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Tri-Agency Reliability Engineering Guidance: Post Mission Disposal and Extension Assessment

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Forward

The Trilateral partners — the European Space Agency (ESA), Japan Aerospace Exploration Agency (JAXA), and National Aeronautics and Space Administration (NASA) and the United States Government (USG) in their execution of safe and successful missions, have a long-standing history of sustaining the shared space environment of operational Earth-Moon orbits with their global space-stewardship, or spacekeeping, of these areas.

This has driven missions to limit the generation of new and long-lived debris, control debris releases, minimize accidental explosions and collisions, and ensure Post-Mission Disposal of space systems, so that the environment remains safe for future operations and explorations. Given the continued need for space systems to support global mandatory infrastructure and commercial enterprise, spacefarers are extending beyond the Trilateral partners, more and smaller satellites are being deployed, and current assets are being utilized much longer than expected. This is making space more congested than ever; therefore, the Trilateral partners are evaluating potential future debris mitigation strategies, evolving technology, developing on-orbit servicing capabilities, and advancing their abilities to assess disposal and mission extension plans. They are also sharing their lessons learned and identifying opportunities for future state-of-the-art advancements for current and future space enterprises.

Sustaining the space environment cannot be ensured by any one agency or country. Thus, the Trilateral authors have shared their lessons learned, insights, and guidance, herein, on disposal and mission extension assessment strategies with the gratitude of each agency. As such, this document is not prescriptive, but was formulated to enhance value-and-risk-balanced operational decision-making, support policy refinement, and guide spacefaring partners beyond these agencies to assess their activities in space with safety and a global space-stewardship, or spacekeeping, in mind. This includes not only the disposal and mission extension assessment addressed herein, but also preserving space history, ensuring collaboration/interoperability of technology, supporting fellow operators without interfering, and the utilization of in-situ resources for the common benefit of humankind.

It is the intention of the Trilateral partners that this document evolves based on community lessons learned and the introduction of new assessment methodologies. So, all readers are encouraged to share their insights with the authors from their own application of this guidance or other strategies to ensure each mission has a successful, safe, and judicious life and conclusion.

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ESA RAMS Section Activities

The mission of the Quality, Dependability and Safety Assurance division (TEC-QQ) is to contribute to the success of ESA projects and activities by providing expert support, disseminating knowledge in its areas of responsibility, and establishing quality management systems within ESA. The disciplines covered by the division include system safety, dependability (i.e. reliability, availability and maintainability), quality assurance and quality management, and software quality. Quality assurance, safety and dependability engineering are primarily concerned with the development and implementation of methods, techniques and processes to achieve confidence in a safe and reliable system design, manufacturing, operation and disposal. ESA RAMS (Reliability, Availability, Maintainability and Safety) section (TEC-QQD) is part of the TEC-QQ and consists of RAMS experts across ESA, which are involved in the following activities across all agency:

- <u>RAMS support to ESA projects</u>
  The team has as main goal to support ESA projects and missions from the definition of RAMS requirements to their verification. Our team also has the task to perform, review and provide feedback on Technical Risk assessments in support to the ESA Concurrent Design Facility (CDF).
- <u>Research and Development</u>
  The team has a comprehensive past and present background in performing RAMS R&Ds activities across topics such as : Model Based Mission Assurance (MBMA), assessment of Life Extension or End-of-Life decision, development of new methods for reliability prediction, investigating means to increase RAMS for small satellites. Last but not least, the section is also investigating how failure prognostic through Artificial Intelligence could help at providing a better prediction of when a mission should opt for End of Life, or for Life Extension.
- <u>In-orbit Return of Experience (REX)</u>
  The team aims at gathering feedback though observing and analyzing In-orbit Reliability and Availability data for ESA's major missions, with two main objectives: to optimize satellite design and to support End-of –Life decision.
- <u>External Collaborations</u>
  The team is involved in various external collaborations such as: participation to Trilateral Task Forces, providing RAMS support and trainings to the European Southern Observatory (ESO), collaborating with Academic Institutions, organizing and attending regular bilateral with European Space Industries and European National Space Agencies.
- <u>Working Groups and Standardization</u>
  The team is involved in contributing to standardization and providing trainings for RAMS relevant ECSS standards. The RAMS team is also involved in various European Working Groups that consist of national Agencies, Industries and Academia, such as: the Close Proximity Operations (CPO) WG which aims at developing technical guidelines for rendezvous and capture of in-orbit non-human rated missions such as In-Orbit Servicing or Active Debris Removal and also the FDIR working group which focuses on updating the existing SAVOIR FDIR Handbook (e.g. dedicated FDIR design and processes for CPO missions, etc.), Human Dependability Steering Group and others.
- <u>RAMS expertise & Knowledge Management</u>
  The RAMS team is also focused on expertise, knowledge management and sharing which is performed through activities such as the RAMS Conference where European entities gather together to share their experiences and lessons learned from European missions with respect to RAMS. Moreover, the RAMS team is also strongly involved in developing and providing RAMS trainings and materials for various levels. These trainings are used either in the frame of ESA projects, ESA Academy and for ESA employees and partners.

1.0 Purpose

The intent of this guidance document is to assist spacefaring entities in assessing their designs and operational plans for extending missions and Post Mission Disposal (PMD). Ideally, spacefaring entities will consider, in their assessments and decision-making, the sustainability of our shared space environment for current and the future activities, system value, and related the capability to continue to providing value, as well as their system's probability of successful disposal operations, to comply with the applicable requirements (ISO 24113:2019 [1], JMR-003C/D [2], JERG-2-026 [3], NASA STD 8719.14b [4], NPR 8715.6B [5], AF91-202 [6,7], ECSS-U-AS-10(C Rev. 1) [8], Space Activity Act [9], ODMSP [10], FCC 20-54/04-130 [11,12], US 2020 National Space Policy [13], 2018 Space Policy Directive-3 [14]), as shown in Table 1. However, since the aforementioned requirements do not specify what methodologies and conditions should be taken into consideration for PMD and mission extension probability evaluation, a Trilateral team including Reliability, Availability, and Maintainability (RAM) experts, from European Space Agency (ESA), Japan Aerospace Exploration Agency (JAXA), and National Aeronautics and Space Administration (NASA), are enabling the utilization of knowledge and lessons learned to provide the guidelines and clarifications herein.

2. Scope

The information herein is limited to guidance for analysts performing pre-launch through in-situ evaluation of probability and viability by presenting the objectives of each method together with the related challenges. The guidance herein is not intended to dictate analysis methods implemented on any mission or to limit the strategies developed and used by any analyst or community.

3. PMD and Extension Prediction: Definitions and Objectives

3.1 Definitions

Concept	Explanation
Geosynchronous Earth Orbit (GEO)	*A* circular orbit 35,786 kilometers (22,236 miles) above the Earth and following the direction of Earth's rotation, including geostationary orbit above Earth's equator and following the direction of Earth's rotation.
Low Earth Orbit (LEO)	Earth-centered orbit with an altitude of 2,000 km (1,200 mi) or less (approximately one-third of the radius of Earth).
Medium Earth Orbit (MEO)	Intermediate *C*ircular Orbit (ICO), in the region of space around Earth above LEO (altitude of 2,000 km (1,243 mi) above sea level) and below GEO.
Mission Remaining Useful Life/Lifetime	The residual time asset is available and of value for continue mission operations after the intended mission life is complete or at any point desired and is compliant with disposal requirements.
Mission Extended Life/Lifetime	The approved time interval for which the asset is available for continued mission operations after the intended mission life is complete.
Prime Mission Life/Lifetime	The required time interval to complete all mission objectives or the design/nominal/baseline duration of the mission.

