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DOCUMENT

GSTP Element 1 “Develop” - Compendium of Potential Activities: Clean Space

Prepared by TEC-TI
Reference ESA-GSTP-TECT-PL-003997
Issue 1
Revision 1
Date of Issue 20-01-2017
Status
Document Type
Distribution

APPROVAL

Title GSTP Element 1 "Develop" - Compendium of Potential Activities: Clean Space	
Issue 1	**Revision** 1
Author TEC-TI	**Date** 20-01-2017
Approved by TEC-T	**Date**

CHANGE LOG

Reason for change	Issue	Revision	Date

CHANGE RECORD

Issue 1	**Revision** 1		
Reason for change	**Date**	**Pages**	**Paragraph(s)**

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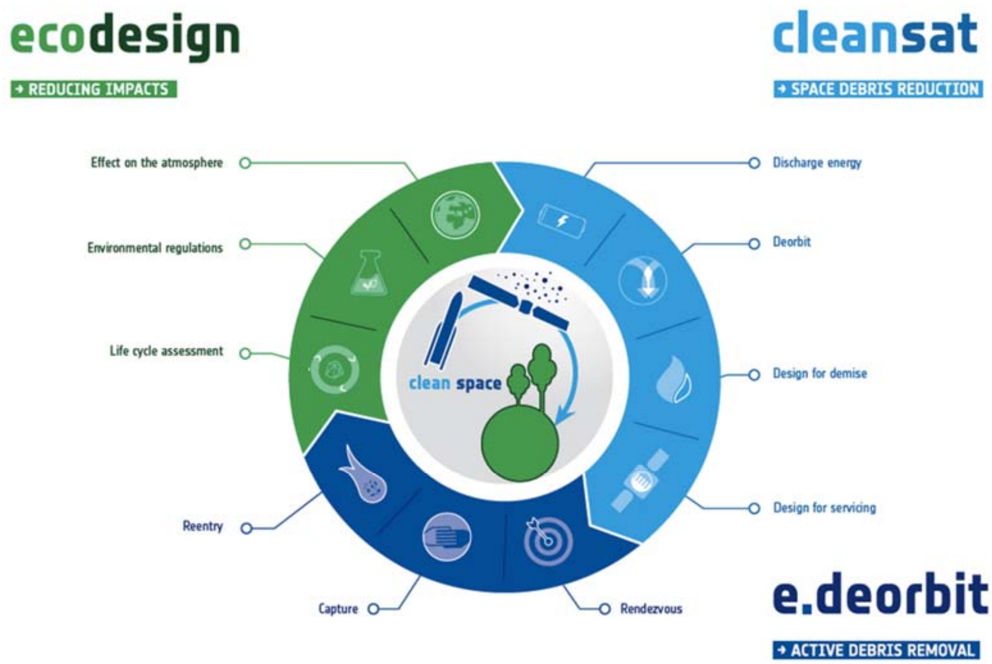
1 INTRODUCTION

This document provides an additional list of candidate activities to the Work Plan of the GSTP Element 1 “Develop”, following the process outlined in the September 2012 IPC: ESA/IPC(2012)98 - Preparing the work plans for the GSTP-6 Element 1.

This document is a revision of the activities belonging to the Clean Space Specific Area published originally in the GSTP-6 Element 1 – Compendium of Generic Technology Activities issued in February 2013 (ref. TEC-SGT/2013-007/NP) and revised in February 2016 (ref. TEC-T/2016-03/NP) and therefore replaces the Clean Space specific area of the previous document.
This document includes technology activities in the three branches of Clean Space:

- **CleanSat** – Including system and technology activities for space debris mitigation in line with the CleanSat Proposal ESA/IPC(2016)98 presented to IPC in September 2016 and its revision (ESA/IPC(2016)98,rev.1).
- **e.Deorbit** - Including activities to complete the e.Deorbit Maturation Phase in line with the eDeorbit Proposal ESA/IPC(2016)97 presented to IPC in September 2016 and its revision (ESA/IPC(2016)97,rev.1).
- **EcoDesign** – Including activities to assess and reduce environmental impacts of space missions. These activities are from previous compendium



According to the ESA-wide process described in ESA/IPC(2008)61 rev 1, the activities which are part of this compendium have been pre-selected following an intensive internal exercise which included programmatic screening, technical evaluation and consistency checking with technology strategy and THAG Roadmaps.

This compendium is issued to Delegations of GSTP Participating States and their industries for comments. Such comments will be considered in the following updates of the work plan for this GSTP Element 1 "Develop".

The objective is to have a good indication of the developments the Participants intend to support, in order to present updates of the GSTP Element 1 "Develop" Work Plan with a consolidated set of activities to the IPC for approval.

2 CLEAN SPACE: BACKGROUND AND MAIN CONSIDERATIONS FOR TECHNOLOGY DEVELOPMENT

Clean Space is an ESA cross-cutting initiative that directly addresses, through the Agency's technology programmes, the sustainability of space activities on Earth and in orbit. Since 2012, the Clean Space initiative has enabled ESA to become a global pioneer and leader on the sustainable use of space, in particular by bringing a system level approach that addresses the entire lifecycle of the various Agency's space projects, from the early stages of conceptual design until after the End of Life, including preparation for active debris removal.

Clean Space, as indicated in the Information Note to IPC "Preparation of the Future & Technology Innovation Programmes" (ref. ESA/IPC(2016)92) addresses the sustainability pillar of the technology strategy by developing technologies to guaranteeing the future of space activities by protecting the environment.

Within Clean Space, two proposals have been presented to the ESA Member States at IPC.

- **CleanSat: Technologies for Debris Mitigation:**

  The objective of CleanSat, which is not itself a satellite, is the maturation of the technologies necessary to achieve full compliance with Space Debris Mitigation requirements. This is carried out in a coordinated approach involving ESA, system integrators and subsystem and equipment manufacturers.

  Space Debris Mitigation has been identified by all European Large System Integrators as the most impacting new requirements for future missions and high priority for the evolution of the current platforms, both for the institutional and commercial markets. Platforms capable to carry out uncontrolled re-entry or controlled re-entry will be necessary and require very distinct technologies, that have been identified and studied in the last years.

  In order to bring these technologies to TRL 7 for their systematic use in future missions, consolidated requirements are necessary to guarantee that the actual needs of the platform integrators are taken into account. This in turn facilitates the integration of innovative technologies in the next generation of LEO platforms.

  Specific details on this initiative including the regulatory perspective, the market assessment, the coordinated approach including the concurrent engineering phase, the previous technology developments and the proposed future technology developments are provided in the CleanSat Proposal (ESA/IPC(2016)98 and its revision ESA/IPC(2016)98,rev.1).

- **e.Deorbit: First Active Debris Removal Mission**

  e.Deorbit's Mission Goal is to capture a heavy, ESA-owned item of debris and remove it from an altitude of 800–1000 km in a near-polar orbit. The technical challenges to approach, capture and re-enter uncooperative objects need to be solved.

  Advancements in several technology fields are necessary, in particular the following: Advanced Image Processing Systems, Complex Guidance Navigation and Control (GNC) and Innovative Robotics. The above mentioned building blocks are also required to perform various other in-orbit tasks such as: in-orbit servicing, cargo and satellite delivery (space tug) and in-orbit assembly.

