive FCC authorization. Cygnus spacecraft prior to NG-21 have received FCC authorization.

In addition to the information provided herein describing the design and operational strategies used by Cygnus to mitigate orbital debris, NGSC has previously developed and submitted to NASA, pursuant to contractual requirements, a "Cygnus Re-entry Analysis for NG-12+ Missions" (6472-ER6106). Also, through collaborative testing and analysis with the NASA JSC MMOD group, a Cygnus Micrometeoroid and Orbital Debris (MMOD) shielding design was developed and verified, as described in Design Note DN-CRS2-SE-099.

4.2 § 5.64 (b)(1)

Requirement

(1) A statement that the space station operator has assessed and limited the amount of debris released in a planned manner during normal operations. Where applicable, this statement must include an orbital debris mitigation disclosure for any separate deployment devices, distinct from the space station launch vehicle, that may become a source of orbital debris;

Assessment

No planned explosions or intentional collisions are performed for Cygnus. For the Cygnus vehicle itself, there is no planned object or debris release from Cygnus during the mission.

4.3 § 5.64 (b)(2)

Requirement

(2) A statement indicating whether the space station operator has assessed and limited the probability that the space station(s) will become a source of debris by collision with small debris or meteoroids that would cause loss of control and prevent disposal. The statement must indicate whether this probability for an individual space station is 0.01 (1 in 100) or less, as calculated using the NASA Debris Assessment Software or a higher fidelity assessment tool;

Assessment

In the NGSC/NASA collaborative MMOD analysis (DN-CRS2-SE-099), penetrations are defined as damage to the Cygnus vehicle that "results in loss-of-vehicle or endangers crew on-orbit during mated phases only." Using the NASA Bumper 3 software, separate Finite Element Models (FEM) are used for Cygnus berthed at ISS Node 2 Nadir and Node 1 Nadir with 180° clocking. Also considered were contingency attitudes, Dual Berthed Visiting Vehicle (DBVV) scenarios, and optional equipment mounted or unmounted external to the Spacecraft that affects critical equipment inside.

The analysis was intended to address safety of the astronauts while Cygnus is berthed to the ISS and not the un-crewed, remotely operated Cygnus while in free flight. Cygnus will arrive at the ISS generally within 3 days after launch, remain berthed for a minimum of 100 days, and de-orbit within 7 days after departing the ISS. An extended mission could increase the berthing period to 180 days with re-entry lasting less than 48 hours. Alternatively, after berthing for up to 120 days, departure and de-orbit may continue out to 180 days (i.e., FCC STA expiration). Mission Probability of No Penetration (PNP) and the requirements are evaluated in DN-CRS2-SE-099 based on calendar year using 100-day and 180-day berthed durations as shown below.

Cygnus PNP Results for 100 Days

Total Cygnus PNP (REQ 0.99958)

Year	Node 1	Node 2
2019	0.99978	0.99973
2020	0.99979	0.99974
2021	0.99977	0.99971
2022	0.99979	0.99974
2023	0.99979	0.99974
2024	0.99980	0.99975

Cygnus PNP Results for 180 days

Total Cygnus PNP (REQ 0.99925)

Year	Node 1	Node 2
2019	0.99961	0.99951
2020	0.99963	0.99954
2021	0.99959	0.99949
2022	0.99963	0.99954
2023	0.99963	0.99953
2024	0.99964	0.99955

For a berthed duration of 100 days, the worst-case Probability of No Penetration (PNP) is 0.99971, meaning the maximum probability of a MMOD collision causing loss of spacecraft control and prevention of disposal is 1 - 0.99971 = 0.00029. For a berthed duration of 180 days, the worst-case PNP is 0.99949, meaning the maximum probability of a MMOD collision causing loss of spacecraft control and prevention of disposal is 1 - 0.99949 = 0.00051. Both PNP values meet the FCC requirement of ≤ 0.01 with significant margin.

