A Codification of Technical Considerations and Mission Assurance to Enable Viable Servicing/Active Debris Removal/Assisted Debris Disposal (ADR/ADD)

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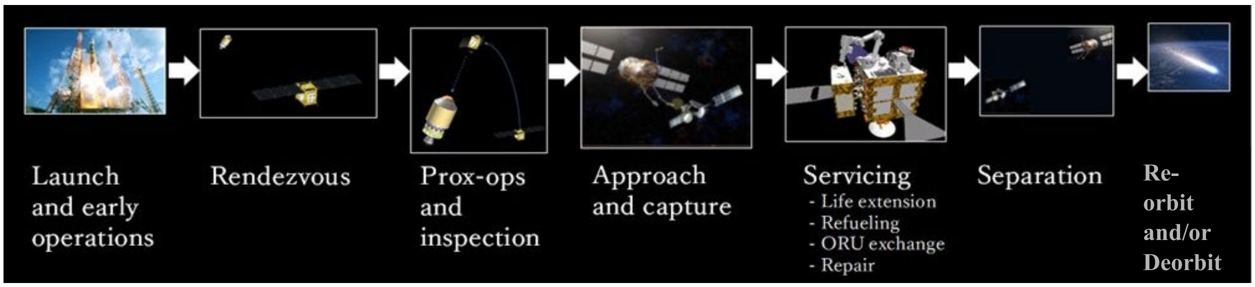
Introduction

The intent of Servicing or Active Debris Removal (ADR or Assisted Disposal (ADD)) is to sustain the space environment for useful assets or spacekeeping. This means enhancing current asset utility through repair and service. It also means eliminating debris and un-useable assets without creating additional hazards/debris. Therefore, Servicing or ADR missions have the overall goal of “Do no harm to space environment assets involved and other assets” and generally have the following life cycle:



However, as with any space mission servicing and ADR are complex and potentially risky undertakings. There are risks to the client, to the servicer, and the orbital environment but the rewards can be great. The risks include attitude control impacts (imparting loads/spin), functionality losses, collisions, debris generation, and modified reentry operations. Whereas, the rewards include additional use or replenishment of a costly system, increased availability of orbital space, reduced potential for conjunctions, reduced debris, and reduced risk of cascading conjunctions (domino effect), or Earthly large debris impacts.

Therefore, this paper provides a framework to assist spacefaring entities in assuring that their designs and operational plans for Servicing/ADR mission are as safe or risk reduced as possible.

Mission Assurance Support Framework:

To develop a mission assurance support framework for servicing/ADR, the authors compared their related policies (See Table 1) and conducted servicing/ADR stakeholder interviews to ascertain their needs and challenges in planning/designing their missions. From this research the authors have determined they have common policies/goals and that no new mission assurance methods will be needed to support ADR/servicing. Further the authors have determined that current methods will need to increase their scope/updates to provide all the risk-to-value information needed (e.g., risk to the space environment, risk to other space assets, risk to client/servicer, casualty risk, risk/plausibility of service) on a timely basis and to assist spacefaring entities in assuring that their designs and operational plans for servicing/ADR mission are as safe as possible.

As mission assurance activities cover a broad gamut of disciplines (i.e., Reliability, Safety, Quality, etc.) the expansion of methods and underlying data needs/interchanges would as well. Therefore, the authors determined that the best method to capture the complexities and interrelationship between applied methods was to codify their findings with the Goal Structured Notation (GSN) or a Goals, Objectives, Strategies, and Tactics/Tasks (GOST) breakdown. In this method a general goal is broken into achievable specific objectives, which in turn are broken into general strategies for how to achieve the specific objectives. Then these general strategies are decomposed into actionable tactics/tasks [1]. As a result, the Mission Assurance Support Framework shown in Figure 2 was developed.

By using the GOST form of GSN the authors were able to breakdown the overall goal of servicing/ADR of "Do no harm to space environment assets involved and other assets," into these strategic objectives of how to meet that goal: "Perform service w/o damaging client," "Perform service w/o damaging servicer," "Perform service w/o generating debris," "Relocate client to correct orbit/trajectory," "Return client/servicer to operations," and "Prevent client/servicer from transitioning to and remaining in debris state." These were then broken down into the interrelated strategies of: "Avoid disabling client/servicer functionality and maintain passivation compliance," "Avoid collisions," "Avoid bumps/unacceptable contacts," "Define operations to mitigate debris," "Maintain De-orbit and Casualty Compliance," "Release Client or Dispose of stack," and "Enable Servicer transition to client." As shown in Figure 2, each of these strategies assists in meeting multiple objectives and is supported by one or more tactics shown in Figure 2. Further, each of these tactics is supported by specific tasks from multiple disciplines as shown below:

- Task 1: Perform DNH/Failure Analysis (FMECA/FTA)
- Task 2: Perform Probabilistic Assessment
- Task 3: Perform Process FMECA/FT
- Task 4: Assess Probability of De-orbit
- Task 5: Perform Serviceability/Maintainability Analysis
- Task 6: Perform Release Operations Risk Assessment
- Task A: Life/Aging (systems/materials/structures) analysis of Client/Debris
- Task B: Inspect Client from Ground, TLM, or On-orbit
- Task C: Perform debris/break-up Testing /Modeling
- Task D: Conduct Design Reviews to Ensure Serviceability Technology is present
- Task E: Perform Orbit Analyses
- Task F: Perform Casualty Analyses
- Task G: Part/Material Testing/ Part/Material/Component Evaluation
- Task H: Perform Entanglement/Release Risk and Hazard Assessments
- Task I: Verify Trajectory is Safe
- Task J: Perform collision avoidance operations
- Task K: Select Capture method