  Through the e.Deorbit mission, European suppliers have the opportunity to become the global leaders for robotic and rendezvous technologies which could enable space tugs to become a reality, having first-mover advantage and with it, the ability to lead the new era of space services and in particular on-orbit servicing.

  Specific details on this proposed mission including the current status, legal considerations which justify the need for this mission, the needed technology developments and the plan for the future is provided in the e.Deorbit Proposal (ESA/IPC(2016)97 and its revision ESA/IPC(2016)97,rev.1).

In addition there is a third initiative within Clean Space: EcoDesign

Eco-design focuses on reducing the environmental impacts on Earth from space activities. LCA studies previously performed by ESA looked at both spacecraft and launchers and identified the environmental impact across the entire lifecycle of a space mission in terms of various environmental indicators such as Global Warming Potential, Ozone Depletion Potential and Human Toxicity Potential.

The results from these studies helped identify the most environmentally impacting aspects of space missions (hotspots), which in turn provides a good insight into the areas of space mission design where the environmental impact can be reduced. Through the Ecodesign branch of Clean Space, ESA is now taking the next step, to target environmental reduction. This is being carried out through ongoing studies, notably one to perform a redesign of a spacecraft from the beginning taking into account its environmental impact. This study also includes finding alternatives to REACH-endangered substances.

Currently included in this compendium are existing activities previously proposed, however as a result of the ongoing studies, follow on activities, both at material, manufacturing process and equipment level will be added on an ad-hoc basis.

3 TRACEABILITY OF ACTIVITIES FROM PREVIOUS COMPENDIA

ANNEX I – ACTIVITIES IN GSTP E1 "DEVELOP" WORK PLAN / PROCUREMENT PLAN:

The Clean Space activities from the initial Compendia published in 2013 and 2016 that are already part of the GSTP Element 1 "Develop" Work Plan/Procurement Plan (approved by IPC) are not included in this revision of the GSTP Element 1 "Develop" Compendium. However, for traceability these activities are listed in Annex I of this document.

ANNEX II– ACTIVITIES WITHDRAWN FROM THE PREVIOUS COMPENDIA:

The activities from the initial Compendia published in 2013 and 2016 that have been considered obsolete or absorbed by the new defined activities in e.Deorbit or CleanSat subareas are withdrawn from the Clean Space Compendium. For traceability these activities are listed in the Annex II of this Compendium revision. The description for these activities is not provided in this document.

4 LIST OF ACTIVITIES

Specific Area: CLEAN SPACE

The activities will be implemented in close coordination with all the main technology competence responsible units.

The activities in this compendium are divided in 3 branches:

CleanSat

GSTP-6 Reference	Title	Budget(K€)
G61C-050SY	Activities to support the development of LEO platforms compliant with Space Debris Mitigation (SDM) requirements	600
G61C-051EP	Battery Passivation – Safety Testing	250
G61C-052EC	Development, test and qualification of demisable magnetorquer	600
G61C-053MP	Development, test and qualification of demisable propellant tanks	2,800
G61C-054EP	Electrical Passivation – PCDU upgrade for power passivation	700
G61C-055MP	Development and qualification of a Shape Memory Alloy Valve for propulsion passivation	700
G61C-056MP	Development, test and qualification of monopropellant arcjets to support controlled reentry	3,000
G61C-057MP	Development and test of Electronic Pressure Regulator	2,000
G61C-043MS	Prototype and qualification of a drag augmentation de-orbiting subsystem	3,000
	Total	**13,650**

e.Deorbit

GSTP-6 Reference	Title	Budget(K€)
G61e-001SY	e.Deorbit Preliminary Definition Phase (Phase B)	13,500
G61e-002SY	e.Deorbit Robotics Subsystem	11,500
G61e-003SY	e.Deorbit Net Subsystem	6,000
G61e-004SY	e.Deorbit GNC Subsystem	10,000
	Total	**41,000**

EcoDesign

TD 24- Materials and Processes

GSTP-6 Reference	Title	Budget(k€)
G61C-035QT	Development of a complete Cr-VI anticorrosion system and process scale-up at industrial level	500
G61C-044QT	Alternatives to processes affected by REACH for the manufacture of PCBs	500
	Total	**1,000**

TD 26- Others

GSTP-6 Reference	Title	Budget(k€)
G61C-045SW	REIM - Resource Efficiency through Improved Methods for treatment of recycling products	350
	Total	**350**

5 DESCRIPTION OF ACTIVITIES

5.1 Specific Area: Clean Space - CleanSat

Specific Areas	*CLEAN SPACE – CLEANSAT*
Technology Domain	*TD26 - Others*

Ref. Number: **G61C-050SY** **Budget (k€): 600**

Title: **Activities to support the development of LEO platforms compliant with Space Debris Mitigation (SDM) requirements**

Objectives: This activity shall guarantee that the development of the needed LEO platforms compliant with SDM requirements are coordinated to be compliant and capable to integrate the building blocks developed within the CleanSat initiative. This will reduce the cost of switching to SDM requirement compliant LEO platforms making European industry, as a whole, more competitive.

Description: The introduction of Space Debris Mitigation (SDM) requirements by a growing number of countries and agencies has a significant impact at system and subsystem level on LEO platforms. The European Systems Integrators consider it the most impacting aspect for future missions and high priority for the evolution of the current platforms, both for the institutional and commercial markets. The casualty risk requirement states that during atmospheric reentry, the risk of causing a casualty on Earth must be less than 10-4. This risk is driven by the on-ground footprint of reentering objects, and is particularly demanding for medium and large LEO satellites. Depending on the payload, mission and system design, either an uncontrolled reentry can be performed or a controlled reentry is required. Both have very different implications at system level. An uncontrolled reentry can take up to 25 years, and requires the satellite to demise during reentry as well as to passivate power and propulsion systems. Controlled re-entry – performed when compliance with the casualty risk is not possible through uncontrolled reentry - requires efficient propulsion means to perform the required maneuvers.

The CleanSat approach aims at supporting the compliance with these new requirements by taking a coordinated approach to new technology development. The involvement of integrators and suppliers guarantees on the one hand that the suppliers receive adequate requirements to develop innovative technologies compatible with several platforms, making them more competitive, and on the other hand that the integrators can integrate in a fast and more effective way these technologies in their future platforms, becoming themselves more competitive in the international market. This coordinated approach has been used in early phases of CleanSat with great success.

This activity aims at continuing the coordinated effort to support the European industry complying with these new requirements by evolving LEO platforms both for uncontrolled and controlled reentry. This will be achieved through an active participation of the System Integrators on the definition of the requirements, system level analyses and trade-offs to support the various building block developments. At the same time, promoting their smooth integration in future missions in LEO.

The tasks to be performed by the System Integrators are:

- Definition of mission profiles for future LEO platforms performing a controlled reentry or an uncontrolled reentry at End of Life.
- Identification and refinement of use cases for CleanSat technologies by means of system-level trade-offs.
- Define functional architecture and redundancy approaches for the identified LEO platform developments.
- Define requirements for the building blocks to be integrated on future platforms, including: Interface requirements, functional requirements, performance requirements, thermo-mechanical requirements, operational and environmental requirements.
- Follow up building block developments by supporting Interface Reviews with the suppliers and the Agency.
- Carry out the necessary thermal, structural analysis to derive and refine building block requirements.
- Assess operational needs and integration of building blocks in the avionics architecture, including necessary software interfaces and updates (taking into account SAVOIR architectures).
- Perform Reliability, Availability, Maintenance and Safety (RAMS) analysis for the systems, including: Mission reliability, EoL reliability, risk identification and mitigation and Failure Detection, Isolation and Recovery (FDIR).