4.4 § 5.64 (b)(3)

Requirement

(3) A statement that the space station operator has assessed and limited the probability, during and after completion of mission operations, of accidental explosions or of release of liquids that will persist in droplet form. 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 should 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, NGSC 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 crew. Fault tolerance has been verified through detailed NGSC FMEA and hazard assessments, which have been accepted by the NASA ISS Safety Review Panel (SRP).

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 such an 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 re-entry is performed at the end of the Cygnus mission, and into the South Pacific in an uninhabited area. Because 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.

4.5 § 5.64 (b)(4)

Requirement

(4) A statement that the space station operator has assessed and limited the probability of the space station(s) becoming a source of debris by collisions with large debris or other operational space stations.

Assessment

NGSC has assessed and limited the probability of the Cygnus vehicle becoming a source of debris by collisions with large debris and other operational space stations including the ISS, as detailed in the sub-sections below.

4.5.1 § 5.64 (b)(4)(i)

Requirement

(i) Where the application is for an NGSO space station or system, the following information must also be included:

Assessment

The Cygnus spacecraft is a Non-geostationary Satellite Orbit (NGSO) system.

4.5.1.1 § 5.64 (b)(4)(i)(A)

Requirement

(*A) A demonstration that the space station operator has assessed and limited the probability of collision between any space station of the system and other large objects (10 cm or larger in diameter) during the total orbital lifetime of the space station, including any de-orbit phases, to less than 0.001 (1 in 1,000). The probability shall be calculated using the NASA Debris Assessment Software or a higher fidelity assessment tool. The collision risk may be assumed zero for a space station during any period in which the space station will be maneuvered effectively to avoid colliding with large objects.*

Assessment

During free-flight operations, NASA (with support from JSPOC) performs conjunction screening before and after Cygnus phasing Delta-V burns. Phasing burns are adjusted as necessary to clear any identified conjunctions.

The collision risk is assumed to be zero during free flight since Cygnus can be maneuvered effectively to avoid colliding with large objects. When Cygnus is berthed to the ISS, it will be part of the ISS conjunction assessment and collision avoidance maneuver process.

4.5.1.2 § 5.64 (b)(4)(i)(B)

Requirement

(B) The statement must identify characteristics of the space station(s)' orbits that may present a collision risk, including any planned and/or operational space stations in those orbits, and indicate what steps, if any, have been taken to coordinate with the other spacecraft or system, or what other measures the operator plans to use to avoid collision.

Assessment

After separation from launch vehicle booster stages, orbital insertion, and orbit raising maneuvers, the resulting trajectory places Cygnus in the same orbital vicinity as the ISS. NGSC has assessed and limited the probability of unintended contact with the ISS. The Cygnus approach to the ISS is closely coordinated between ISS and Cygnus operations staff. The approach involves successive maneuvers of Cygnus to a series of waypoints 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; that is, any failure will leave Cygnus in a trajectory that does not intersect with the ISS. Refer to the assessment of § 5.64 (b)(6) for what happens when Cygnus is in the immediate vicinity of the ISS for proximity operations.

Antares – the launch vehicle used for Cygnus – has its own communications equipment and uses different frequencies, and is therefore covered under a separate STA. Orbital debris assessments for Antares will be included in the Antares STA application.

4.5.1.3 § 5.64 (b)(4)(i)(C)

Requirement

(C) If at any time during the space station(s)' mission or de-orbit phase the space station(s) will transit through the orbits used by any inhabitable spacecraft, including the International Space Station, the statement must describe the design and operational strategies, if any, that will be used to minimize the risk of collision and avoid posing any operational constraints to the inhabitable spacecraft.

Assessment

The Cygnus spacecraft is a Non-geostationary Satellite Orbit (NGSO) system that operates in Low Earth Orbit up to 500 km in altitude and is trackable with ground radar.

The Cygnus spacecraft contains RF equipment to enable communication with the TDRS system and various ground stations. The Cygnus spacecraft also contains equipment to communicate with the GPS constellation for precise knowledge of the spacecraft's location. The spacecraft location knowledge is shared with the NASA ISS flight control team for active tracking of the spacecraft.