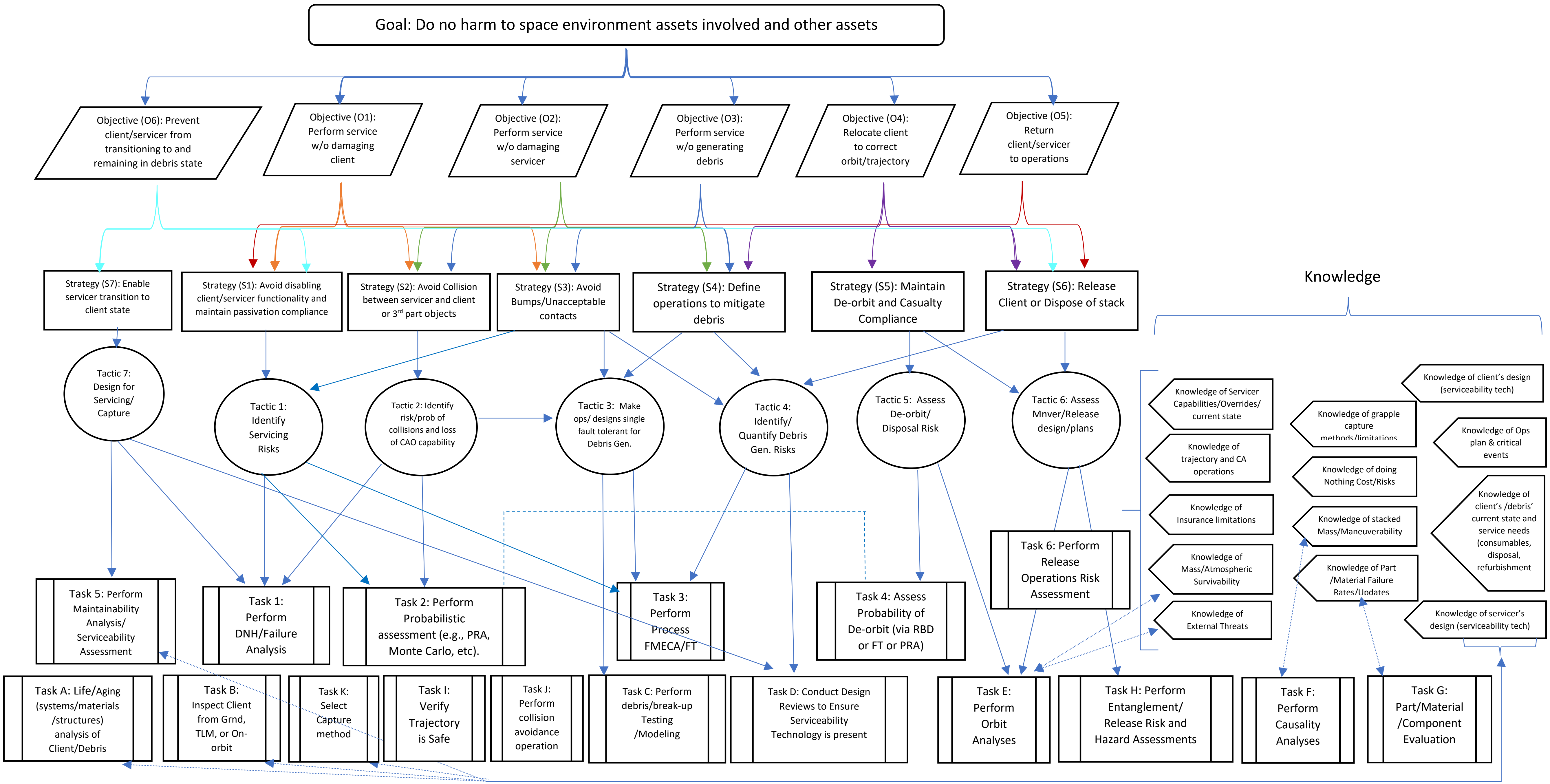
The numbered tasks are primarily Reliability Engineering and lettered tasks are support or knowledge capture tasks (See Appendix) from additional Assurance or other disciplines that provide the knowledge to inform Reliability Engineering efforts, each other, or tactic execution directly.

See the framework detail sections below for further details on how each of the primarily Reliability Engineering tasks, performed as recommended in Table 2 of the conclusion, supports the GOST-chain directly or indirectly with data to ultimately ensure the best and safest servicing/ADR mission is chosen and executed.

Table 1: Servicing/ADR Policy Comparison

	International (IADC & ITU) [2, 10]	United States [4, 5, 6, 7, 8]	Japan [3]	France [9] (France is part of Europa but has specific National requirements as well)	Europe
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

Figure 2: Servicing/ADR Goal Structure



Framework Supporting Details:

Task 1: Perform DNH/Failure Analysis (FMECA/FTA)

There are many methods that can be used for failure and failure propagation analysis, but experience has shown that Failure Mode and Effects Analysis (FMEA), Failure Modes, Effects, and Criticality Analysis (FMECA), and/or Fault Tree Analysis (FTA) are likely to be the most efficient for servicing/ADR support.

Do No Harm (DNH) FMEA and FMECA are methods used to identify ways a product can fail, and they show in the event of failure, the presence/absence of acceptable risks of coincident detriment beyond product itself. Whereas an Operations (Ops) FMECA/FMEA are methods used to identify ways a product can lose capability and assesses how required operations will be impacted. Therefore, for servicing and/or ADR, DNH Ops FMECA/FMEAs should inductively assess each client-to-servicer interface or servicer-component failure and assess its implications (i.e., servicer failure propagation to client, Servicer loss of collision avoidance/maneuvering, client loss of function/passivation capability, etc.) and risk. Theses analyses and risks will assist with servicer design, operations planning, and risk-informed decision making. So they are best performed iteratively from servicer/FDIR design through mission formulation/planning, testing, and operations (i.e., client/servicer functional change, after rendezvous, in-situ inspection, testing, etc.) to keep knowledge current and allow for real-time contingency analysis/planning.

Since a Fault Tree Analysis (FTA) is a deductive analysis of foreseeable, undesirable states or events, multiple FTAs should be performed for servicing/ADR considering the top-level events of Disabling Client Capabilities (Functionality or Passivation), Disabling Servicer, Capture Failure, Service/ADR Incomplete, and Servicer-Client Collision/Unacceptable Contacts, at a minimum. Each of these top-level events would have its own logically, combined contributing failures/events of the servicer and client with probabilities, which permits FTA result to show the potential risk/probability of that end-state/event. This result and those of the contributing events will assist decision makers in determining the risks of using a particular servicer and/or performing servicing/ADR operations before and during operations. These FTAs should also be performed iteratively from servicer/FDIR design through mission formulation/planning, testing, and operations (i.e., client/servicer functional change, after rendezvous, in-situ inspection, testing, etc.) to keep risk-informed decision making current and allow for real-time contingency analysis/planning.