Deliverables: Reports, TN: Evolution of LEO satellites to comply with SDM requirements; TN: Building blocks requirements and evaluation

Current TRL: N/A **Target TRL:** N/A **Duration (months)** 36

Target Application / Timeframe : Spacecraft in LEO having to perform and uncontrolled or a controlled reentry.
All ESA missions launched after 2020 shall be compliant with SDM requirements contained in ESA/ADMIN/IPOL(2014)2.

Applicable THAG Roadmap: Not related to a harmonisation subject

Specific Areas	*CLEAN SPACE – CLEANSAT*
Technology Domain	*TD3 – Spacecraft Power*

Ref. Number: **G61C-051EP** **Budget (k€):** **250**

Title: **Battery Passivation – Safety Testing**

Objectives: The objective of the activity is to demonstrate the safety of the batteries after passivation at the end of life and provide inputs for power passivation guidelines for future missions. In particular, in this activity the following tasks are foreseen:

- Characterise further the safety of Li-ion batteries at end of life through a series of dedicated test campaigns.
- Identify critical aspects relating to end of life safety of Li-ion batteries and update the recommended passivation approach based on the test results.
- Determine key tests to be carried out on future battery developments and the criteria that they must meet.
- Perform these tests on existing cells to check compliance with criteria and define acceptance conditions score for future developments.

Description: For passivation, it is required that the electrical power sources on-board a spacecraft after its operational phase are depleted or made safe. This requirement is driven by the fact that some accidental satellite breakups have been caused by the battery in the past. However it was mainly with old technologies that have been superseded by the current Lithium-Ion batteries. The safety of these Lithium-Ion batteries after spacecraft disposal currently contains some knowledge gaps. At the end of its operational life a spacecraft undergoes a disposal phase and as a result it is left without attitude or thermal control. This can cause the battery to be subject to extreme environmental conditions due to the loss of spacecraft attitude and thermal control. The cells age in an uncontrolled and unknown manner, which could have a negative impact on their safety. Battery overdischarge or overcharge might also occur.

Tests are currently being carried out within the scope of an ongoing ESA Activity: "Battery Passivation". The goal is to test aged battery cells and/or modules under various conditions that could be encountered after EoM. This GSTP activity will address knowledge gaps arising from tests not performed within this previous activity and in particular tests at module or battery level. Furthermore, the goal is to define and carry out tests that all future battery developments should perform during development. This will provide an essential input to define battery safety guidelines.

In this activity the following tasks will be performed;

- Definition of tests to be performed, taking into account at least the following: cell/module/battery level, aged or new cells, sample size, test order, cell type
- Carrying out of tests to further characterize Li-ion batteries at end of life with respect to passivation: high dose radiation, high temperature over discharge, thermal runaway (ARC Accelerated Rate Calorimetry and high temperature tests), micrometeroid, ...

Report the test results and lessons learnt

- Provide inputs for passivation guidelines based on test results
- Definition of passivation testing to be performed as part of future battery developments, considering the following tests: thermal runaway, over-discharge module, charge and overcharge module, high-dose radiation, High temperature over-discharge storage. Clearly defining cell/module/battery level, aged or new cells, sample size, test order and cell type and stating the criteria needed to pass the qualification with respect to passivation.

- Performing the defined tests on various cell types, stating clearly the results of the tests and the acceptance status

Deliverables: Public document compiling all characterization of Li-ion batteries with respect to passivation.
Battery passivation guidelines.
List of passivation tests to be included in future battery developments including acceptance test results.

Current TRL: 5 **Target TRL:** 7 **Duration (months)** 18

Target Application / Timeframe : All spacecraft launched after 2020 will have to perform passivation, which means that these technologies need to be qualified as soon as possible to help the compliance. This activity aims in particular LEO satellites below 2000 kg e.g. the ESA Earth Explorers and Sentinels, but the results can also be useful for other missions in the commercial market and also for MEO or GEO missions

Applicable THAG Roadmap: Electrochemical Energy Storage

Specific Areas	*CLEAN SPACE – CLEANSAT*
Technology Domain	*TD5 Space System Control*

Ref. Number: **G61C-052EC** **Budget (k€):** **600**

Title: **Development, test and qualification of demisable magnetorquer**

Objectives: The objective of this activity is to develop and demonstrate the competitiveness and performance of a family of Magnetorquer (MTQ) designed for demise.

Description: Magnetorquers are among the critical elements often found in re-entry simulations. Due to their nested design and materials, magnetorquers are often well shielded from the external atmospheric flow during the reentry. In addition, they normally stay attached to the satellite structural panels until very late during the reentry being even further shielded. This results in existing magnetorquers being one of the common elements to survive reentry and fall to ground. Therefore, the development of demisable magnetorquers is considered of high priority by the LSIs for their uncontrolled re-entry LEO platforms.

During the CleanSat Concurrent Engineering Phase, a set of harmonized requirements for performant magnetorquers designed for demise has been agreed among European LSIs. The coordinated work between supplier and integrators is a key aspect of CleanSat, guaranteeing that the technology is developed in line with the needs of the end users. Furthermore, a conceptual design and feasibility analysis was carried out showing that innovative design solutions result in a significant improvement on the demisability of this equipment imposing very limited constraints at system level. The consolidated requirements establish a solid basis to support this development.

This activity will be implemented in two phases, consisting of the following main tasks:

- Phase 1 (250 Keuro, 12 months)
  - Requirements assessment, consolidation and completion – including requirements related to competitiveness.
  - Detailed design and analysis of a family of magnetorquers designed for demise providing a dipole momentum of ±75 Am2, ±200 Am2 and ±300 Am2, with a focus on cost efficiency.
  - Design for demisability validation via analysis with state-of-the-art simulation tools.
  - Manufacturing and qualification requirements assessment.
  - Qualification Model design.
  - CDR.

- Phase 2 (350 Keuro, 16 months)
  - Qualification Model Manufacturing and Testing.
  - QR (Qualification Review).

A coordinated approach with the LSIs will be continued during this activity in order to guarantee a seamless introduction of this equipment in their future platforms.

Deliverables:	Qualification Model				
Current TRL:	3	**Target TRL:**	7	**Duration (months)**	30
Target Application / Timeframe :	Spacecraft in LEO, mass: 800 – 4000 kg (EOP Sentinels and Earth Explorer class). All ESA missions launched after 2020 shall be compliant with SDM requirements contained in ESA/ADMIN/IPOL(2014)2.				

Applicable THAG Roadmap: AOCS Sensor and Actuatorss

Specific Areas	*CLEAN SPACE – CLEANSAT*
Technology Domain	*TD19 Propulsion*

Ref. Number: **G61C-053MP** **Budget (k€):** **2,800**

Title: **Development, test and qualification of demisable propellant tanks**

Objectives: The objective of this activity is to develop, test and qualify demisable metallic propellant tanks for LEO satellites, aiming in particular at chemical monopropellant propulsion systems.