Concept	Explanation
Probability	The likelihood that an event will occur or will not occur.
Qualified Life/Lifetime	The life that the system or asset is proven, by test or prior to use, to safely sustain its specified lifetime (degradation(s) compliant with the specification).
Reliability	The probability that a product, system, or mission will perform its intended function adequately for a specified period of time or will operate in a defined environment without failure or repair.
Spacekeeping	Actions to maintain and sustain an operational orbital environment, such as Space Debris Monitoring, Space Debris/Asset Removal, Fragment/Collision Prevention, and Space Asset Management (Recordkeeping/Care/ Servicing/Refurbishment).
Space Asset	Equipment or systems that are or can be placed in space (e.g., a satellite or a launch vehicle) that provides value.
Space Debris	Human/Non-natural orbital items or elements thereof that serve no further operational value or are non-functional, such as discarded rocket bodies/stages, inactive payloads/spacecraft, operational remnants (e.g., lens covers, payload shrouds, bolts, pyrotechnic material, surface degradation/flaked material, solid rocket ejecta, and biological remains), and anomaly/collision fragments.
Spacecraft/Launch Vehicle Disposal	The actions (i.e., maneuver, retrieval, aerodynamic drag, etc.) performed to remove a space asset from its operational orbit or end its mission.
Consumables or Life limited Items	System or resource that reduces its quantity, life expectancy, or functionality with use (i.e., fuel, lasers, batteries, optics, etc.)

3.2 Objectives

Inter-agency Space Debris Coordination Committee (IADC), International Organization for Standardization (ISO) and major space agencies specify the Spacekeeping and Disposal requirements in order to preserve and sustain the Earth's space environment for current and the future activities. Therefore, the objective of each spacefaring initiative should be to manage their assets in such a way as to 1) achieve the fundamental requirement for successful and reliable post-mission disposal actions, currently no less than 0.9 probability for successful removal from designated regions, as shown in Table 1A; 2) keep a compliant or in a non-debris operational state until disposal operations are completed (See Table 1B for assisted disposal/repair criteria); 3) mitigate debris generation (not covered in this consensus); and 4) avoid fragmentations and/or collisions (not covered in this consensus).