These analyses require the following knowledge/data from supporting activities (i.e., Tasks A, B, D, G, and H shown in Figure 2):

- Client’s design (inherent and serviceability)
- Servicer’s design (inherent and serviceability)
- Servicer capabilities/overrides/current state
- Client’s/debris’ current state
- Part failure rates/updates
- Operations plan and critical events

This ensures the plausibility of tactics 1, 2, and 7; assists in making strategies 1, 2, 3, and 7 achievable; and assures objectives 1, 5, and 6 are attainable, as shown in Figure 2.

Task 2: Perform Probabilistic Assessment (e.g., PRA, Monte Carlo, etc.) -

The intent of a probabilistic, or quantitative, assessment is to estimate the probability of a sequence events (and each contributing event occurring). For servicing/ADR this would be the probability of the servicer achieving its servicing events with the client, becoming a client, and maintaining proper capabilities to avoid all collisions. There are several traditional methods that can be used for probabilistic or quantitative analysis, such as Reliability Block Diagrams (RBDs), Markov models, Fault Trees (FTs) or Fault Tree Analysis (FTA), Probabilistic Risk Assessment (PRA). Not all provide risk drivers like FTs and PRA, but all of them can provide a reliability prediction. The method chosen is typically based on system or operational complexity, specific needs, and previous analyses. For example, very simple systems may be sufficiently analyzed using an RBD. However, systems with complex redundancy or those with a variety of failure recovery scenarios (e.g., failure of one, two or three thrusters lead to different recovery scenarios and timelines), may require a PRA or Markov model to deal with the complexity. Additionally, complex situations, such as servicing/ADR plans that have multiple contingency options, multiple recovery options, or foreseeable perturbations that are known not to be permanent failures/situations (e.g., solar weather, collision avoidance, SEU events, computer resets), may require Markov or similar modeling to identify failure scenarios that can then be quantified with an FTA (as described under task 1) [11].

The risk insights provided by any of these methods delivers critical details to the RIDM process, such as redundancy influences, operational feasibilities, system and/or process vulneraries. Therefore, it is helpful if these analyses are performed early and iteratively, with system changes (i.e., loss of consumables or functionality, aging, mission extension, etc.) to help with the design, mission formulation and planning, testing, servicing/operations/disposal evaluations, etc., to ensure an acceptable mission and risk profile is maintained, and to allow for real-time contingency analysis and planning. However, given the uncertainty in numerical predictions, this should not be the sole risk criterion for decision making. Stakeholders/decision makers should consider risk scenarios, risk drivers, preventions, and mitigation options as well as the numerical predictions. All these inputs are necessary to assist the decision makers in evaluating the design and determining the risk of using a particular Servicer and/or performing servicing/ADR operations.

This assessment and underlying analyses require the following knowledge/data from supporting activities (i.e., Tasks A, B, E, I, J, and G shown in Figure 2):

- Trajectory/orbit and Collision Avoidance Operations (CAO)
- Knowledge of client/servicer's system design and current operational state
- Operations plan and critical events
- Fault scenarios (FTs) from Task 1
- Preventative or mitigating actions
- Knowledge of failure rates/probabilities
- Knowledge of potential external threats

This ensures the plausibility of tactics 1, 2, 3, and 5; assists in making strategies 1, 2, 3, and 5; achievable; and assures objectives all objectives are attainable, as shown in Figure 2.

Task 3: Perform Process FMECA/FT

Process FMEA and FMECA are methods used to identify ways a process/procedure can fail and the resulting impacts. Therefore, for servicing and/or ADR, process FMECA/FMEAs should inductively assess servicing/ADR task/step for failure likelihood, implications, (i.e., Service failure, Servicer/Client damage/loss, Debris generation, loss of operations/disposal, etc.) and assess its risk. The analysis and resultant risks will assist with service (nominal and contingency) planning and servicer design and risk-informed decision-making. So they are best performed iteratively from servicer/FDIR design through mission formulation/planning, and testing to keep knowledge current. As well as referenced during servicing execution for anomaly responses and updated when real-time condition changes (i.e., client/servicer functional change, in-situ inspection findings, etc.).

Since an FTA is a deductive analysis of foreseeable, undesirable states or events, it should be performed for servicing/ADR considering the top-level events of not completing any servicing mission phase (e.g., Launch/Early Ops, Rendezvous, Prox. Ops/Inspection, Approach, Capture, Servicing, Separation, Commence Post-Service Operations (return to service or disposal)) and/or the steps/tasks within a phase. Each phase-level FTA will alert the analyst if additional step/task-level analyses are warranted via the resultant cut-sets and probabilities, and these lower-level FTAs should be completed to fully characterize and mitigate procedural risks. Given that these analyses and results will assist decision makers in determining the risk of performing selected servicing/ADR operations, they should be performed and referred to before and during operations.

These analyses require the following knowledge/data from supporting activities (i.e., Tasks A, B, C, D, G, H and K shown in Figure 2):

- Client’s design (inherent and serviceability)
- Servicer’s design (inherent and serviceability)
- Servicer capabilities/overrides/current state
- Client’s /debris’ current state
- Part failure rates/updates
- Operations/servicing plan and critical events
- Debris/break-up testing /modeling (based on manipulation, intended/unintended contact)
- Capture method/plan

This ensures the plausibility of tactics 1, 3, and 4; assists in making strategies 1, 3, 4, and 6 achievable; and assures objectives 1, 2, 3, 4, 5, and 6 are attainable, as shown in Figure 2.

Task 4: Assess Probability of De-orbit

Given the best possible reference or developed reliability estimation for each system and any uncertainties associated with those estimates, an estimate of the space asset’s disposal plans’ probability of success can be quantitatively determined for risk-informed decision-making. This can be done using Reliability Block Diagrams (RBDs) / Reliability Logic Diagrams, disposal event trees, disposal fault trees, a PRA of the disposal events, or some other quantitative analysis that is appropriate [12]. However, given that ADR or servicing assisted disposal is much more complex than executing a single-mission operation at a specific point in its life, the RBD/RLD or single-FTA approaches are not usually sufficient or representative of operational probabilities, unless only stacked disposal is planned. In the stacked case, the ADR-servicer would be assessed in the RBD/RLD or FT for its probability of de-orbiting itself while the client is attached. In the more complex cases of deorbiting after servicing in a non-combined configuration, FTAs can be used to assess the probability of completing release and subsequent client/servicer de-orbit independently (immediately or after continued operations). Alternatively, a PRA can be applied to servicing-assisted disposal, in the stacked or non-combined configurations, where events or event trees would be limited to the actions planned for disposal (e.g., stack/servicer/client maneuvering, release, natural-decay, passivation) in one analysis and not the service (e.g., refueling, capture) unless desired.