Description: Propellant tanks, due to their materials and the very high area to mass ratio that make them decelerate fast during reentry, are among the elements that survive reentry. In addition, tanks are normally quite enclosed within the satellite structure making them surviving the re-entry and having a large on-ground footprint. Therefore, the development of demisable tanks is considered of the highest priority by the LSIs for their uncontrolled re-entry LEO platftorms.

The LEO spacecraft carrying out uncontrolled re-entry at the End of Life (i.e. up to 1 to 2 tons, depending on the payload) are generally based on monopropellant systems in a blow down configuration, given the low Delta-V needed. Typical Maximum Expected Operating Pressures are in the order of 24 bar.

The preliminary activities indicate that the development of a monolithic tank on Aluminum alloys (e.g. AA2219) is a very interesting choice to improve the tanks' demisability. It also allows building upon the heritage from the development of other tanks, such as the on-going Vega-C tanks and the industrial experience regarding processes and manufacturing. Also, application of more advanced aluminium alloys such as AlLi are expected to have limited benefit and higher cost.

The use of Carbon Overwrapped pressurized Vessels (COPV) has also been investigated for monopropellant tanks. However, the demisability of composite materials is extremely complex and not yet fully understood. Tests show that depending on the resin and fiber properties, the overwrap can actually become a heat shield for the tank. Moreover, for monopropellant tanks only low internal pressure is required, and given the size of tanks targeted, the mass benefit of using a COPV is limited and the recurrent costs higher than a monolithic option. Therefore, this option is not considered for this phase.

During the CleanSat Concurrent Engineering Phase a set of harmonized requirements for propellant tanks designed for demise has been agreed among the European LSIs. The coordinated work between supplier and integrators is a key aspect of the CleanSat project, guaranteeing that the technology is developed in line with the needs of the end users.
Furthermore, a conceptual design and feasibility analysis was carried out showing that innovative design solutions result in a significant improvement on the demisability of these equipment imposing very limited constraints to the system.

The consolidated requirements establish a solid basis to support this development.

This activity will be implemented in a phased approach:

- Phase 1 (800 Keuro, duration14 months)
  - Consolidate propellant tank design requirements, in line with requirements harmonized with the users.
  - Detailed design of tanks shell and diaphragm. Analysis of the compliance with the interface, performance, thermo-mechanical and environmental requirements.
  - Tests for sample characterization regarding long-term compatibility of shell material, diaphragm material, seal material and welding for process validation, with monopropellants, simulants and pressurant gasses.
  - Demisability test at sample level and design analysis consolidation with state-of-the-art simulation tools.
  - PDR.
- Phase 2 (1600 Keuro, duration 16 months)
  - Engineering model design
  - Manufacture full-scale EM, demonstrate manufacture processes
  - Design verification by test, including: proof pressure, vibration testing at qualification level and leakage.
  - CDR.
- Phase 3 (400 Keuro, duration 6 months)
  - Qualification Model Development Manufacturing and Testing.
  - QR (Qualification Review).

A coordinated approach with the LSIs will be continued during this activity in order to guarantee a seamless introduction of this equipment in their future platforms.

Deliverables: Qualification model and relevant documentation

Current TRL:	4	**Target TRL:**	7	**Duration (months)**	36

Target Application / Timeframe : All spacecraft in LEO, with a particular importance to those with mass: 500 – 2000 kg (EOP Sentinels, Earth Explorer).
All spacecraft launched after 2020 will have to be compliant with SDM requirements, which means that these technologies need to be qualified as soon as possible to help the compliance.

Applicable THAG Roadmap: Not related to a harmonisation subject

European Space Agency
Agence spatiale européenne

Specific Areas	*CLEAN SPACE – CLEANSAT*
Technology Domain	*TD3 Spacecraft Power*

Ref. Number: **G61C-054EP** **Budget (k€):** **700**

Title: **Electrical Passivation – PCDU upgrade for power passivation**

Objectives: Develop and test a passivation technique to provide the isolation of the solar arrays embedded in the PCDU. Development and manufacture of electric breadboard for demonstration of proposed approach.

Description: For passivation, it is required that the electrical power sources on-board a spacecraft after its operational phase are depleted or made safe. This requirement is driven by the fact that some accidental satellite breakups have been caused by the battery in the past. One of the drivers of such battery explosion is being at high state of charge. At the end of mission, the solar panels continue to provide charge to the battery, particularly if the satellite once uncontrolled ends up sun pointing, which increases the chance of battery explosion. As such, it is necessary to isolate the solar panels in order to ensure that no further charge is provided to the battery. The simplest and more effective way to implement this is within the PCDU. The development of reliable passivation methods is considered of high priority by the LSIs.

Preliminary studies have shown that many solutions exist to provide the passivation function within the PCDU. The scope of this study will be to select the best passivation technique, taking into account robustness, PCDU design impact but also impacts on the performance and at system level.

During the CleanSat Concurrent Engineering Phase a set of harmonized requirements has been agreed among the European LSIs. The coordinated work between supplier and integrators is a key aspect of CleanSat, guaranteeing that the technology is developed in line with the needs of the end users. The consolidated requirements establish a solid basis to support this development.

In this activity design, manufacture and test a full electrical breadboard of the PCDU module will be performed in a phased approach:

- Phase 1 – Passivation Technique Selection and Testing (300 Keuro, 9 months)
  - Selection of at least two passivation techniques
  - Design maturation of the selected passivation techniques
  - Testing of the passivation solutions
  - Testing to ensure the robustness of the proposed solutions to the severe conditions possible during the entire mission. As a minimum the following tests should be performed: Thermal cycling, Shock and vibration tests.
    Electrical characterization shall be performed out to measure the isolation of the passivation solution.
  - Based on the test results, a tradeoff shall be done between the passivation techniques. In this tradeoff the following aspects shall be considered: converter efficiency, control electronics (analog,

  - digital), complexity, development risk, cost, dimension/mass, flexibility to various missions, impact on overall PCDU
  - Architecture review of the selected solution

- Phase 2 – Design and development of electrical breadboard (400 Keuro, 15 months)
  - Detailed design of the module hardware, including FDIR and FMEA analysis, performance assessment, routing constraints and thermal constraints
  - Manufacture of EBB
  - Testing of EBB
  - Definition of future qualification steps

A coordinated approach with the LSIs will be continued during this activity in order to guarantee a seamless introduction of this equipment in their future platforms.

Deliverables: Component test results
Electrical bread board of PCDU module
Test results of EBB

Current TRL:	4	**Target TRL:**	6	**Duration (months)**	24

Target Application / Timeframe : All spacecraft launched after 2020 will have to perform passivation. This activity aims in particular LEO satellites below 2000 kg e.g. the ESA Earth Explorers and Sentinels, but the results can also be useful for other missions in the commercial market and also for MEO or GEO missions.

Applicable THAG Roadmap: Not related to a harmonisation subject

Specific Areas	*CLEAN SPACE – CLEANSAT*
Technology Domain	*TD19 Propulsion*

Ref. Number: **G61C-055MP** **Budget (k€):** **700**

Title: **Development and qualification of a Shape Memory Alloy Valve for propulsion passivation**

Objectives: Develop, test and qualify a shape memory alloy (SMA) passivation valve for end of life passivation compatible with monopropellant and bipropellant systems.