Table 1A: Post-Mission Disposal Policy Summaries

	International (IADC & ITU) [1]	United States [4, 5, 6, 7, 10, 11, 12, 13, 16, 18]	Japan [2, 9]	France [15, 56] (France is part of Europa but has specific National requirements as well)	Europe [1, 8]
Post-Mission Disposal	IADC /ITU Remove mission terminated spacecraft from the useful regions. LEO: Limit life to 25 years (IADC) GEO: raise perigee by 235 km + 1000*Solar pressure with eccentricity of 0.003 (IADC) GTO: shorten lifetime of objects left in GTO (ITU) Includes Canada, Germany, France, UK/Ireland, Italy, Nigeria, Poland, Russia, and more **ISO (24113:2019)** 6.3.1.1 the probability of successful disposal of a spacecraft or launch vehicle orbital stage shall be at least 0.9 6.3.1.2 During the design of a spacecraft for which a disposal maneuver has been planned, an assessment shall be made of the risk that a space debris or meteoroid impact will prevent successful disposal. 6.3.2.1 A launch vehicle orbital stage shall be disposed of in such a way that long-term permanent perturbation forces do not cause it to enter the GEO protected region within 100 years after the end of life. LEO: 6.3.3.1 The orbit lifetime of a spacecraft or launch vehicle orbital stage shall be < 25years for continuous or periodic stays; 100years for intersection/transitional stays in LEO. Disposal methods allowed are: a) retrieval b) controlled re-entry c) natural decay d) maneuver for natural decay e) adding drag enhancement GEO: 6.3.2.2 GEO disposal shall satisfy one of the following: • 235 km + 1000*Solar pressure with eccentricity of 0.003 • the orbit has a perigee altitude sufficiently above GEO that long term perturbation forces do not cause entry of the GEO region for 100years. 6.3.2.3 A spacecraft operating in GEO with a periodic presence shall be disposed so that long-term perturbations do not cause it to enter GEO for 100years. 6.3.4 Re-Entry Casualty risk is to be defined by approving agency.	Requirement 4.5-2 limits the probability of spacecraft being disabled and left in orbit at End-of Mission (EOM), which would contribute to the long-term growth of the orbital debris environment by subsequent collision or explosion fragmentation. (NPR 8715.6B) ○ the ODAR and EOMP for all phases of flight including the launch phase per applicability in Section 4.5 NASA STD 8719.14b ○ The analyses documented in the ODAR and EOMP need to include not only collisions that produce large amounts of debris, but also collisions that will terminate a spacecraft's capability to perform PMD. This documentation should also address methods being used to reduce risk such as MMOD impact shielding options, or operational collision avoidance and any trade-offs between cost, mission requirements, and risk reduction for each method. (NASA STD 8719.14b) Remove spacecraft and orbital stages from LEO to reduce collision threat to future space operations (NASA STD 8719.14b) ○ Remove spacecraft and orbital stages from GEO to reduce collision threat to future space operations ○ Govern intermediate disposal orbits ○ Assess reliability of PMD ○ Assess options for disposal beyond Earth's orbit consistent with Planetary Protection Reliability of PMD maneuver operations in Earth orbit: ≥ 0.90 at EOM to achieve the following conditions and shall not to cause a violation of Requirement 4.7-1 pertaining to limiting the risk of human casualty. (NASA STD 8719.14b) a) For LEO assets - Leave the space structure in an orbit in which natural forces will lead to atmospheric reentry within 25 years after the completion of the mission (NASA & NRO); or maneuver the space structure into a controlled de-orbit trajectory as soon as practical after completion of mission; or Store: maneuver the space structure into an orbit with perigee altitude above 2000 km and ensure its apogee altitude will be below 19,700 km, both for a minimum of 100 years; or Retrieve the space structure and remove it from orbit within 10 years after completion of the mission. (4.6.2.2 & NRO) b) For near GEO assets (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 a predicted maximum apogee of GEO – 200 km (35,586 km) for a period of at least 100 years after disposal) – Leave in an orbit between LEO and MEO with a perigee altitude greater than 2000 km and apogee altitude below 19,700 km for 100 years; or leave in an orbit between MEO and GEO) with a perigee altitude greater than 20,700 km and apogee altitude below 35,300 km for 100 years. (4.6.2.3) Disposal (NRO): a) Between MEO and GEO Maneuver to an orbit with perigee altitude above 20,700 km and apogee altitude below 35,300 km (approximately 500 km above semi-synchronous altitude and 500 km below synchronous altitude). b) Above GEO: Maneuver to an orbit with perigee altitude above 36,100 km (approximately 300 km above synchronous altitude). c) Heliocentric, Earth-escape: Maneuver to remove the structure from earth orbit, into a heliocentric orbit. d) Retrieval upon completion of the mission The probability of successful PMD should be no less than 0.9 (AF 91-202)with a goal of 0.99 or better by Maneuvers (1) a reentry trajectory or (2) a heliocentric, Earth-escape orbit or atmospheric drag for less than 25 years (DOD – US Debris Mitigation Std. & AF91-202). DOD below AF see NASA-STD. a. Maneuver to an eccentric disposal orbit (e.g., GEO transfer) where (1) perigee altitude remains above the LEO zone for at least 100 years, (2) apogee altitude remains below the GEO zone for at least 100 years, and (3) the time spent by the structure between 20,182 +/- 300 km is limited to 25 years or less over 200 years; or, b. Maneuver to a near-circular disposal orbit to (1) avoid crossing 20,182 +/- 300 km, the GEO zone, and the LEO zone for at least 100 years c. Storage above GEO above 35,986 km for 100 years. (AF91-202 as well), d. Long term reentry MEO/GEO/etc. limit to 200 years total, LEO to 25 years (AF91-202 as well) and limit the probability of collisions with debris 10 cm and larger to less than 0.001 (1 in 1,000) during orbital lifetime. e. Retrieval within 5 years. f. Small satellites, including CubeSats, limit LEO life to <25 years. and object-time <100 years. Space Policy directive 6 (SPD-6) ", raising or storing assets on-orbit that is " sufficiently high orbit is one in which the orbital lifetime of the spacecraft is long enough for the fission products to decay to a level of radioactivity comparable to that of uranium-235 by the time it reenters the Earth's atmosphere, and the risks to existing and future space missions and of collision with objects in space are minimized" "Spacecraft operating fission reactors in low-Earth orbits shall incorporate a highly reliable operational system to ensure effective and controlled disposition of the reactor FCC/ODMSP (FCC-20-54A para 2 points to ODMSP) 4-2. Reliability of disposal: The probability of successful post-mission disposal should be no less than 0.9 with a goal of 0.99 or better. The GEO zone is defined as the region between the altitudes of 35,586 and 35,986 km. The low Earth orbit (LEO) zone is defined as the region below 2000 km altitude. The MEO is the region between LEO and GEO. Because of fuel gauging uncertainties near the end of mission, a program should use a maneuver strategy that reduces the risk of leaving the structure near an operational orbit regime. 4-1. A spacecraft or upper stage may be disposed of by one of the following methods: a. Direct reentry or heliocentric, Earth-escape: Maneuver to remove the structure from Earth orbit at the end of mission into (1) a reentry trajectory or (2) a heliocentric, Earth-escape orbit. These are the preferred disposal options. For direct reentry, the risk of human casualty from surviving components with impact kinetic energies greater than 15 joules should be less than 0.0001 (1 in 10,000). Design-for-demise and other measures, including reusability and targeted reentry away from landmasses, to further reduce reentry human casualty risk should be considered. b. Atmospheric reentry: Leave the structure in an orbit in which, using conservative projections for solar activity, atmospheric drag will limit the lifetime to as short as practicable but no more than 25 years after completion of mission. If drag enhancement devices are to be used to reduce the orbit lifetime, it should be demonstrated that such devices will significantly reduce the area-time product of the system or will not cause spacecraft or large debris to fragment if a collision occurs while the system is decaying from orbit. The risk of human casualty from surviving components with impact kinetic energies greater than 15 joules should be less than 0.0001(1 in 10,000). c. Storage between LEO and GEO: I. Maneuver to an eccentric disposal orbit (e.g., GEO transfer) where (1) perigee altitude remains above the LEO zone for at least 100 years, (2) apogee altitude remains below the GEO zone for at least 100 years, and (3) the time spent by the structure between 20,182 +/- 300 km is limited to 25 years or less over 200 years; or, II. Maneuver to a near-circular disposal orbit to (1) avoid crossing 20,182 +/- 300 km, the GEO zone, and the LEO zone for at least 100 years, and (2) limit the risk to other operational constellations, for example, by avoiding crossing the altitudes occupied by known missions of 10 or more spacecraft using near-circular orbits, for 100 years. d. Storage above GEO: Maneuver to an orbit with perigee altitude sufficiently above 35,986 km (upper boundary of the GEO zone) to ensure the structure remains outside the GEO zone for at least 100 years. e. Long-term reentry for structures in MEO, Tundra orbits, highly inclined GEO, and other orbits: Maneuver to a disposal orbit where orbital resonances will increase the eccentricity for long-term reentry of the structure. In developing this disposal plan, the program should (1) limit the post-mission orbital lifetime to as short as practicable but no more than 200 years, (2) limit the time spent by the structure in the LEO zone, the GEO zone, and between 20,182 +/- 300 km to 25 years or less per zone; and (3) limit the probability of collisions with debris 10 cm and larger to less than 0.001 (1 in 1,000) during orbital lifetime. To limit human casualty risk from the reentry of the structure, surviving components with impact kinetic energies greater than 15 joules should have less than $7\ m^2$ total debris casualty area or less than 0.0001 (1 in 10,000) human casualty risk. f. Direct retrieval: Retrieve the structure and remove it from orbit preferably at completion of mission, but no more than 5 years after completion of mission.	Remove post-mission spacecraft from high value regions by requiring that :**(JMR-003D)** LEO: (1) Retrieve (2) Controlled re-entry (3) Atmospheric reentry will occur in 25 years due to natural causes, (4) Maneuvering to an orbit with atmospheric re-entry will occur in 25 years due to natural causes (5) Reducing orbital lifetime in 25 years by deploying a device GEO: Raise perigee by 253 km + 1000*solar pressure with eccentricity of 0.003 GTO: Apogee altitude remains below the GEO -200 km for at least 100 years The probability of successful disposal is 0.9 or higher. **Space Activity Act** Article 22, item (iv): (a) - The applicant provides measures for the controlled reentry (e.g., trajectory, landing point) while ensuring the safety of an expected point of landing or water landing. - The spacecraft or its component, etc., for reentry into Earth has a configuration to be completely ablated, or as a result of sufficient ablation, etc., the risk to the expected point of landing or water landing will not exceed the level stipulated in the international standards or standards provided by the space agency of each state. (b) - The applicant provides measures to elevate the spacecraft to the altitude that would not have any adverse effect on the control of other spacecraft. (c) - The applicant provides measures to put the spacecraft into the orbit around a celestial body other than the Earth or guide it to fall to the celestial body, without any risk of significantly deteriorating the environment of the celestial body. (d) (Article 24 of the Cabinet Office Order) - The applicant provides measures to vent residual energy, including residual propellant and electricity, which may cause break-up of the spacecraft or to prevent the breakup. - Upon the termination of the control of the spacecraft, the following measures are to be taken for the protected regions: - Efforts must be made so that the spacecraft will be removed from the low earth orbit region within 25 years from the termination of the control. - The spacecraft is to be removed from the geosynchronous orbit immediately.	The probability of having sufficient energy resources to successfully carry out the disposal maneuvers mentioned in paragraphs 3, 4 and 5 above must be at least 0.9. (IADC Compendium and reinforced by the French Space Operation Act (FSOA)) Remove post-mission spacecraft from high value regions by: a) Atmospheric reentry will occur in 25 years due to natural causes. b) Maneuvering space systems to a storage orbit above 2000km and below 35,500 km, c) Maneuvering space systems to a storage. Components stationed in an orbit in or passing through protected region B are placed in an orbit, which does not interfere with this region for more than one year. This orbit must be such that, under the effect of natural disturbances, the launcher or its components do not return to protected region B within 100 years following the end of the operational orbit 235km above GEO.	Each project shall have a debris mitigation plan including a disposal plan for removal of post-mission space vehicles in accordance with the following: a) The operator of a space vehicle shall perform maneuvers to limit orbital lifetime (periodic or permanent) to 25 years maximum via direct reentry, natural reentry, or disposal orbit placement. b) GEO vehicles shall be re-orbited into a disposal orbit 235 km + 1000*solar pressure with eccentricity of 0.003 above GEO. (IADC) - ESA has requirements for LEO and GEO Protected Regions as from IADC and in ECSS-U-AS-10C, Rev. 1 / ISO 24113:2019. - ESA has a "10^{-3} break-up risk until end of life" requirement as in in ECSS-U-AS-10C, Rev. 1 / ISO 24113:2019. - ESA has a passivation requirement as in ECSS-U-AS-10C, Rev. 1 / ISO 24113:2019. - ESA is using a "0.90 absolute probability of successful disposal" requirement as in ECSS-U-AS-10C, Rev. 1 / ISO 24113:2019. - ESA is using 10^{-4} re-entry casualty risk as in ESSB-ST-U-004.