This analysis requires the following knowledge/data from supporting activities (i.e., Tasks B, E, F, and shown in Figure 2):

- Operations plan and critical events related to de-orbit
- Trajectory and Collision Avoidance Operations (CAO)
- Fault scenarios (FMECAs/FTs) from Task 1 and 6
- Orbital analysis
- Mass/atmospheric reentry survivability

This ensures the plausibility of tactic 5, assists in making strategy 5 achievable, and assures objective 4 is attainable, as shown in Figure 2.

Task 5: Perform Serviceability Assessment/Maintainability Analysis

Serviceability assessment is not a discrete event but a continuum of iterative inputs, analyses, and trades from concept definition through mission termination. It includes all disciplines and mission stakeholders to ensure that a product can be safely and effectively sustained throughout its operations and disposal.

Mission operational concepts that are desired to have sustainability beyond that which is in-place at launch must have designs that are required to be sustainable, validated to achieve the sustainability required, and verified as sustainable. This is just an expansion of the well-proven mission design and implementation practices of the authoring agencies. For instance, Systems Engineers do not limit requirements to performance only but include service/maintainability requirements as well; Designers not only provide for access during integration and testing but also adopt servicer-cooperative ports/fittings, connectors, and ergonomic and location/capture features (See Figure 3); testing and operations plans for and tests capture plausibility (Task I of Figure 2) and the feasibility of contingencies, repair, refurbishment, and enhancement capabilities as well as system functionality; whereas Reviewers and Mission Assurance experts assess adequacy, safety, and maintainability of designs, implementations, and documentation/requirements for mission functions and servicing. Although each of these expansions may sound simple, they will likely require multi-discipline collaboration to adopt new methods and practices. However, there are some existing practices and mission assurance activities that can be leveraged today. Those from mission assurance are described below:

- System Reviewers – Review teams, with experts from research, design, and mission assurance, can provide Agency leadership with an independent assessment of mission designs and plans as part of the mission development process. For serviceability, these teams begin by evaluating concepts and requirements for their consistency with the desired level of accessibility and evolvability. They continue in unison with mission development and operations by examining developmental and system-as-is engineering analysis results (e.g., updated structural integrity analysis) to comment on or concur with a system's suitability and compatibility with planned or potential servicing/ADR (Task D of Figure 2).

- Safety/Environmental Protection – Safety and environmental engineers are responsible for determining the risk of accidents or harmful outcomes by Monte-Carlo analysis, System-Theoretic Process Analyses (STPA) of hazards (Task H & K of Figure 2), and/or Fault Tree hazard analyses (similar to those discussed in Task #1). For servicing/ADR operations and systems these analyses can find the risk of creating debris, collisions, re-entry, and/or harming a human servicer during development and continually as the deployed system ages. Therefore, it is essential that space environmental monitoring and demise/collision testing be performed and that the in-situ client and servicer conditions be acquired and shared with these engineers to ensure safety and environmental risks (e.g., collision, debris generation, astronaut EVA system damage, entanglement of servicer) are current for decision makers.

- Reliability Engineering – Reliability teams can evaluate serviceability via failure analysis, lifetime estimation, and maintainability analysis.

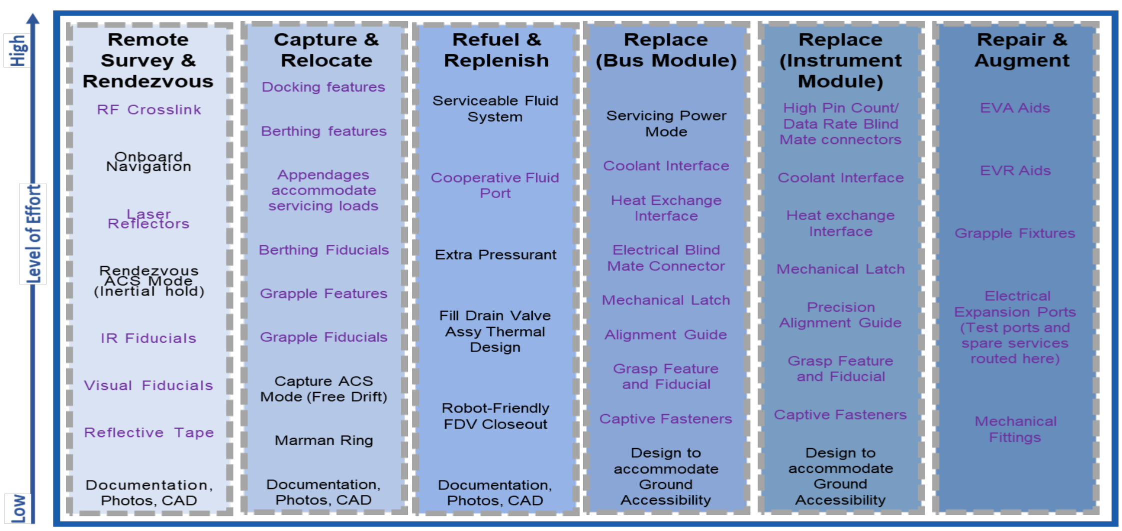
  Failure analysis in support of serviceability assessments takes two forms: inherent failure susceptibility and service (enhancement/preventative/corrective) action impacts. Inherent failure susceptibility assessments are made using the as-designed FMECAs/FTs/PRAs and results, as discussed in tasks 1-3, and identification/generation of the best possible failure rate estimates for each system in the design(s) and any uncertainties associated with those estimates (Task G of Figure 2) to determine the practicality of service. Whilst enhancement/preventative/ corrective action impacts can be assessed with updated or enhanced FMECAs/FTs/PRAs that are inclusive of these actions and or ORU/LRU replacement dependencies. The results of these, serve to establish serviceability in terms of the risks of service and the risks mitigated by service, versus the risks of not servicing.