Description: The propulsion system is a cause of accidental satellite breakups. Currently thrusters are not qualified to operate at low enough pressures to fully vent the remaining propellant at end of life. Furthermore, studies have shown that at the end of the mission, when attitude control is lost, the satellite can end up sun pointing causing a big increase in tank temperature. This increase is particularly concerning because it can cause dissociation of the residual propellant, beginning an exothermic reaction that result in a thermal-runaway, creating high increases in pressure such as to burst the tank.
In order to fully reduce the risk of such breakups, it is necessary to create a venting path so that all propellant can be safely vented throughout the disposal phase. The most efficient way to do this is through the use of a nominally closed passivation valve. Given that the passivation should occur around 10 (and sometimes as long as 15) years after launch, current pyro valve technology which gives up to 8 years lifetime is not sufficient. The Shape Memory Alloy (SMA) valve provides many potential advantages, such as unlimited lifetime, robustness, possibility to detect and stop involuntary activation, lower shock, low cost and no pyro handling constraints.

Work within the CleanSat project have demonstrated the potential of such a valve for the passivation application, but also for other applications as a replacement to pyro valves within the propulsion system. This development was considered of high priority during the concurrent engineering phase for the development of uncontrolled reentry LEO platforms. The coordinated work between supplier and integrators is a key aspect of the CleanSat project, guaranteeing that the technology is developed in line with the needs of the end users.
In this activity the following tasks will be performed;

- Phase 1 – Development Activities (200 k€ - 12 months)
  - Analysis and consolidation of requirements following LSIs inputs. Assessment of applicability of passivation valve to other applications
  - Consolidation of all the design elements (actuator material, valve housing assembly, heater design, filter, interface)
  - Consolidation of requirements towards the valve and its components which originate from the need for late operation at the EOL of SC.
  - Performance of any low level development tests and material tests (SCC, Radiation)
  - Establishment of preliminary design

- Performance of preliminary analyses
- Establishment of preliminary test plan
- PDR
- Development of design software models for necessary mechanical analysis
- Establishment of Detailed design
- Development / procurement of jigs and tools for testing
- Manufacture and integration of development hardware (engineering models)
- Development testing using the EM, to include as a minimum: Mechanical testing (t-vac, vibration, shock, pressure)
- Qualification test plan and procedures
- CDR

- Phase 2 – Qualification Activities (500 k€ - 9 months)
  - Manufacture and integration of qualification hardware (qualification models)
  - Test readiness review (TRR)
  - Testing, including: vibration testing, shock test, pressure cycling, priming test, leakage tests, thermal vacuum cycling, activation tests at vacuum at various initial temperatures, destructive testing, final inspections
  - Preparation of qualification review data package
  - TRB
  - Qualification review

A coordinated approach with the LSIs will be continued during this activity in order to guarantee a seamless introduction of this equipment in their future platforms.

Deliverables: Qualification model

Current TRL: 4 **Target TRL:** 7 **Duration (months)** 21

Target Application / Timeframe : For all missions with propulsion on board, in accordance with ESA space debris requirements, passivation should be performed. Therefore the applicable missions are many (as a minimum all LEO and GEO missions) and the needed date is as soon as possible.

Applicable THAG Roadmap: Not related to a harmonisation subject

Specific Areas	*CLEAN SPACE – CLEANSAT*
Technology Domain	*TD19 Propulsion*

Ref. Number: **G61C-056MP** **Budget (k€):** **3,000**

Title: **Development, test and qualification of monopropellant arcjets to support controlled reentry**

Objectives: Development, test and qualification of monopropellant arcjets to support controlled reentry including the Power Processing Unit, arcjet thruster and valves system up to connection with existing monopropellant systems.

Description: A propulsion system based on an arcjet would allow combining the advantages of electric propulsion and chemical propulsion in a single system to optimize the performance of controlled re-entry. Arcjet technology can use hydrazine and other chemical propellants at a much higher specific impulse by using an electric arc to heat up the decomposition gasses. For hydrazine, the specific impulse of these systems can be higher than 500s, instead of the typical 220s provided by combustion engines.

An arcjet is significantly cheaper and less complex than electric propulsion systems and it has the advantage that it can be used in combination with existing monopropellant systems, by making use of the same propellant. For spacecraft having to perform a controlled reentry from LEO, high thrust will be necessary for the final reentry, hence a chemical propulsion engine is required. If the perigee lowering, which accounts for more than two thirds of the deorbit delta V, is done with a system with a much higher specific impulse it can save significant mass of propellant, taking advantage of the extra power available in the platform in phases where the payload is not being used. If this system is on board and can be used in other mission phases, e.g. orbit raising at Beginning of Life, then the mass savings can even allow increasing the useful payload mass at the operational orbit with respect to a satellite where no deorbit is performed at all.

This development was considered of high priority by LSIs to enhance the performances for controlled reentry LEO platforms.

The Arcjet system development would therefore focus on the system downstream from the propellant tank, designed to be an add-on to the propulsion subsystem already on-board. It includes Propellant Manage Assembly (PMA), Power Process Unit (PPU), Gas Generator and the Arcjets thrusters.

During the CleanSat concurrent engineering phase, a set of requirements for an arcjet system have been agreed among the European LSIs and a feasibility analysis has been performed allowing for a consistent development in line with their needs for future missions. The coordinated work between supplier and integrators is a key aspect of the CleanSat project, guaranteeing that the technology is developed in line with the needs of the end users. These requirements establish a solid basis for this development.

This activity will be implemented in three consecutive contractual phases, consisting of the following main tasks:

- Phase 1 (1000 Keuro, 9 months)
  - Requirements definition
  - System design definition
  - SRR
  - Arcjet development (design, manufacturing, test with hydrazine simulants)
  - Gas generator development (design, manufacturing and testing with hydrazine)
  - PMA development (design, manufacturing and testing)
  - PPU (design, manufacturing and testing)
  - Subsystem Coupling Test
  - Engineering Model Design
  - PDR

- Phase 2 (1400 Keuro, 18 months)
  - System engineering model manufacturing and assembly
  - Detailed development test at subsystem level: Functional tests, lifetime and cycling tests with hydrazine
  - Long lead items procurement
  - Qualification Model design
  - CDR

- Phase 3 (600 Keuro, 9 months)
  - Qualification model Manufacturing Assembly and Integration
  - Functional, mechanical and thermal testing
  - QR (Qualification Review)

A coordinated approach with the LSIs will be continued during this activity in order to guarantee a seamless introduction of this equipment in their future platforms.

Deliverables: Qualification Model and relevant documentation

Current TRL:	3	**Target TRL:**	7	**Duration (months)**	36

Target Application / Timeframe : Spacecraft in LEO with masses between: 800 kg – 4000 kg (EOP Sentinels and Earth Explorer and MetOp classes) having to perform controlled reentry.

Applicable THAG Roadmap: Not related to a harmonisation subject

Specific Areas	*CLEAN SPACE – CLEANSAT*
Technology Domain	*TD19 Propulsion*

Ref. Number: **G61C-057MP** **Budget (k€):** **2,000**

Title: **Development and test of Electronic Pressure Regulator**

Objectives: This activity aims to develop an electronic pressure regulator (EPR). This electronic pressure regulator shall be used during the overall mission lifetime of the spacecraft. It shall enable the re-pressurisation of the propulsion system for several platforms (namely LEO and GEO applications). It shall include the overall power supply and control logic to use it as a one equipment replacement for the currently used mechanical pressure regulator.