The Cygnus spacecraft is also registered with the 18th Space Defense Squadron (18 SDS) via the NASA ISS flight control team interfaces and active tracking is performed by the NASA team. (18 SDS was formerly called the 18th Space Control Squadron, or 18 SCS.)

The Cygnus trajectory data (ephemeris) and maneuver plans are shared with the NASA ISS flight control team. The NASA ISS flight control team provides the Cygnus data to 18 SDS via NASA interfaces and procedures.

18 SDS, located at Vandenberg Space Force Base, CA, provides 24/7 support to the Space Surveillance Network (SSN), maintains the space catalog, and manages United States Space Command's Space Situational Awareness (SSA) sharing program for the benefit of U.S.

Government, foreign government, and commercial entities. The squadron conducts conjunction assessment for the ISS and Cygnus missions, including the free-flight and de-orbit phases. In the event of a possible conjunction with the ISS or other spacecraft, 18 SDS immediately notifies the NASA ISS flight control team and the Cygnus flight team.

4.5.1.4 § 5.64 (b)(4)(i)(D)

Requirement

(D) The statement must disclose the accuracy, if any, with which orbital parameters will be maintained, including apogee, perigee, inclination, and the right ascension of the ascending node(s). In the event that a system will not maintain orbital tolerances, e.g., its propulsion system will not be used for orbital maintenance, that fact should be included in the debris mitigation disclosure. Such systems must also indicate the anticipated evolution over time of the orbit of the proposed satellite or satellites. All systems must describe the extent of satellite maneuverability, whether or not the space station design includes a propulsion system.

Assessment

For standard Cygnus flights to the ISS, the satellite is not in free-flight long enough to require any station-keeping, nor do mission objectives require it. Conjunction screening is performed daily with the assistance of NASA personnel. Any likely conjunctions will result in Cygnus performing an evasive maneuver with its propulsion system.

The Cygnus propulsion system consists of a single 100-lb bipropellant engine for large maneuvers and 3 sets of monopropellant attitude control thrusters that can be used for small, more-precise Delta-V maneuvers. Most debris avoidance maneuvers require a small Delta-V making the attitude control thrusters the preferred thrusters for such burns.

4.5.1.5 § 5.64 (b)(4)(i)(E)

Requirement

(E) The space station operator must certify that upon receipt of a space situational awareness conjunction warning, the operator will review and take all possible steps to assess the collision risk, and will mitigate the collision risk if necessary. As appropriate, steps to assess and mitigate the collision risk should include, but are not limited to: contacting the operator of any active spacecraft involved in such a warning; sharing ephemeris data and other appropriate operational information with any such operator; and modifying space station attitude and/or operations.

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 as necessary to clear any identified conjunctions.

4.5.2 § 5.64 (b)(4)(ii)

Requirement

(ii) Where a space station requests the assignment of a geostationary orbit location, it must 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 or touch. If so, the statement must include a statement as to the identities of those parties and the measures that will be taken to prevent collisions.

Assessment

N/A. The assignment of a geostationary orbit location for Cygnus does not apply.

4.6 § 5.64 (b)(5)

Requirement

(5) A statement addressing the track-ability of the space station(s). Space station(s) operating in low-Earth orbit will be presumed trackable if each individual space station is 10 cm or larger in its smallest dimension, exclusive of deployable components. Where the application is for an NGSO space station or system, the statement shall also disclose the following:

Assessment

The Cygnus spacecraft is a Non-geostationary Satellite Orbit (NGSO) system that operates in Low Earth Orbit up to 500 km in altitude, and is trackable, having dimensions greater than 10 cm.

4.6.1 § 5.64 (b)(5)(i)

Requirement

(i) How the operator plans to identify the space station(s) following deployment and whether space station tracking will be active or passive;

Assessment

The Cygnus spacecraft contains RF equipment to enable communication with the TDRS system and various ground stations. The Cygnus spacecraft also contains equipment to communicate with the GPS constellation for precise knowledge of the spacecraft’s location. The spacecraft location knowledge is shared with the NASA ISS flight control team for active tracking of the spacecraft.