  Estimating the lifetime of a system or its ORU/LRU can support serviceability by determining the value or impact of service in terms of availability, MTTF, and functionality improvements. A lifetime analysis (Task A of Figure 2) identifies the design elements that have or have exhibited limited shelf, or finite operations/cycle lives, or are susceptible to environmental or operational wear and determines the current life ratio (expected life (or remaining useful life for operational systems) ÷ required life). Each design element's life ratio can be used to plan effective sparing and service actions and forecast servicing needs of planned or modified operations. It can also identify system/material manipulation debris generation risks based on material aging data from Task G.

  Maintainability analysis takes three forms: process initiation, process evaluation, and quantification. Maintenance process initiation analysis can use Ops FMECA results, as discussed in Task 1, to provide optimized sensor inclusion and system/servicing responses resulting in proactive maintenance or service recommendations. Maintenance process evaluations can be performed using process FMECA/FTA, as discussed in Task 3, to identify the feasibility and risk of a proposed action to the maintenance target or coexisting/dependent systems. While maintenance or service activity quantification can assess the MTTR or MDT, and/or update the MTTF/Availability of a system. It is best if these quantifications are based on actual maintenance-performance measures, but in space operations simulated performance measures may be all that is available, so uncertainty is probable until servicing is a common practice. Regardless, these quantifications can be used by mission planners to optimize service while maintaining performance goals.

- Quality Assurance/Testing/Operations – Quality and Testing/Operations professionals are responsible for verifying the system is built and performs as designed and documentation is complete. For serviceability, this verification begins with drawing and parts reviews to ensure cooperative servicing features are in place (See Figure 3); and continues with routine in-process inspections and extends to virtual/in-situ inspections, monitoring of ORU/LRU replacement demonstrations/testing and ergonomic/accessibility checks/testing, and adding of close-out assurance steps to ensure that close-outs remain cooperative for servicing/ADR and are well documented. Further for the servicer, Quality and Testing/Operations professionals can also ensure that the capture; attitude/orbit; and replacement units, consumables, or other item(s) are compatible with planned operations via routine methods and enhanced two-system testing/simulations (Tasks B, E, I, & J).

Figure 3: Serviceability Enabling Technology [13, 14]



These analyses require the following knowledge/data from supporting activities (i.e., Tasks A, B, D, E, G, H, I, and K shown in Figure 2):

- Client's design (inherent and serviceability)
- Servicer's design (inherent and serviceability)
- Servicer capabilities/overrides/current state
- Client's/debris' current state (including entanglement features present)

- Operations plan and critical events relative to orbit and attitude maintenance
- Capture method
- Expert review and recommendations

This ensures the plausibility of tactic 7, assists in making strategy 7 achievable, and assures objective 6 is attainable, as shown in Figure 2.

Note: The authors of this paper acknowledge and recognize the serviceability area needs further multi-discipline collaborative brainstorming and practice development; and recommend the above be viewed as a catalyst for further work only.

<u>Task 6: Perform Release Operations Risk Assessment</u> -

A Release Operations Risk Assessment (RORA) can be performed using results of an Ops FMECA/FMEA (from Task 1) and/or a new Release Ops Failure FMECA/FMEA or FTA.

In order to support a RORA, an Operations FMECA/FMEA can be performed on the release-actions. This analysis would focus traditional FMECA/FMEA failure/risk identification techniques, as described in task 1, on only those system elements (i.e., Servicer release mechanism failure, Servicer loss commanding, etc.) that are involved or can impact client-release and assess their impact to release only. This is normally a subset of the full Ops FMECA/FMEA, so a new analysis may not be warranted if a full OPS FEMCA/FMEA's results are available. However, care must be used to ensure all failure modes involved in this single operation are covered or collected. The gathering or identification of release-risks from these failure modes will assist with servicer design and operations/contingency planning. So they should be assessed iteratively from servicer/FDIR design through mission formulation/planning, testing, and operations (i.e., client/servicer functional change, after rendezvous/service, in-situ inspection, testing, etc.) to keep risk-informed decision making current and allow for real-time contingency analysis/planning.

While a FMECA/FMEA can support a RORA, the best analysis to use is the FTA. This is because FTA is a deductive analysis of foreseeable, undesirable states or events, that contribute to a single top-level event. For RORA support the top-level event would be "Client is not Released from Servicer". The FT of the FTA would have all of release failure contributions of the servicer and client with probabilities entered/calculated until the end-state/event probability is formed. These results will assist decision makers in determining the risk of the client-servicer remaining stacked when using a particular Servicer and/or performing servicing/ADR operations before and during operations. Therefore, these analyses should be performed iteratively from servicer/FDIR design through mission formulation/planning, testing, and operations (i.e., client/servicer functional change, after rendezvous, in-situ inspection, testing, etc.) to keep risk-informed decision making current and allow for real-time contingency analysis/planning.

These analyses require the following knowledge/data from supporting activities (i.e., Tasks A, B, C, E, G, H and K shown in Figure 2):

- Client's design (inherent and serviceability)
- Servicer's design (inherent and serviceability)
- Servicer capabilities/overrides/current state

- Client's/debris' current state (including entanglement features present)
- Part failure rates/updates
- Operations plan and critical events relative to release
- Capture method

This ensures the plausibility of tactic 6; assists in making strategies 5 and 6 achievable; and assures objectives 4, 5, and 6 are attainable, as shown in Figure 2.

Summary and Recommendations

In planning a Servicing/ADR mission it essential that all enterprises "Do no harm to space environment assets involved and other assets" (Top Objective from Figure 2). This is a complex objective for any mission to achieve and should inspire mission managers/staff to use risk-informed decision making (RIDM). The use of RIDM will provide a process to amalgamate qualitative and quantitative reliability/technical risk data with safety (e.g., ground, orbital) and other concerns (i.e., policy compliance, costs, politics, debris generation/mitigation, etc.) to make the best decision for missions from formulation through disposal.