Table 1B: Servicing and Removal Policy Summaries

	International (IADC & ITU) [1, 20]	United States [10, 11, 13, 14, 17]	Japan [3]	France [19] (France is part of Europa but has specific National requirements as well)	Europe
Additional Spacekeeping (Servicing and Debris Removal)	**IADC 2007: “Retrieval is also a disposal option.”** **ISO/CD 24330 (under development until 2022)** **Space systems — Rendezvous and Proximity Operations (RPO) and On Orbit Servicing (OOS) — programmatic principles and practices** **ISO (24113:2019) does not address servicing or proximity operations.**	**United States Government (USG) ODMSP –Rendezvous, proximity operations, and satellite servicing: In developing the mission profile for a structure, the program should limit the risk of debris generation as an outcome of the operations. The program should (1) limit the probability of accidental collision, and (2) limit the probability of accidental explosion resulting from the operations. Any planned debris generated as a result of the operations should follow the standard practices for mission-related debris set forth in Objective 1 - CONTROL OF DEBRIS RELEASED DURING NORMAL OPERATIONS.** **5-4. Safety of Active Debris Removal (ADR) operations: In developing the mission profile for an ADR operation on a debris structure, the program should limit the risk of debris generation as an outcome of the operation. The program should (1) avoid fragmentation of the debris structure, (2) limit the probability of accidental collision, and (3) limit the probability of accidental explosion resulting from the operations. Any planned debris generated as a result of the operations should follow the standard practices for mission-related debris set forth in Objective 1. The operations should be designed for the debris structure to follow applicable PMD practices set forth in Objective 4 - POSTMISSION DISPOSAL OF SPACE STRUCTURES** **2020 National Space Policy: “Evaluate and pursue, in coordination with allies and partners, active debris removal as a potential long-term approach to ensure the safety of flight in key orbital regimes.”** **SPD-3: “The United States should pursue active debris removal as a necessary long-term approach to ensure the safety of flight operations in key orbital regimes. This effort should not detract from continuing to advance international protocols for debris mitigation associated with current programs. “** FCC: Proximity Operations 59 (FCC-CIRC1811-02). With increasing interest in satellite servicing and other non-traditional missions, there have been an increasing number of commercial missions proposed that involve proximity operations and rendezvous of spacecraft. We propose that applicants be required to disclose whether the spacecraft will be performing any space rendezvous or proximity operations. The statement would indicate whether the satellite will be intentionally located or maneuvering near another spacecraft or other large object in space. Such operations present a potential collision risk, and operators will need to address that risk, as well as any risk of explosions or generation of operational debris that might occur through contact between spacecraft, as part of debris mitigation plans. Accordingly, we propose a disclosure requirement regarding these types of operations FCC 20-54 Proximity Operations 122. In the Notice, the Commission noted the increasing number of commercial missions proposed involving proximity operations and rendezvous of spacecraft. The Commission proposed that applicants be required to disclose whether the spacecraft is capable of, or will be, performing rendezvous or proximity operations. The Commission also sought comment on whether the rules should include anything more specific regarding information sharing about proximity operations with the 18th Space Control Squadron or any successor civilian entity. We adopt a disclosure requirement that would identify situations where there are planned rendezvous and proximity operations and provide a vehicle for further review of those operations. **The disclosure requirement follows the general approach in the revised ODMSP of analyzing such operations within the framework of standard debris mitigation objectives—limiting debris release, preventing accidental explosions, and limiting collision risk.** Commenters generally supported this approach. We note the evolving and developing nature of these operations, and accordingly find that more specific technical or operational requirements are premature at this time. Member of CONFERS (The Consortium for Execution of Rendezvous and Servicing Operations) Studies	JERG-2-026 **On-orbit service:** Intentional interference by a servicing spacecraft with a client spacecraft for refueling, resupplying, adding or replacing functionalities and assisting PMD. Active Debris Removal (ADR) for inactive spacecraft / target debris and transportation to/from a space station is also a part of on-orbit servicing. ADR shall be taken in to **(1) Avoid unintended generation of debris caused by a collision upon RPO, physical contact and docking with a target as well as the loss of debris mitigation functions are defined as a critical hazard (e.g., serious effect on environment)**.(2) Conduct a hazard analysis of the entire system integrating a servicing spacecraft, target and ground system, and take safety measures to address the identified hazards and hazard causes based on fault tolerance. (3) Additional fault tolerance or equivalent measures are considered when a collision could lead to a catastrophic consequence such as serious threat to the manned spacecraft because of its size, orbit, and/or payload properties. (4) Avoid inducing failures direct or indirect (impingement, contamination, etc.) in servicing of client system. (5) Inability to separate client and servicing if required.	In 2019, France released its Space Defense Strategy, in which it acknowledged the increasing importance in-orbit services will have in the future due to the high number of objects in orbit and the need to remove debris. France is involved in the development of IOS in the field of Active Debris Removal, reconfiguration, and de-orbiting. France has contributed to the development of Space Debris Mitigation Guidelines of the Committee, the European Code of Conduct for Space Debris Mitigation, and the IADC Space Debris Mitigation Guidelines. The French Technical Regulation is consistent with these guidelines, as well as with the ISO 24113 standard. France is currently using debris mitigation policies to guide Close Proximity Operations (CPO) and RPO.	ESA’s Close Proximity Operations (CPO) Working Group is preparing the safety/sustainability requirements (e.g. technical, operational, verification & validation) for non-human rated missions executing rendezvous, proximity and capture operations. The CPO Working Group will provide technical inputs to the European Cooperation for Space Standardization (ECSS) Space Traffic Management Working Group on technical aspects concerning the development of worldwide RPO) and OOS draft guidelines and best practices handbook for 2022 release. Currently using debris mitigation policy to guide CPO and RPO. Member of CONFERS

4. Assessment Guidance

In order to reasonably evaluate the reliability/viability of extended operations and PMD actions, ESA, JAXA, and NASA experts have found that there are several methodologies and two strategies (i.e., qualitative and quantitative) that have been effective in performing these evaluations as described below.

4.1 Timeframe/Timeline

Optimally, the best time to perform an extended mission or PMD evaluation of probability and mission viability/reliability is at the earliest point at which the results can impact design, decisions, and/or operational concepts. Pre-launch evaluations of Intended Mission Life, planned Extended Life, and PMD execution are found to be effective once the sufficient design data is available to assess (see Section 4.3) life and disposal scenarios, which normally occurs best during the preliminary design through critical design phases, so that design decisions and changes are reflected in the assessment. However, these evaluations may warrant updating if Integration and Test (I&T) issues or configuration changes dictate. Whereas, in-situ (operational, extended, decommissioning) evaluations have shown the most value when performed either just prior to intended/extended mission life expiration or as qualification margins are depleted or after an anomaly or failure or consumable depletion that impacts the viability or life of the mission. This timing allows for continuous operational risk versus Return-On-Investment versus spacekeeping decision-making and/or disposal/mission planning.

4.2 Prerequisite Information

Ideally, analysts would have sufficient data to calculate the actual probability of a space asset's planned or current components and would be able to definitively predict actual performance. However, analyst should practically acquire as much data as possible to enable the best assessment possible. As a minimum these data are:

- Space asset configuration data: Functional block diagrams to define assessment breadth and health and status of systems and redundancy lost or still available
- Design data: Parts list and detailed design stress information (e.g., temperature, current/voltage, etc.) to select/adjust failure rates
- Previous usage of systems: Details of previous issues or failures or successful performance to develop a custom failure rate and similarity in use and configuration to proposed/current concept.
- Current usage system performance: Details on issues or failures or successful performance and actual stress information such as operating temperature or duty cycles can be used to develop a custom or adjust a failure rate.
- Mission operations concept: Description of systems needed for mission success or continue mission success.
- Disposal operations concept/scenarios: Description of systems needed for disposal operations or methods of disposal planned.