Description: A controlled reentry results in a very high increase of the mission Delta-V for the deorbit phase, which can be 2 times or 3 times more than the one needed for the operational phase. Due to the usage of a blow-down system during the mission and also for the deorbiting phase, the corresponding drop pressure and therefore specific impulse is leading to an additional increase of the propulsion system (mainly the tanks). The benefit of the electronic pressure regulator and the corresponding stable inlet pressure of the thruster is therefore leading to a huge saving of propellant mass, propulsion system mass and therefore cost. Considering also the complete life-time of the spacecraft, the benefit of using such a system is even higher. Electronic Pressure Regulator is a high priority building block for the Large System Integrators (LSI) development of a LEO Controlled Reentry Platform.

Mechanical pressure regulator are imported from the US and normally only used during the orbit raising GEO missions due to lifetime issues. The development of EPR would therefore also bring an increased overall performance of the propulsion systems during the complete mission life-time. This technology has therefore the potential to be used for several applications.

During the CleanSat Concurrent engineering phase a set of requirements for an electronic pressure regulator have been agreed among the European LSIs and a feasibility analysis has been performed, concluding in a consistent development roadmap in line with their needs for future missions. These requirements establish a solid basis for this development.

This activity will be implemented in three consecutive contractual phases, consisting of the following main tasks:

- Phase 1
  - Analysis & consolidation of requirements
  - Definition of pressure regulation conceptual design including market survey on valve types, orifice types, filter types, control loop systems
  - Functional & Dimensional Sizing incl. simulations and design work
  - Design of EPR breadboard including: valves, orifices, electronic box
  - Manufacturing & Integration of breadboard
  - Functional tests and test evaluation

- Preliminary EPR Design & Analysis
- Preliminary Design Review (PDR)

• Phase 2

- Design of EPR EM
- EM Manufacturing & Integration incl. update of jigs & tools, and control electronics
- EM Test incl. pressure ripple in ullage volume, optimisation of valve cycles etc.
- Design of QM RPM/Layout/Manufacturing Drawing/Jigs & Tools final design
- Update of EPR Analysis
- CDR

• Phase 3 (800 Keuro, 12 months)
- Manufacturing Readiness Review (MRR)
- QM Manufacturing & Integration
- Test Readiness Review (TRR)
- QM Qualification Testing
- Preparation of QR Data Package
- QR

A coordinated approach with the 3 LSIs will be continued during this activity in order to guarantee a seamless introduction of this equipment in their future platforms.

Deliverables: Qualification model and relevant documentation

Current TRL:	3	**Target TRL:**	7	**Duration (months)**	33

Target Application / Timeframe : Spacecraft in LEO with masses between: 800 kg – 4000 kg (EOP Sentinels and Earth Explorer and MetOp classes) having to perform controlled reentry. Spacecraft in GEO using bi-propellant for orbit raising. Other applications of this technology are also interplanetary missions (eg. EDM Exomars).

Applicable THAG Roadmap: Not related to a harmonisation subject

Specific Areas	*CLEAN SPACE – CLEANSAT*
Technology Domain	*TD20 Structures and Pyrotechnics*

Ref. Number: **G61C-043MS** **Budget (k€):** **3,000**

Title: **Prototype and qualification of a drag augmentation de-orbiting subsystem**

Objectives: The objective of this activity is to develop, manufacture and fully qualify the PFM of a de-orbiting sub-system for LEO spacecraft.

Description: Intense spaceflight activity during the past 60 years has resulted in a growing population of debris objects that pose hazards to safe space navigation. In 2013, experts estimate that 29 000 objects larger than 10 cm are orbiting Earth. Spacecraft industries are facing the problem of achieving compliance with the 25 years de-orbit requirement, while minimising any impact on the cost and effectiveness of their missions.
Technologies for the development of sail material, architectural design of passive de-orbiting subsystem and of a Guidance, Navigation and Control (GNC) subsystem for deployable drag-augmentation devices have been supported by ESA during the last years raising their maturity to TRL levels of 5 to 6.

Sail materials have been developed, addressing issues as impacts with debris, and consequent crack propagation, packaging and deploying methodologies. Recently ESA has supported an activity to develop sail materials able to withstand the very severe Atomic Oxygen (AtOx) and Ultra Violet (UV) environment. The architectural design of a scalable and modular drag augmentation device has been developed and will be tested up to TRL 6 in parallel with the development of a GNC sub-system which includes a functional numerical engineering simulation tool to assess quickly controllability and effectiveness of sails in various AOCS/GNC configuration and modes. The validation of the GNC system will reach TRL 4.

These technologies are now ready for integration into a Proto Flight Model (PFM) of a subsystem for de-orbiting spacecraft in LEO including structures, mechanisms, and GNC. The proto-flight demonstration shall ensure the de-orbit in less than 5 years, in order to have a validation of the subsystem considering the GNC, mechanical and aerothermo-dynamical aspects. The spacecraft to be considered shall have a total mass of 20-40 Kg, considering VEGA as reference launcher and an SSO orbit with an altitude of at least 700 km.

The activity shall be organised in two phases.
In phase 1, the PFM shall be designed and manufactured, including additional instrumentation needed for a demo flight, i.e. data telemetry systems, on-board camera, sail health monitoring system (against AtOX, UV and debris impact). It may be necessary to consider PFM model philosophy in order to cover possible design changes for the Flight demonstration.
The GNC sub-system shall be validated up to TRL 5/6, meaning that it shall be simulated in a flight representative environment, including processor-in-the-loop (PIL) and HW-in- the-loop (HIL) tests of the flight SW.

The second phase shall be dedicated to the full flight qualification of the PFM, including FM correlation. Specific tasks shall include:

Phase 1:
- Design and development of the PFM.
- Mathematical Model of the PFM de-orbiting performances.
- Verification and Validation of GNC system up to TRL 5/6 (starting from the preparation of the sail deployment up to the stabilisation of the sail and the passivation of the GNC).
- Manufacturing of the PFM and of all instrumentation needed for the flight demonstrationqualification and acceptance tests.
- Delivery of DDVP targeting full qualification.

Phase 2:
- Test campaign.
- Data recording.
- PFM (Proto Fligth Model) correlation

Deliverables: Engineering Model, Test data, PFM model correlations

Current TRL: 5 **Target TRL:** 7 **Duration (months)** 24

Target Application / Timeframe : Spacecraft sail de-orbiting; 2018

Applicable THAG Roadmap: Not related to a harmonisation subject

5.2 Specific Area: Clean Space – e.Deorbit

Specific Areas	*CLEAN SPACE – E.DEORBIT*
Technology Domain	*TD26 - Others*

Ref. Number: **G61e-001SY** **Budget (k€):** **13,500**

Title: **e.Deorbit Preliminary Definition Phase (Phase B)**

Objectives: The objective of this activity is to mature the overall e.Deorbit system architecture in particular working on those areas identified during the internal Systems Requirement Review (iSRR) that require further consolidation prior to finalization of the preliminary system design. Those aspects include in particular:

- Enhancing the system design, with particular emphasis on communications, on-board autonomy, processing, control algorithms, accommodation of GNC and robotic equipment.
- Elaboration on the GNC architecture such as defining the modes, the final approaches, the performance capability of the control system including thruster configuration and performance of the selected GNC hardware based upon the final selection of the approach and rendezvous manoeuvres.
- Elaboration on the Robotic architecture such as refining the design of the clamping mechanism, gripper, robotic arm and visual servoing system, together with identifying the robotic control algorithms based on the selected approach.
- Further development of risk mitigation strategies, cost and the master mission schedule.