Mission assurance/reliability engineering can help with the mission RIDM process and assure servicing or Active/Assisted Debris Removal/ Disposal objectives are met, but only if utilized, analyses and supporting knowledge is kept current, and results are timely, shared freely, and unambiguous. Therefore, based on extensive experience of the Trilateral team authors and stakeholder inputs, it is recommended that the framework activities contained herein be performed during each design/ planning/operational phase shown in the Table 2 with the support of the collaborative activities shown in the Appendix. It is essential when performing these that analysis teams consider the benefits and limitations of analysis techniques and the following, since each will impact results:

- Servicing need and/or goal (e.g., ORU replacement, fueling, ADR-attachment)
- Final desired configuration (stacked or released)
- Operations plans (e.g., capture, contingency, release, or re-boost options)
- Licensing, insurance, and/or statute requirements.

Further, since the application of well-proven mission design and implementation methods (See Task 5) to serviceability assessment is a relatively novel concept, it is recommended that methodology to support this concept continue to be developed and refined with the collaboration of all disciplines and mission stakeholders. This methodology could be defined in guidance to multidisciplinary teams or statue/procedural requirements. A defined methodology will ensure that Systems Engineers do not limit requirement definition to performance only but include service/maintainability requirements as well; Designers provide for servicing access and adopt servicer-cooperative ports/fittings, connectors, and ergonomic and location/capture features (See Figure 3); testing and operations plans for and tests capture and close-proximity operations plausibility (Task I of Figure 2) and the feasibility of contingencies, repair, refurbishment, and enhancement capabilities as well as system functionality; and Reviewers and Mission Assurance experts assess adequacy, safety, and maintainability of designs, implementations, and documentation/requirements for mission functions and servicing (See Task 5).

These recommendations and the data herein, are offered for the advancement of the applicable agency/industry requirements and practices for current and future missions (i.e., interstellar, lunar, Mars, etc.) and to assist servicing missions to be safely and effectively designed, planned, and executed.

Future Work

In the process of developing this framework, this Trilateral team noted the benefit of continuing collaboration on all mission types and topics to ensure every agency and mission can learn and leverage the knowledge, innovations, and advancements of any one agency in all disciplines. For Reliability, this would involve on-going sharing of knowledge, innovations, and methods (in regard to capture-mechanism analysis, sensor/prognostic optimization and assessments, maintainability analysis, system failure mode generation, aging impact calculations, evolvable mission methodologies, model-based reliability engineering, field-data sharing, probability calculation, and other activities) through this Task Force, other task forces (e.g., MB Mission Assurance), or other inter-Trilateral team and/or peer-to-peer collaboration. This continued collaboration, no matter the form, would not only assist each agency ensure all missions are successful, dependable, and valuable, but would help sustain the space environment as well.

Table 2: Notional Task Phasing Recommendation

*Indicates efforts that are continuous, as needed, and/or outside of mission phasing.

Mission Phase / *Task Recommended*	Client	Client	Client	Client	Client	Servicer	Servicer	Servicer	Servicer	Servicer	Pre-Service & Proximity Ops				
	Conceptual Design	**Preliminary Design**	**Detailed /Critical Design**	**Implementation & Testing**	**Launch & Early Ops**	**Conceptual Design**	**Preliminary Design**	**Detailed Design**	**Implementation & Testing**	**Launch & Early Ops**	**Client/ Servicer Ops**	**Rendezvous & Inspection**	**Approach and Capture**	**Servicing**	**Re-orbit and/or Deorbit**
Task 1: Perform DNH/Failure Analysis (FMECA/FTA)						Created	Update	Update	Update	Final		Update	Use as Anomaly Diagnostic tool		
Task 2: Perform Probabilistic Assessment						Created	Update	Update	Update	Final	Refined	Update			Update
Task 3: Perform Process FMECA/FT						Created	Update	Update	Update	Final	Refined	Update	Use as Anomaly Diagnostic tool		
Task 4: Assess Probability of De-orbit		Created	Update	Update	Final		Created	Update	Update	Final	Update				Update
Task 5: Perform Serviceability/ Maintainability Analysis	Created	Update	Update	Update	Final		Created	Update	Update	Final	Update	Update	Use as Anomaly Diagnostic tool		
Task 6: Perform Release Operations Risk Assessment							Created	Update	Update	Final	Refined	Update	Use as Anomaly Diagnostic tool		
Task A: Life/Aging (systems/materials/ structures) analysis of Client/Debris		Created	Update	Update	Final						Update	Update/ Verify		Verify	
Task B: Inspect Client from Grnd, TLM, or On-orbit					Created						Update	Update		Update	Update
Task C: Perform debris/break-up Testing/Modeling*			Created	Updated				Created	Updated						Verify/ Update

Mission Phase / *Task Recommended*	**Client**	**Client**	**Client**	**Client**	**Client**	**Servicer**	**Servicer**	**Servicer**	**Servicer**	**Servicer**	**Pre-Service & Proximity Ops**				
	Conceptual Design	**Preliminary Design**	**Detailed /Critical Design**	**Implementation & Testing**	**Launch & Early Ops**	**Conceptual Design**	**Preliminary Design**	**Detailed Design**	**Implementation & Testing**	**Launch & Early Ops**	**Client/ Servicer Ops**	**Rendezvous & Inspection**	**Approach and Capture**	**Servicing**	**Re-orbit and/or Deorbit**
Task D: Conduct Design Rvws to Ensure Serviceability Technology is present	Created	Updated	Updated	Updated	Updated	Created	Updated	Updated	Updated	Updated					
Task E: Perform Orbit Analyses	Created	Updated	Updated	Updated	Updated	Created	Updated	Updated	Updated	Updated	Updated Client	Updated (both)	Update (both)		Update (both)
Task F: Perform Casualty Analyses		Created	Updated	Updated			Created	Updated	Updated						Updated/ Verify
Task G: Part/ Material/Component Evaluation*		Created	Updated	Updated			Created	Updated	Updated			Updated			
Task H: Perform Entanglement/ Release Risk and Hazard Assessments						Created with Client considered	Updated	Updated	Updated	Updated	Updated with Client State	Updated with Client Condition		Update	Update
Task I: Verify Trajectory is Safe						Created	Updated	Updated	Updated	Updated	Updated In-Situ	Update/ Verify	Update/ Verify		Update/ Verify
Task J: Perform 3rd party collision avoidance for nominal operations*					Initiated					Initiated					Update/ Continues
Task J: Perform collision avoidance between servicer and client*											initiated	Update/ Verify	Update/ Verify	Conditional	Update/ Continues
Task K: Select Capture method						Created	Updated	Updated	Updated		Verify	Verify	Verify		

Note: Client/Servicer task phasing may be sequential (with either client or servicer being first) or coincident or any combination of those.
And any significant plan or design/condition changes may require additional recurrence or initiation of tasking.