- Mission lifetime expended: Mission time that has elapsed or orbit lifetime.
- Mission lifetime planned/required: Mission time that is planned prior to EOM and disposal.
- Previous prediction of the system's probability or similar system's probability
- Qualified life
- Mission/System remaining useful life
- Consumable or limited life item limits
- Etc.

4.3 System Quantitative Assessment Techniques

A quantitative assessment is used to show consistency with risk tolerance requirements and trade strategies for mission continued viability or to show compliance of PMD action plans with disposal requirements, currently no less than 0.9 probability. To be useful, this assessment must be kept consistent with known or newly derived/refined redundancy configurations, reliability estimates, usage profiles, and other risk factors as system performance metrics (e.g., duty-cycling, system failures, parameter trends) warrant.

4.3.1 Discrete Reliability Calculation Techniques

In a quantitative assessment, it is essential that the most precise/realistic reliability estimation be developed for each system required for space asset disposal or mission extension so that life and risk decisions can be made accurately. The more precise the estimation is, the more likely it is that over-design, premature mission termination, or erroneous mission execution/extension will be avoided. Therefore, it is necessary that the appropriate statistical methods are applied, given the data available, or efforts may need to fall back to more-conservative/ obsolete/incomplete handbook data (e.g., MIL-HDBK-217 [21] or FIDES [22]). From experience, this Trilateral team has found that it is essential to critically forecast and routinely reassess the system reliability, based on performance of all configuration items, especially batteries, solar arrays/strings, mechanisms, optics/sensors, and propulsion systems. The most commonly used methods and how they are effectively applied by this Trilateral team are summarized here:

<u>Engineering Judgement, Performance Data, and Assumptions</u> – This method is best used for in-situ updating of probabilities since it depends on having a previous prediction for the system. If a system shows no signs of degradation or wear-out based on performance data and diagnostic trends, then a "good-as-new" probability (1.0) can be assumed at the beginning of the mission or mission extension period with either the original failure rate or an applicable statistically updated failure rate or distribution (e.g., Bayesian). However, if similar systems have shown degradation/wear-out over time in operations or in test (i.e., batteries, solar cells, etc.) but the system being assessed has not exhibited these symptoms, the original failure rate cannot be used with the "good-as-new" assumption. Under this condition the system's underlying failure rate could be adjusted with an approved adjustment factor (e.g., 1.5 x Failure Rate) to impute unseen degradation, while a "good-as-new" probability (1.0) is still assumed [23]. Conversely, if the system has shown degradation, then the "good-as-new" assumption and engineering judgment adjustment factors should not be used.

In addition, if operating conditions (i.e., voltage, current, temperature, duty cycle, health check results, etc.) have changed, additional analysis (e.g., part stress, derating, trend analysis, and worst-case) is warranted that can either adjust the failure rate directly or to support engineering judgement adjustments.

Weibull/Weibayes[24] – This method is best applied when there is sufficient on-orbit/test data available from the system under analysis or similar system(s) or historical system(s) that demonstrates an increasing failure probability or aging or increasing degradation. In this method, failure/anomaly data over time is fit to a corresponding Weibull distribution or mix of Weibull distributions to postulate a new failure rate for the system from the start of its operations. Weibull distributions (see Figure 1) with $\beta < 1$ have a failure rate that decreases with time, also known as infantile or early-life failures. Weibull distributions with β close to or equal to 1 have a fairly constant failure rate, similar to handbook data but reflective of actual space/test performance. Weibull distributions with $\beta > 1$ have a failure rate that increases with time, also known as wear-out failures will likely be risk factors in disposal and/or extension decisions. If you only have historical failure data, a very small sample set, and/or the current system has not failed yet, but it is known that similar systems have had degradation trends (i.e., performance, temperature, power-loss, increased/decreased torque, etc.), it may be best to perform a Weibayes analysis (a Weibull with an assumed beta) to generate a new failure rate but Weibull is preferred. Note: The “good-as new” assumption cannot be used with Weibull/Weibayes updates.

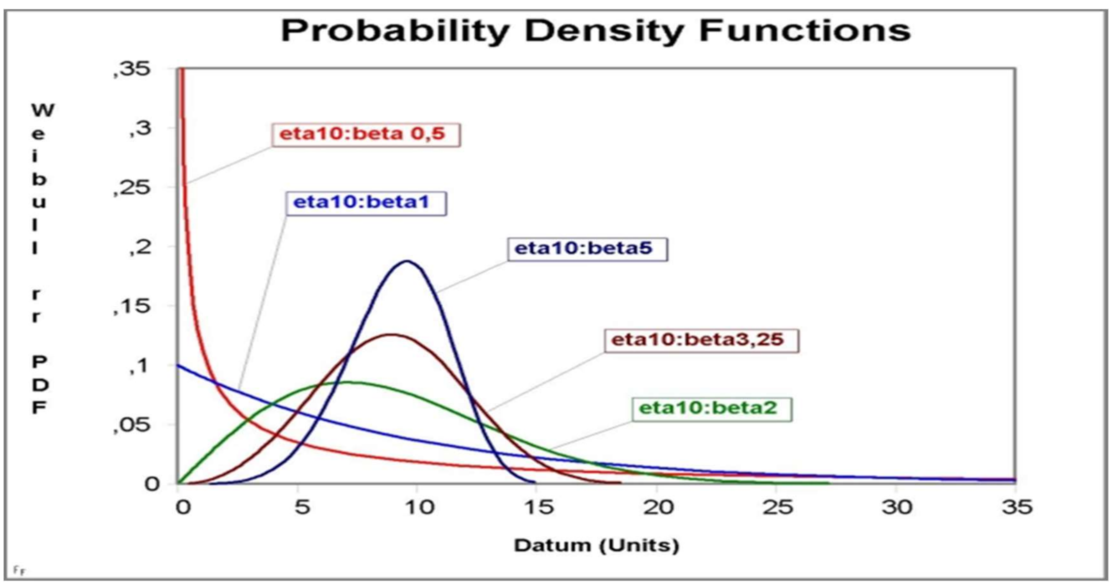

Figure 1: Weibull PDF Distributions

Bayesian Statistical Inference for Updating Failure Rates [25, 26] – This method is a classical statistical method that is best used when there are components for which the on-orbit/test failure data is insufficient to calculate a new failure rate; however, there is enough success and failure on-orbit/test data to consider updating the existing failure rate assumed. This method can be used prior to design, prior to operations, or in-situ and learns from data incrementally until convergence on a new failure rate is reached.

Bayes' Rule: $$\pi(\rho|E) = \frac{L(E|\rho)\pi_0(\rho)}{\int L(E|\rho)\pi_0(\rho)d\rho}$$

For example, if a Bayesian inference is begun with a prior failure rate from a handbook, it will be a constant value of n failures in time, that may be conservative, but it will not be an elicited value or a complete prior distribution. Therefore, a Gamma prior distribution should be developed with an elicited guess at or agreed upon assumed standard deviation or coefficient of variation CoV(λ), such as 0.5; thereby making a subjective prior distribution (or an uninformative or weak prior [27] or Jeffrey's prior [28] as considered by some analysts) that can be used to generate a Gamma posterior (new failure distribution) but will not overly bias results. To generate the posterior distribution, the prior should be combined with experience data (failures (r) and time (T), or Poisson data) or point estimate at the assumed CoV:

$$\lambda_{Bayesian} = \frac{\delta'}{\rho'} = \frac{\delta + r}{\rho + T}$$

given $\rho = \frac{\delta}{E(\lambda)}$ and $\delta = \frac{1}{[CoV(\lambda)]}$

Any representative prior and distribution type (e.g., binomial for failures in n demands, Poisson for events in time, gamma for n failure in time) can be used with enough data and will converge on the same posterior distribution. Once a posterior is attained it should be routinely update so its distribution (most precise if used) or a selected point estimate (i.e., mean) can be used for the component in further system assessment along with the good-as-new assumption.