The Preliminary Definition Phase shall finish through the consolidation of the design through the Preliminary Design Review (PDR).

Description: e.Deorbit is a mission with a goal to capture a heavy, ESA-owned items of debris in LEO and remove it from orbit. The Phase B1 of e.Deorbit was completed in Q4 2016 and following this the e.Deorbit Consolidation Phase aimed to further develop some of the main system trade-offs. This activity aims to firstly raise the maturity of e.Deorbit to SRR level and then in a second phase develop e.Deorbit through the Preliminary Design Review (PDR).

The Preliminary Definition Phase (Phase B) shall focus on the following tasks:

1. **System Engineering and Verification:** Composed of two main sections, the Preliminary System Design Tasks and System Trade-off Tasks.
   - The Preliminary System Design Tasks focuses on using Model Based System Engineering (MBSE) to develop the entire system model through requirements configuration, consolidation of requirements, defining the system architecture through definitions of functions, use cases, and assessment of the verification methods. This also includes tailoring of ECSS standards, management of the system risk mitigation and detailed definition of interfaces.
   - System Trade-Offs Tasks will focus primarily on the open trades-offs following the Phase B1 SRR in order to consolidate the design. This may include trades within the communication architecture,

collaborative vs. combined control, and how to stabilize the two spacecraft following capture.

2. **Space Segment Engineering:** From the major conclusions and results reached in the Phase B1, and based on the overall Systems Requirement Document, the main tasks are to finalise the mission analysis, assess the reentry footprint for the two spacecraft, and conduct a platform and critical subsystems design.
   - The Platform Design aims to elaborate on the subsystems such as structure, thermal, propulsion, power, platform software, platform data handling.
   - The Critical Subsystems Design aims to elaborate on the subsystems such as:
     - Robotics: define the target chaser interface; development and performance assessment of the arm, gripper, visual servoing system and clamping mechanism; assessment of robotic test bed; development of robotic controller.
     - GNC: elaborate on the GNC modes; enhance the definition of the approach manoeuvres; further derive the requirements for hardware developments (LIDAR, infrared/multispectral, far range camera, close range camera); mature the thruster configuration based on the approach and stabilisation manoeuvres; establish the processing requirements together with identifying the critical algorithms.
     - Communications: mature the communications architecture taking into consideration an analysis of the blockage(s) of communications due to the target during the different mission phases; analyse the interference produced from the target satellite.
     - Data Handling: define the requirements for the new high performance processing hardware in order to meet the demands of the system; optimize the design and split of algorithms across different processor cores.
3. **Ground Segment Engineering** should focus on consolidating the ground segment architecture and operational requirements. Following this the capability of the selected ground stations can be identified and cross checked with the mission needs.
4. **Launch Segment Engineering:** Definition of the launcher type and interfaces with such
5. **Product Assurance and Safety** addresses the aspects concerning reliability including failure modes and affects analysis and fault tree analysis, product and software assurance addressing the dependability and safety analysis, and further definition of the safety constraints for on-board monitoring and ground supervision.

   Cost Management: implementing a design to cost methodology; identify the cost risks making recommendations on how to control such; conducting cost trade-offs.
6. **Development, Validation, Deployment and Operations Planning** shall primarily focus on creating a detailed master schedule plan, a critical technologies validation plan and deriving the e.Deorbit spacecraft manufacturing and AIT plan. This should include the plan for the development of the necessary GNC and robotic test beds.

The maturation phase will be concluded with the **Preliminary Design Review (PDR)**. This review will verify the preliminary design of the selected concept and technical solutions against project and system requirements and update the preliminary design accordingly.

This activity is split into two phases:

- Phase 1 – e.Deorbit Delta B1 (3,500 k€, 10 months)
  - To close the open trade-offs following the e.Deorbit Consolidation Phase.
  - Develop the system design in order to complete the Systems Requirement Review (SRR).

- Phase 2 – e.Deorbit Phase B2 (10,000 k€, 20 months)
  - To consolidate the preliminary design of the chaser and payload.
  - Elaborate on the definition of the critical subsystems such as GNC, Robotics and Communications.
  - Develop the system design in order to complete the Preliminary Design Review (PDR).

Deliverables: Phase 1 – SRR Datapack
Phase 2 – PDR Datapack

Current TRL:	N/A	**Target TRL:**	N/A	**Duration (months)**	30

Target Application / Timeframe : 2019 in order to achieve maturity to request full funding of the mission at Ministerial conference in 2019

Applicable THAG Roadmap: Not related to a harmonisation subject

Specific Areas	*CLEAN SPACE – E.DEORBIT*
Technology Domain	*TD26 Others*

Ref. Number: **G61e-002SY** **Budget (k€):** **11,500**

Title: **e.Deorbit Robotics Subsystem**

Objectives: The objective of this activity is to develop the key robotic technologies required for a robotic debris removal mission, namely e.Deorbit, such as the robotic gripper, clamping mechanism, robotic arm, visual servoing system, and the capture and robotic control algorithms together with the associated test beds. The final output is all hardware integrated and tested in a single Hardware-in-the-Loop (HIL) test demonstrating autonomous capture, rigidisation (arresting of relative motion between chaser and target) and clamping through visual servoing and force compliance to achieve a TRL 6 of the robotic subsystem.

After these developments, all critical robotic technologies will be available for integration to the e.Deorbit design at PDR.

Description: e.Deorbit is a mission with a goal to capture a heavy, ESA-owned items of debris in LEO and remove it from orbit. Following completion of the Phase B1 in Q4 2016, it was recommended to initiate the technology developments for the mission. Within the Phase A and Phase B1 contracts, one of the most promising capture methods identified and studied is the use of a robotic arm and gripper to perform the initial capture of the target object, together with a clamping mechanism that can transfer the high loads generated during the disposal burns.
This activity will entail the development of these key robotic technology developments, such as:

- Robotic Arm and Robotic Arm Control Software: Development and assembly of all components for a 7-DOF robotic arm such as joints, breaks, structures, harnessing, sensors and control algorithms. The robotic arm shall be designed for operation in the relative environment, but should be testable and verifiable on-ground.
- Gripper: Perform the maturation, through integration and testing of the components for a gripper/end-effector of a robotic arm to capture the launch adapter ring (LAR). To achieve this the gripper shall be tested in laboratory conditions for representative test cases/approaches to the LAR.
- Clamping Mechanism: The target spacecraft is in the initial phase captured by the chaser's robotic arm in order to establish a mechanical link between the two bodies. The robotic arm is, however, not sufficiently strong and stiff to be only relied on for the final deorbit manoeuvres where large forces have to be transferred between the two bodies. The clamping mechanism which will be located on the chaser spacecraft will clamp to the LAR. After clamping, the mechanism shall provide structural link between the two spacecraft in order to transfer the disposal loads generated during the deorbit burn manoeuvres.
- Visual Servoing System: Development and testing of a camera will be placed on both the clamping mechanism and the gripper in order to provide the images required to track the grasp and clamp

locations. The development includes the bread boarding and development of the image processing algorithms.