Definitions:

Active debris removal (ADR) - On-orbit servicing that removes either a spacecraft whose mission is terminating or space debris from the current orbit to an orbit for disposal (including orbits for the Earth's atmospheric reentry).

Bump - Uncontrolled or inadvertent or unacceptable touching.

Capture - A sequence of operations to establish a structural engagement between the servicer spacecraft and the client object.

Client object - A functioning or non-functioning on-orbit spacecraft or space debris to which on-orbit servicing is provided.

Collision - Conjunction of two space assets that does not result in capture (example: an old asset capture gentleness)

Collision Avoidance Operations (CAO) - Maneuvering operations to mitigate the risk of collision with debris or another space asset.

Collisional trajectory - An approaching trajectory which could interfere with the client object or its dynamic envelope, if the servicer or client spacecraft loses its functionality.

Component - A configuration item or logical functional element within space system such as a unit, circuit, assembly, or even a set of hardware (or software in limited cases) but not the constituent parts (i.e., resistor, bolt, etc.).

Deorbit - A course of action that results in a spacecraft deliberately leaving its current orbit and beginning its descent/demise.

Do No Harm (DNH) - A course of action that causes no self or coincident detriment.

FDIR - Fault detection, isolation, and recovery is a concept enacted through software and/or hardware systems that effectively detects faults, accurately isolates them to a failed component, and autonomously takes action to remove failed-component from operations and recovers the lost functionality through redundant or functionally redundant means.

Final approach and capture phase - Where the servicer spacecraft performs final approach to the client object and captures it.

FMECA - Failure Modes Effects and Criticality Analysis is the inductive analyses of the impacts of each plausible discrete failures of function, interface, and/or process, each failure mode with an impact or severity, detectability, and likelihood, and the identification of Single-Point Failure vulnerabilities.

FTA - A Fault Tree Analysis (FTA) is a deductive analysis of foreseeable, undesirable states or events.

Hazard - A state or a set of conditions, internal or external to a system, which has the potential to cause harm (Source - NPR 8715.3).

Implementation & Testing - Are the processes and actions that fabricate/manufacture, integrate, and test (in simulated in-situ environments and scenarios) components, units, and systems to produce a spacecraft/observatory.

Line Replaceable Unit (LRU) - A modular component of a system that can be removed and replace in-situ.

Maintainability - The extent to which a client is capable of triggering, receiving, or recovering from preventative, condition-based, or corrective maintenance or refurbishment (e.g., refueling).

Mission Assurance (also known as Safety and Mission Assurance SMA)) – The composite discipline of safety, quality, and reliability engineering that protect or ensure the continued function and resilience of assets (i.e., missions, ground systems, test facilities, information systems, etc.) and their associated logistics, infrastructure, and supply chain.

On-orbit servicing (OOS) - An act by a spacecraft to intentionally influence another spacecraft for the purposes of resupply, inspection, replacement, repair, modification and/or augmentation, or to remove either a spacecraft whose mission is terminating or space debris from orbit.

On-orbit Replacement Unit (ORU) - A modular component of a spacecraft/system that can be removed and replace on-orbit.

PRA - Probabilistic Risk Assessment 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 a successful system or operation.

Proximity operations - Operations performed while two objects are connected or in a very close range. This includes to include testing (e.g., capture mechanism opening and closing), rehearsals, and motion synchronization.

Proximity operation phase - Where the servicer spacecraft is operated in a very close distance but not coming into contact with the client object.

RBD - Reliability Block Diagrams (RBDs) / Reliability Logic Diagrams are a logical representation of a particular system’s individual functional elements. These diagrams can be quantitatively assessed for their and the system’s potential for successful performance.

Rendezvous - An act of approaching a client object by controlling the relative positions, relative velocities and other parameters within a designated range.

Rendezvous phase - Where a servicer spacecraft approaches a client object by controlling relative position, relative velocity, and other parameters within a designated range.

Re-Orbit - The action(s) of returning the client or servicer to an acceptable operational/storage orbit.

Safe trajectory - A trajectory which does not interfere with other object’s maintenance of the allowable dynamic envelope for operations or storage during servicing/ADR operations.

Separation phase - Where the servicer spacecraft separates and departs from the client object and returns to its solo operations. (When servicing multiple clients, it shifts to the next rendezvous phase.)

Servicing - Where the servicer spacecraft performs various services (e.g., life extension by station-keeping, refueling, ORU replacement, repairs, etc.) for the client object (spacecraft, etc.). If the servicer spacecraft is to be disposed of altogether with the captured client object, the sequence of applicable phases ends here.

Serviceability - The extent to which a client is acquirable, capable of providing diagnostic data, receiving or recovering from preventative, condition-based, or corrective maintenance, and is designed for enhancement/augmentation.

Serviceability technology - Design features (figure 3) that enable locating, acquiring, maintenance/ augmentation, and release/disposal.

Servicer spacecraft - A spacecraft that provides on-orbit servicing.

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).

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Appendix: Collaborative Activities and Knowledge Capture Activity Descriptions