<u>Physical Stress Analysis / Physics of Failure</u> [29] – This method is best applied when there is knowledge of the physical stresses on the element as well as the in-situ condition of the element, but there is not enough data to perform a classical statistical evaluation. Using this data and this method calculates the probability of failure cause or failure mechanism, such as distortion, fracture/fatigue, wear, electro-migration, corrosion, or material degradation. [30] This calculation is generated for each cause by using a validated algorithm to assess the physical functional model of the system and the physical stresses it is exposed to or its performance degradation parameters. As such, the results of this method will likely need to be combined with each other and classical statistical estimations to formulate a complete estimation that can be used in further system assessment along with the good-as-new assumption. These combinations will need to factor in the dependency or independence of each estimation.

<u>Handbook / Database Data</u> [21, 31] – In some cases it may be necessary to use of a handbook, such as MIL-HDBK-217 (all version of the MIL handbook), or generalized databases of reference part failure rates, such as Telcordia [32], PRISM [33], RDF-2000 [34], FIDES [22], or canceled references (i.e., Siemens SN29500 [35]), to estimate a unit's reliability based on its constituent parts. In these cases, limitations and uncertainty of those data uses must be considered and

reflected in further system assessments. All these handbooks assume the components of the system have constant failure rates with modification factors to account for various quality, operating, and environmental conditions. [36] This issue is that these factors are too generalized to give the most accurate prediction of reliability and their use may lead to misleading results. These handbooks may also not contain the exact part being used in the system, so a similar part will need to be substituted and may not characterize the part accurately. However, the "good-as-new" assumption is still plausible with this method.

In addition, if handbook data is selected with actual performance temperatures versus predicted design upper limits then failure rate estimation accuracy will be increased. This may result in a probability of success change as shown in Figure 2.

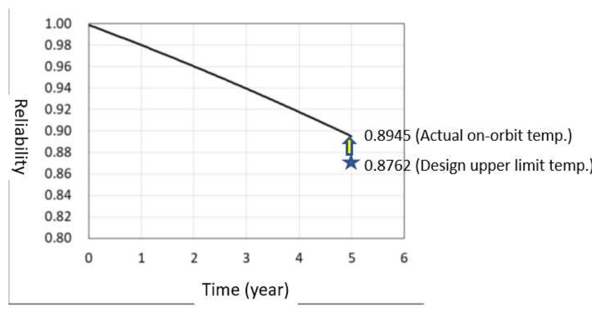

Figure 2: Actual Temperature Adjustment [37]

4.3.2 System Probability Calculation Techniques

Given the best possible reference or developed reliability estimation for each system (see Section 4.3.1) and any uncertainties associated with those estimates, an estimation of the space asset's disposal or mission extension plans' probability of success can be quantitatively determined for life and disposal risk decision-making. This consensus team has found that the following methods are most effective in making this estimation:

Reliability Block Diagrams (RBDs) / Reliability Logic Diagram [38, 39, 41, 42] – RBDs are a logical representation of a particular system individual functional elements. They provide a thorough depiction of the interaction of the system's sub-systems and can be tailored for particular scenarios of interest. A system's reliability prediction is generated by applying reliability discrete estimations to the RBD, using the appropriate reliability formulas for system redundancy, and including redundancy swapping success likelihoods. It should be noted that an RBD is neither an electrical nor a mechanical connection diagram.

When applying this method to extended mission reliability, it is best to understand what the desired mission outcome in extension is and what is needed to achieve it. This may be different than the intended mission goals and may require the same or less of the in-situ systems. This information will define/refine the RBD structure. In addition, if there have been failures these systems will need to be removed from the RBD, as shown in Figure 3.

When applying this method to PMD probability it is best to understand what the desired disposal actions are and what is needed to achieve it. This will usually be less than the system needed for the intended mission and likely even less than the in-situ systems and will change the RBD in a similar fashion, to the failure system removal shown in Figure 3.

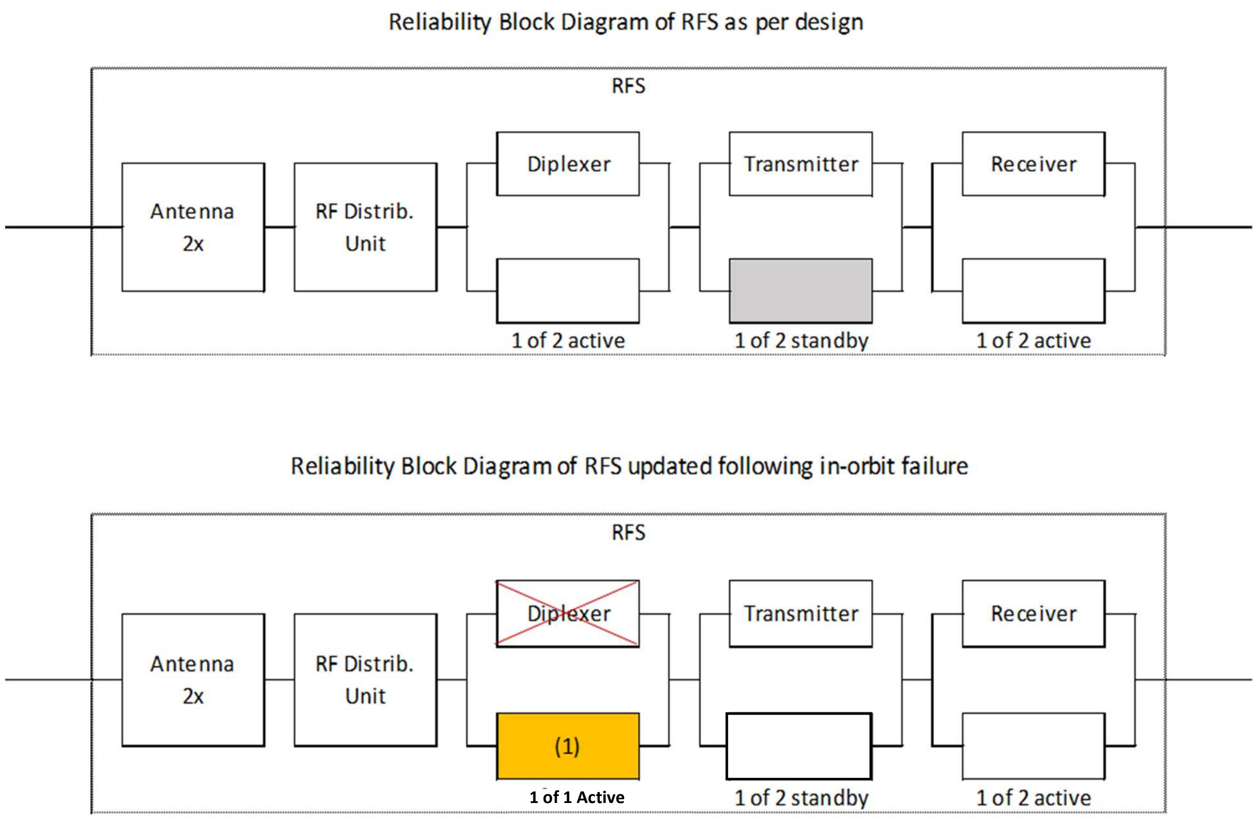

Figure 3: Example of RBD during design phase and updated following in-orbit failure

Fault Tree [38, 39, 40, 41, 42] - A Fault Tree Analysis (FTA) is a deductive analysis of foreseeable, undesirable states or events. As such the fault trees includes a top-level event and all the contributing failures/events combined logically with functions, such as AND and OR, that can be quantified with discrete reliabilities (see Section 4.3.1) at a specific time (e.g., at the end of the extension period or proposed disposal date). This allows the top-level event and the contributing branches to numerically assessed using Boolean math.