4.6.2 § 5.64 (b)(5)(ii)

Requirement

(ii) Whether, prior to deployment, the space station(s) will be registered with the 18th Space Control Squadron or successor entity; and

Assessment

The Cygnus spacecraft is registered with the 18th Space Defense Squadron via the NASA ISS flight control team interfaces and active tracking is performed by the NASA team.

4.6.3 § 5.64 (b)(5)(iii)

Requirement

(iii) The extent to which the space station operator plans to share information regarding initial deployment, ephemeris, and/or planned maneuvers with the 18th Space Control Squadron or successor entity, other entities that engage in space situational awareness or space traffic management functions, and/or other operators.

Assessment

The Cygnus trajectory data (ephemeris) and maneuver plans are shared with the NASA ISS flight control team. The NASA ISS flight control team provides the Cygnus data to the 18th Space Defense Squadron via NASA interfaces and procedures.

4.7 § 5.64 (b)(6)

Requirement

(6) A statement disclosing planned proximity operations, if any, and addressing debris generation that will or may result from the proposed operations, including any planned release of debris, the risk of accidental explosions, the risk of accidental collision, and measures taken to mitigate those risks.

Assessment

Cygnus approach to the ISS involves planned proximity operations. No intentional debris generation, explosions, or collisions are planned during proximity operations.

NGSC has assessed and limited the probability of unintended contact with the ISS. The Cygnus approach to the ISS is closely coordinated between ISS and Cygnus operations staff. The approach involves successive maneuvers of Cygnus to a series of waypoints 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; that is, 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 with and accepted by NASA prior to each mission. The flight software is built on previous testing and on-orbit experience, going back to the Cygnus Demonstration mission.

4.8 § 5.64 (b)(7)

Requirement

(7) A statement detailing the disposal plans for the space station, including the quantity of fuel - if any - that will be reserved for disposal maneuvers. In addition, the following specific provisions apply:

Assessment

Cygnus will have a controlled re-entry that will occur over an unpopulated ocean area. Given compliance with the re-entry trajectory constraints provided in the response to § 5.64 (b)(7)(i), the population density beneath the trajectory is extremely small and assumed to be 0. For each

Cygnus mission, NGSC provides advance notification 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.

The Cygnus spacecraft is single failure tolerant to conducting controlled re-entry operations. NGSC will reserve sufficient fuel for re-entry operations.

4.9 § 5.64 (b)(7)(i)

Requirement

(i) For geostationary orbit space stations, the statement must disclose the altitude selected for a disposal orbit and the calculations that are used in deriving the disposal altitude.

Assessment

The altitude selected for disposal is Low Earth Orbit at 75 km with the point of re-entry over the South Pacific Ocean. The declared re-entry zone for Cygnus controlled re-entry is defined by the following boundary coordinates:

- 50.0 °S, 130.0 °W
- 30.5 °S, 130.0 °W
- 30.5 °S, 160.0 °W
- 50.0 °S, 160.0 °W

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

4.9.1 § 5.64 (b)(7)(ii)

Requirement

(ii) For space stations terminating operations in an orbit in or passing through the low-Earth orbit region below 2,000 km altitude, the statement must disclose whether the spacecraft will be disposed of either through atmospheric re-entry, specifying if direct retrieval of the spacecraft will be used. The statement must also disclose the expected time in orbit for the space station following the completion of the mission.

Assessment

Cygnus spacecraft will be de-orbited within 21 days of departure from the ISS and disposed of through atmospheric re-entry into the South Pacific ocean. Retrieval of the spacecraft will not occur.

4.9.2 § 5.64 (b)(7)(iii)

Requirement

(iii) For space stations not covered by either paragraph (B)(7)(ii) of this section, the statement must indicate whether disposal will involve use of a storage orbit or long-term atmospheric re-entry and rationale for the selected disposal plan.