	Description (include performed by or add column?)	Knowledge Gained	Potential Users (by GOST)	Required data
Task A: Life/Aging (systems/materials/structures) analysis of Client/Debris	A life analysis identifies components that potentially have a finite or limited useful life inherent to the performance of their respective functions. It is intended to determine how much of the expected life is consumed by the stresses the component experiences during testing and operation, and to assess if this cumulative damage/use which can be used to determine service needs.	• Knowledge of client's /debris' current state and service needs (consumables, disposal, refurbishment) • Knowledge of Part /Material Failure Rates/Updates • Knowledge of client's /debris' current state and service needs (consumables, disposal, refurbishment)	Task 1: Perform DNH/Ops FMECA/FTA Task 2: Perform Probabilistic assessment (e.g., PRA, Monte Carlo, etc.) Task 3: Perform Process FMECA/FT Task 5: Perform Maintainability Analysis/ Serviceability Assessment Task 6: Perform Release Operations Risk Assessment	• Results from life testing of systems/materials/structures (potentially from Task G) • Results from similar applications of systems/materials/structures
Task B: Inspect Client from Ground, TLM, or On-orbit	Evaluates current condition of a client (especially non-cooperative/non-functional) via inspections to confirm that products and processes meet expected levels of quality/functionality. In which robotic, TLM health status and trends, and remote imaging (telescopes, radar, etc.) are used by operations and mission planning teams to determine servicing/ADR value/need and/or feasibility.	• Knowledge of Servicer Capabilities/Overrides/current state • Knowledge of client's /debris' current state and service needs (consumables, disposal, refurbishment) • Knowledge of External Threats	Task 1: Perform DNH/Ops FMECA/FTA Task 2: Perform Probabilistic assessment (e.g., PRA, Monte Carlo, etc.) Task 3: Perform Process FMECA/FT Task 4: Assess Probability of De-orbit Task 5: Perform Maintainability Analysis/ Serviceability Assessment Task 6: Perform Release Operations Risk Assessment	• Current Design data • Current Operations plans • Client TLM health status and trends if available • In-situ condition imaging
Task C: Perform debris/break-up Testing /Modeling	Analysis of system demise and fracture due to collision, bumps, and reentry. Performed by Debris Modeling teams.	• Knowledge of Mass/Atmospheric Survivability	Task 6: Perform Release Operations Risk Assessment	Results from Task 3: Perform Process FMECA/FT
Task D: Conduct Design Reviews to Ensure Serviceability Technology is present	Presentation and review of product or mission development, testing/demonstration results, and service planning against specific criteria (e.g., serviceability, capability, feasibility, risk). Performed by project and stakeholders, where projects present, and stakeholders evaluate and verify design/plan acceptability to move forward and/or suggest changes.	• Knowledge of servicer's design (serviceability tech) • Knowledge of client's design (serviceability tech) • Knowledge of client's /debris' current state and service needs (consumables, disposal, refurbishment) • Knowledge of doing Nothing Cost/Risks • Knowledge of Insurance limitations	Task 1: Perform DNH/Ops FMECA/FTA Task 3: Perform Process FMECA/FT Task 5: Perform Maintainability Analysis/ Serviceability Assessment	• Current Design data • Current Operations plans
Task E: Perform Orbit Analyses	Orbit analysis of current position and planned operations (including CAs as needed) to determine resultant orbit/trajectory is safe and effective. Performed by Orbit Analysts.	• Knowledge of trajectory and CA operations	Task 2: Perform Probabilistic assessment (e.g., PRA, Monte Carlo, etc.) Task 4: Assess Probability of De-orbit Task 5: Perform Maintainability Analysis/ Serviceability Assessment Task 6: Perform Release Operations Risk Assessment	• Current Design data (mass properties) • Current orbital parameters
Task F: Perform Casualty Analyses	Analysis of human (or property) casualty risk from space system components surviving reentry. Performed by Debris Modeling teams.	• Knowledge of Mass/Atmospheric Survivability	Task 4: Assess Probability of De-orbit	
Task G: Part/Material/Component Evaluation	Analysis or testing of parts, materials, or components to characterize intrinsic limitations/advantages, quality, life, susceptibilities (e.g., radiation). Performed by parts and material engineering/control boards.	• Knowledge of Part /Material Failure Rates/Updates • Knowledge of External Threats • Knowledge of Servicer Capabilities/Overrides/current state	Task 1: Perform DNH/Ops FMECA/FTA Task 2: Perform Probabilistic assessment (e.g., PRA, Monte Carlo, etc.) Task 3: Perform Process FMECA/FT Task 5: Perform Maintainability Analysis/ Serviceability Assessment Task 6: Perform Release Operations Risk Assessment Task A: Life/Aging (systems/materials/structures) analysis of Client/Debris	• Results from life testing of systems/materials/structures • Results from similar applications of systems/materials/structures

	Description (include performed by or add column?)	Knowledge Gained	Potential Users (by GOST)	Required data
Task H: Perform Entanglement/Release Risk and Hazard Assessments	Safety analyses performed by safety/reliability engineering to determine hazards and mitigations in place for entanglement and/or releasing client.	• Knowledge of servicer's design (serviceability tech) • Knowledge of client's design (serviceability tech) • Knowledge of External Threats • Knowledge of Ops plan & critical events	Task 1: Perform DNH/Ops FMECA/FTA Task 3: Perform Process FMECA/FT Task 5: Perform Maintainability Analysis/ Serviceability Assessment Task 6: Perform Release Operations Risk Assessment	• Knowledge of External Threats • Knowledge of servicer's design (serviceability tech) • Knowledge of client's design (serviceability tech) • Knowledge of Servicer Capabilities/Overrides/current state
Task I: Verify Trajectory is Safe	Orbit analysis of current position and planned operations (including CAs as needed) to determine resultant orbit/trajectory is safe and effective. Performed by Orbit Analysts prior to Service/ADR and during those operations.	• Knowledge of trajectory and CA operations	Task 2: Perform Probabilistic assessment (e.g., PRA, Monte Carlo, etc.). Task 5: Perform Maintainability Analysis/ Serviceability Assessment	• Knowledge of External Threats • Knowledge of servicer's design (serviceability tech) • Knowledge of client's design (serviceability tech)
Task J: Perform collision avoidance operations	Operations teams maneuver spacecraft to avoid unwanted conjunctions on-orbit with 3rd party systems or between the client and servicer. Performed by Orbit Analyst, Mission Operations, and space situational awareness teams.	• Knowledge of trajectory and CA operations	Task 1: Perform DNH/Ops FMECA/FTA	• Knowledge of External Threats • Knowledge of servicer's design (serviceability tech) • Knowledge of client's design (serviceability tech) • Knowledge of Servicer Capabilities/Overrides/current state • Knowledge of client's /debris' current state and service needs (consumables, disposal, refurbishment)
Task K: Select Capture method	Trade/Design study to select feasible capture method/design for intended service/ADR. Performed by servicer design teams.	• Knowledge of grapple capture methods/limitations	Task 3: Perform Process FMECA/FT Task 5: Perform Maintainability Analysis/ Serviceability Assessment Task 6: Perform Release Operations Risk Assessment	• Knowledge of client's design (serviceability tech) • Knowledge of Servicer Capabilities/Overrides/current state • Knowledge of client's /debris' current state and service needs (consumables, disposal, refurbishment)