When applying this method to extended mission viability/reliability assessments it is best to understand what the desired mission outcome in extension is and what can cause this not to occur. This would translate to top-level states of not providing a particular function or not achieving a mission objective (e.g., loss of the measurement of volatiles in the atmosphere). This may be different than the intended mission goals and may require the same or differing logic and contributors in one or multiple trees. In addition, if there have been failures, tree events will potentially need to be changed as well. The results would be the potential risk for achieving each and/or all continued objectives and would assist decision makers in determining the value of extended operations. In addition, the weakest or lowest probability branches (minimum cut sets) can be identified as primary risk drivers for action.

When applying this method to PMD probability, it is best to understand what the desired disposal actions are and what are subordinate actions. This would translate to top-level states of not providing a particular disposal action or all disposal actions (e.g., inability to dispose of mission). This will be different than the intended mission goals and will require differing logic and contributors in one or multiple trees (see Figure 4). In addition, if there have been failures, tree events will potentially need to be changed as well. The results would be the potential risk for achieving each disposal action and/or all disposal actions and would assist decision makers in determining when disposal must be initiated.

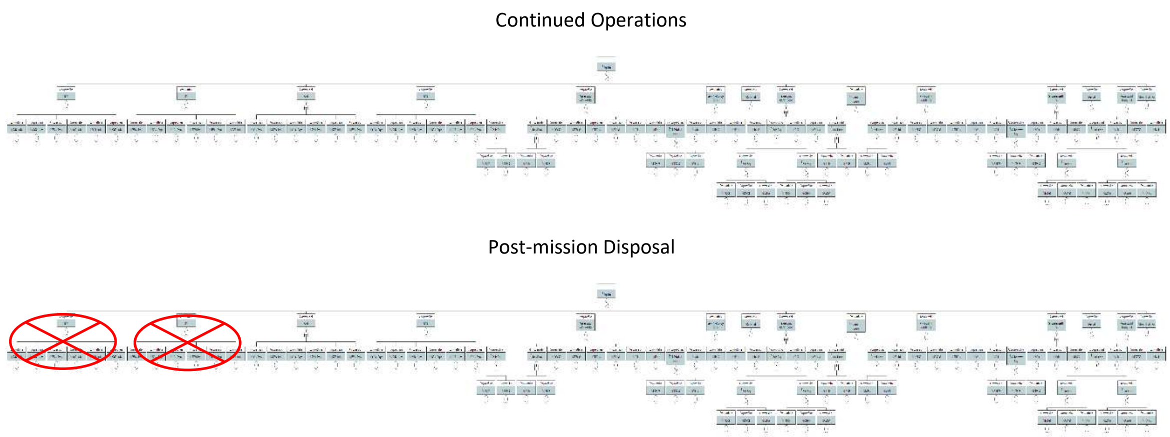

Figure 4: Example of Fault Tree (FT) to illustrate complexity and elimination only that characterize disposal. This is not intended to show design phase /continued operations logic supporting examples will be supplied separately for that purpose.

<u>Event-Based Probabilistic Risk Assessment (PRA)</u> [43] – PRA is a comprehensive, structured, and logical analysis methodology for quantifying the risks to actions or success-states, called events, which a system must realize for success and the probability of success system or operation. As such, this methodology is best applied when the system or operations being analyzed are significantly complex and/or time-phased. When applied to PMD, these events or event trees would be limited to the actions planned for disposal (e.g., maneuver, retrieval, drag-enhancement, dormancy). Whereas for mission extension the events or event trees would include those actions needed for the continuation of specific or all mission operational goals. In either case the events are evaluated in a chronological order and quantified using Fault Trees which are informed and/or quantified by Failure Modes Effects and Criticality Analysis (FMECA/FMEA) and reliability data/RBDs (see Figures 3 and 5). PRA resultant probabilities along with minimum fault tree cut sets can assist decision makers in determining the viability of extended operations or when and how to initiate disposal.

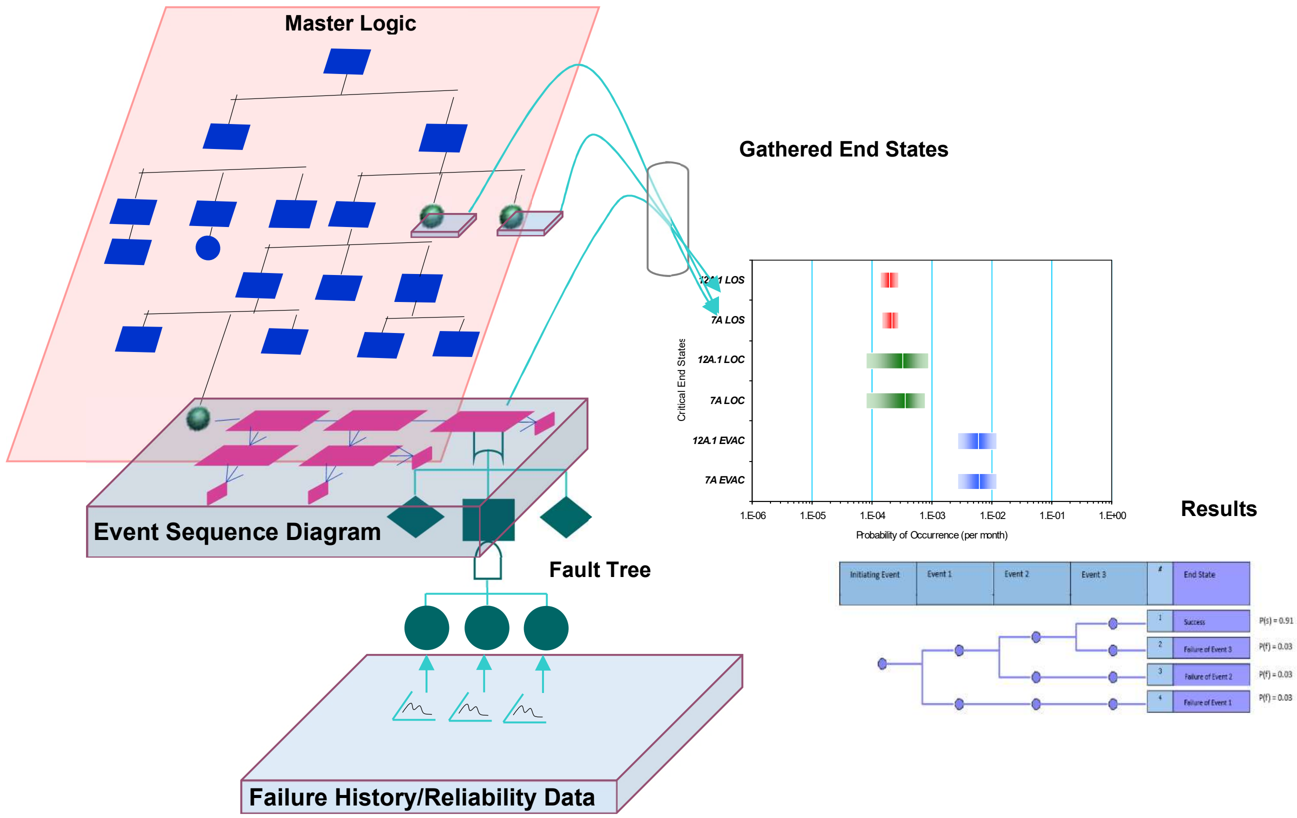

Figure 5: PRA Structure

4.4 System Qualitative Assessment Techniques

Despite diligent efforts to perform reliability predictions (see above sections), there are remaining uncertainties on the quantitative predictions and gaps risk identification (i.e., fuel depletion, repetition limits, etc.). Therefore, qualitative assessments are often used during the design phase to ensure all mission success risks are known and managed. However, this consensus team has found that it is equally important to re-evaluate these qualitative assessments to update risks and limits to viable and useful continued mission operations continuation and disposal. These types of assessments evaluate new/re-evaluate previously determined tolerances to failures given in-situ status and performance tolerance loses (e.g., radiation tolerance reduction from cumulative exposures) to forecasts mission allowable/feasible longevity based on consumables or life-limited items and are described below.