Assessment

N/A. The Cygnus spacecraft is covered by paragraph (B)(7)(i) and (ii). Cygnus disposal will not involve a storage orbit or long-term atmospheric re-entry.

4.9.3 § 5.64 (b)(7)(iv)

Requirement

(iv) For all NGSO space stations under paragraph (B)(7)(ii) or (iii) of this section, the following additional specific provisions apply:

Assessment

The Cygnus spacecraft uses a Non-geostationary Satellite Orbit (NGSO) under paragraph (B)(7)(ii) of this section, so the provisions in § 5.64 (b)(7)(iv)(A) and (B) apply.

4.9.3.1 § 5.64 (b)(7)(iv)(A)

Requirement

(A) The statement must include a demonstration that the probability of success of the chosen disposal method will be 0.9 or greater for any individual space station. For space station systems consisting of multiple space stations, the demonstration should include additional information regarding efforts to achieve a higher probability of success, with a goal, for large systems, of a probability of success for any individual space station of 0.99 or better. For space stations under paragraph (B)(7)(ii) of this section that will be terminating operations in or passing through low-Earth orbit, successful disposal is defined as atmospheric re-entry of the spacecraft within 25 years or less following completion of the mission. For space stations under paragraph (B)(7)(iii) of this section, successful disposal will be assessed on a case-by-case basis.

Assessment

Paragraph (B)(7)(ii) pertains to Cygnus. Cygnus will undergo atmospheric re-entry within 21 days of departure from the ISS. The Cygnus predicted probability of success for a successful re-entry is 0.9937, as documented in 6472-ER6106.

Paragraph § (B)(7)(iii) is not applicable to Cygnus.

4.9.3.2 § 5.64 (b)(7)(iv)(B)

Requirement

(B) If planned disposal is by atmospheric re-entry, the statement must also include:

Assessment

Planned disposal of Cygnus will be by atmospheric re-entry.

4.9.3.2.1 § 5.64 (b)(7)(iv)(B)(1)

Requirement

(1) A disclosure indicating whether the atmospheric re-entry will be an uncontrolled re-entry or a controlled targeted re-entry.

Assessment

Atmospheric re-entry of Cygnus will be a controlled, targeted re-entry.

4.9.3.2.2 § 5.64 (b)(7)(iv)(B)(2)

Requirement

(2) An assessment as to whether portions of any individual spacecraft will survive atmospheric re-entry and impact the surface of the Earth with a kinetic energy in excess of 15 joules, and demonstration that the calculated casualty risk for an individual spacecraft using the NASA Debris Assessment Software or a higher fidelity assessment tool is less than 0.0001 (1 in 10,000).

Assessment

Monte Carlo analysis of possible trajectories and dispersions shows that there is low probability of debris impacts outside of the declared re-entry zone. (Refer to response to § 5.64 (b)(7)(i).)

For controlled re-entry through the declared re-entry zone, the selected Cygnus trajectory ensures that no surviving debris impact with a kinetic energy greater than 15 joules will occur within 370 km of foreign landmasses or within 50 km of the continental U.S., territories of the U.S., or the permanent ice pack of Antarctica.

Cygnus will have a controlled re-entry 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:

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

$(\Sigma\, A_{ci} \times D_{pi})$ = Human Risk factor described in 6472-ER6106, 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 6472-ER61101, the probability of mission success is 0.9451 for a 110-day total mission duration (90 days berthed). For purposes of the re-entry calculation, however, a separate calculation is performed to include only those Cygnus functions required to successfully perform the re-entry. De-orbit and re-entry are controlled from the ground and, therefore, the NGSC MCC-D ground station is included in the calculation. Based on these assumptions, the predicted probability of successful re-entry is 0.9937.

The calculation of casualty risk is then:

$$E_c = (1 - 0.9937) \times (9.1 \times 10^{-4})$$
$$= 5.73 \times 10^{-6}$$

The calculated casualty risk (0.00000573) meets the 0.0001 requirement with significant margin.