> <u>Critical and Single-Point Failure Assessment</u> [38, 39, 41, 42] – This assessment consists of the identification of the risks associated with mission-value or disposal feasibility impacting failures (Critical) or single failure (Single-Point) events that could prevent continued operations or disposal. Therefore, this assessment is primarily informed by results of a FMECA/FMEA, but Fault Tree minimum cut sets (see previous sections above) or associated contributing basic events and RBDs/Reliability Logic Diagram (see previous sections) entries can assist as well.

To identify critical and single-point failure risk via FMECAs, the inductive analyses of the impacts of each plausible discrete failures of function, interface, and process, each failure mode with an impact or severity of Critical or Single-Point would be gathered in a list for risk management. Alternatively, the basic events contributing to the fault tree could be added to the list if similar impacts can be determined. In either case, the resultant list is most effectively used if likelihood and compensating processes or provision, identified in the FMECA or other analyses, of each of these failure modes is also included to allow for risk management prioritization and action plan development. For extended missions or disposal, this may mean developing alternate or revised contingency procedures or preparing for potential software changes on the flight or ground systems and establishing failure triggers for immediate disposal or mission operations termination to mitigate risks.

Limited Life Item and Margin Assessment [44] – This assessment consists of establishing the limits on viable or sustainable system functions based on available acceptable-margins or expiration of sustainability/support or exceedance of finite useful life estimates during the planned operations. However, pre-operations assumptions may be too conservative or assumed that certain operational constraints would protect a system's life; this may not be the in-situ situation. Therefore, for mission extension and disposal, this assessment should update or add to the pre-operations mission life limits as warranted by in-situ conditions, detrimental environmental exposure (i.e., radiation, atomic oxygen, etc.), and/or actual use (e.g., repetitions, age, actual operating temperatures), to re-establish mission life limits or margin risks based on potential revised mission functional goals and disposal plans. Simply stated, a mission cannot plan for fueled-disposal after nominal or extended mission plans have utilized the entirety of fuel on-board prior to disposal; or plan to use a ground system that has an operating system that will no longer be supported; or plan to continue to utilize a mechanism beyond its estimated expected life, but may have longer battery life if actual operating temperatures were lower than predicted. While re-assessment may be sufficient, additional life testing at in-situ use conditions or additional preventive maintenance/service or alternate use strategies may be needed to inform or mitigate some limits or assess further quantify margin risks.

These life limits should assist a mission team in establishing not-to-exceed disposal or mission operations termination targets regardless of probability results and therefore should be updated each time a mission extends its operations. In addition, ratios of expected life to required-life estimates or limited margins can also be used to identify the risks of continued use of life limited systems or consumables not just setting a finite life limit.

4.5 Overall Assessment for support of Risk-Informed Decision Making

Each of the assessments presented above is intended to provide spacefaring entity leaders with an understanding of the in-situ value of their operational system(s) and the probability of it continuing to provide value, along with their planned or in-situ system's probability of sustainability and viability for successful disposal so informed decisions can be made in regard to mission extension and disposal planning (e.g., timing and actions). Therefore, it is paramount that qualitative and quantitative data be amalgamated with safety (e.g., ground, orbital) and other concerns (i.e., policy compliance, costs, politics, planetary protection, etc.) to fully inform this complex decision. From experience, Trilateral team experts have found that most of the effective method for communicating these diverse data and relationships is a risk assessment. While each spacefaring entity may have its own risk assessment focus, process (i.e., Japanese Regulation for Enforcement of the Act on Launching of Spacecraft, etc. and Control of Spacecraft (Cabinet Office Order No. 50 of 2017)[45], NASA's Agency Risk Management Procedural Requirements (NPR 8000.4B)[46], NASA Systems Engineering Processes and Requirements (NPR 7123.1)[47], Air Force Space Command Satellite Operation Instruction (10-1024)[48], ESA Space Project Risk Management (ECSS-M-ST-80C) [49], and techniques, the general principles are the same and must be coordinated with all systems and specialty engineering disciplines to be beneficial. The common risk assessment principles are to identify potential scenarios that could prevent successful actions, make assets (direct or indirectly related) vulnerable, or create a political or legal or return-on-investment issue; analyze what could happen if the scenario occurs; and communicate the findings and recommendations for mitigation in relevant terms of likelihood and consequence severity (i.e., safety, performance, policy compliance, costs, politics, etc.).

For a mission extension, an effective risk assessment or other similar data sharing communication technique has been found by this task force, through years of experience, to focus on the performance characteristics and justifies the extension based on technical capability forecasts and safety. This allows for the reliability/availability information and potential triggers (e.g., diagnostic, health, or performance indicators) for immediate termination actions to be communicated to entity mission leaders. However, informing them of potential safety concerns and policy compliance prospects is also essential so mission leaders can then compare those with the potential for continue positive returns on operations investments to approve, limit, or request an extension proposal. Ultimately each agency will use this data to define and validate a mission's forward plans based on their policies.

Similarly, a PMD risk assessment, or other similar data sharing communication techniques, has been found by this task force to be most effective when it is focuses on the timing and disposal action plan and establishes the potential for unsuccessful asset disposal and compliance with or violation of operational, spacekeeping, terrestrial (human and property) safety, and nuclear safety (if applicable; storage on-orbit until the fission products to decay to a level of radioactivity comparable to that of uranium-235 by the time it reenters the Earth's atmosphere [16]) policies. Therefore, the risk assessment is most useful if it also provides qualitative findings and recommendation(s) for compliant disposal (e.g., scenario, timing, and/or contingency plans) along with basic probability findings, estimation error bounds, and dependencies/sensitivities. These options and insights allow mission leaders to validate and revise planning for compliance with requirements or justification for non-compliant plans for successful disposal.

In summary, extension and PMD decisions are complex and should be product of agreement among all stakeholders, based on transparent criteria and relevant data as described above. As well as have the involve of independent evaluators, like Safety and Mission/Product Assurance personnel, to assure that decision ensure the success on-orbit operations and PMD and preserve the space environment in the near-Earth orbit.

5. Utility and Advancements

It is anticipated that the current guidance in this document will be of value to spacecraft developers/ operators and assist them in performing "reasonable" and "effective" compliance/risk analysis and provide for the sustainability of the space environment as well as maximizing their mission success. However, the task force is also planning to release supporting example addendums to support this guidance in the coming year.

As with any industry and engineering discipline the guidance (e.g., IEEE 1413 [50]), techniques and feasibility of operational and disposal strategies, such as servicing and active retrieval/removal [55], will change over time. Therefore, this guidance will be updated as warranted by those changes as well as analysis methodology advancement (i.e., Explicit State Space and Markov Chain Generation [51], Petri Net Analysis [52], Model-Based Reliability[53], Physics-of-Failure [29], simulations, Quantification of Margins and Uncertainty (QMU) methodology [54], etc.), when proven for this purpose.

In addition, the data herein is also offered for the advancement of the applicable agency/industry requirements and practices for evaluating of and preparing for (e.g., optimizing sensors for effective diagnostic and health monitoring to facilitate operations and probability updates, active debris removal design features) mission extension and PMD evaluation.

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