Following the above technology development to TRL 6, all equipment will be integrated and tested to demonstrate the robotic subsystem. This will involve hardware in the loop (HIL) testing demonstrating the integration of all hardware. The appropriate controllers will then be implemented on a single processor to demonstrate the control algorithms.

The activity will be implemented in two phases with the following tasks:

- Phase 1 – Detailed Definition Phase: (3500 k€, 8 months)
  - Perform a detailed design of the equipment (robotic arm, gripper, clamping mechanism, visual servoing system, capture algorithms etc.).
  - Generate an Engineering Model (EM) for each of the equipment and demonstrate functionality in a relevant environment.
  - Provide a test plan to develop each item to EQM, together with the assembly, integration, test and validation plans at both subsystem and system level.

- Phase 2 – Validation Phase: (8000 k€, 16 months)
  - Generate an Engineering Qualification Model (EQM) for each of the equipment.
  - Integrate and test all equipment on a single test bed, demonstrating functionality of the robotic subsystem as a whole – to autonomously track and capture an object.

Deliverables: Design Definition File, Design Justification File, Detailed Design Drawings
Robotic Arm: Controller, EM, EQM
Gripper: Controller, EM, EQM
Clamping Mechanism: Controller, EM, EQM
Visual Servoing System: Image Processing Algorithms, EM, EQM
Robotic Subsystem Fully Integrated and Tested in a Laboratory
Subsystem Software: Robotic Arm Control Software (source + executable), Autonomous Capture Algorithms, Simulation software

Current TRL: 3 **Target TRL:** 6 **Duration (months)** 24

Target Application / Timeframe : 2019

Applicable THAG Roadmap: not related to a harmonisation subject

Specific Areas	*CLEAN SPACE – E.DEORBIT*
Technology Domain	*TD26- Others*

Ref. Number: **G61C-003SY** **Budget (k€):** **6,000**

Title: **e.Deorbit Net Subsystem**

Objectives: The objective of this activity is to develop the key technologies required for a debris removal mission using the net: full scale net, deployment mechanism, reel mechanism, tether, and tether control algorithms

This activity is split into two separate parts:

- The development, verification and validation of a full scale net and deployment mechanism through a sounding rocket test.
- Development, verification and validation of the tether and reel mechanism together with the control algorithms with testing of each in a relative environment.

Description: e.Deorbit is a mission with a goal to capture a heavy, ESA-owned items of debris in LEO and remove it from orbit. Following completion of the Phase B1 in Q4 2016, it was recommended to initiate the technology developments for the mission. One of the two most promising capture methods identified and studied is the use of a net and tether. This activity will entail the development of a number of key technologies to enable an active debris removal mission using the net. It is split into two sections that should be implemented in parallel:

- Sounding Rocket Experiment: Development of Engineering Models. This phase will get its inputs from current activities for tether development, net development, and rely heavily on high-fidelity simulation tools currently verified in the frame of a TRP activity to consolidate and develop full-scale engineering models of all parts of the net capture system. The main components are net, net closing mechanism, spool and net ejector.

  The above equipment shall then be bridged through a carefully designed series of environmental and mechanical tests. The sounding rocket platform shall undergo Manufacture Assembly and Integration as well as appropriate environmental and mechanical tests. The payload shall be integrated with the sounding rocket and the sounding rocket experiment performed. The experiment shall be fully instrumented, and high speed cameras will record the development with the aim for a full 3D reconstruction of all phases of the net deployment and closure.

- Develop a simulator which can be used to verify the GNC system design of an active debris removal satellite using the net/tether. One function of the simulator should be the capability of changing the starting conditions such as:
  - thruster size (AOCS and for disposal burns);
  - burn duration for disposal burns;
  - orbital altitude;
  - tether characteristics.

  The simulator should be capable of validating the disposal strategy based on the above parameters while highlighting potential issues such as tether rupture, wrapping, controllability, collision risk, safe mode control.

Based on the outputs from the simulator and associated system requirements, develop a tether capable of able to transferring all of the loads generated by the chaser during the disposal burns. The current baseline for an active debris removal mission foresees that the tether is located close to the thrusters needed for the disposals burns, which will induce high temperatures on the tether. Testing in a thermal vacuum is needed in order to characterise how the tether changes during the disposal burns due to plume impingement.

Prior to launch of the net during the capture phase of an ADR mission, the tether needs to be stored, in such a manner that when it is launched, the tether is allowed to deploy with little or no resistance. The most promising method identified is a reel mechanism, whereby the tether is wrapped around a pulley that has a minimal amount of friction. The reel mechanism should provide storage for the tether during launch of the satellite and early operations. Upon launch of the net, the mechanism should enable the tether to unwind at a rate of approximately 5 m/s.

Deliverables: Design Definition File,
Net: Simulator, EM, EQM
Deployment Mechanism: EM, EQM
Reel Mechanism: Simulator, EM, EQM
Tether: EM, EQM
Software: Control Algorithms, Simulator of two bodies connected via a tether

Current TRL: 3 **Target TRL:** 6 **Duration (months)** 24

Target Application / Timeframe : 2019

Applicable THAG Roadmap: Not related to a Harmonisation subject

Specific Areas	*CLEAN SPACE – E.DEORBIT*
Technology Domain	*TD26 -Others*

Ref. Number: **G61e-004SY** **Budget (k€):** **10,000**

Title: **e.Deorbit GNC Subsystem**

Objectives:

The objective of this activity is to develop the key Guidance, Navigation and Control (GNC) subsystem technologies required for a debris removal mission, namely e.Deorbit by consolidating the system design and FDIR approach.
The equipment to be developed is a LIDAR, a far range and close range camera, multispectral camera, infrared camera, 3-DOF camera together with the image recognition and processing for the selected sensor suite and the associated payload computer based on these processing demands. Following the development of all technologies, hardware in the loop (HIL) tests will be conducted using the payload equipment and GNC sensors, achieving a TRL 6 at GNC subsystem level.

This will then ensure that all critical GNC technologies will be available for integration to the e.Deorbit design at PDR.

Description:

e.Deorbit is a mission with a goal to capture a heavy, ESA-owned items of debris in LEO and remove it from orbit. Following completion of the Phase B1 in Q4 2016, it was recommended to initiate the technology developments for the mission. Within the Phase A and Phase B1 contracts, a preliminary design of the GNC sensor suite has been defined, and in order to build upon the work conducted, this activity will work towards the consolidation of an advanced GNC concept for active debris removal using a robotic arm and a clamping mechanism. The activity will focus on:

- The improvement of high-fidelity dynamics and equipment modelling, in particular the robotic arm, the clamping mechanism and the SC flexible modes, including the transients during the capture;
- Design of the GNC system, with particular emphasis placed on synchronization motion of chaser with a tumbling target, the combined control of the chaser and robotic arm during capture and rigidization (including transients), detumbling and the deorbiting manoeuvre (two spacecraft coupled by a clamping mechanism), and the demonstration of global stability during these phases;
- Design the FDIR related to the GNC function including the Collision Avoidance Manoeuvres (CAM) during all mission phases.

From the above system approach, requirements will be derived to develop the required sensor suite as follows:

- LIDAR: The development shall implement novel technologies, for example high efficiency continuous wave (CW) laser sources, including novel detection algorithms and CMOS detector arrays in order to achieve a high level of compactness and low risk. Such a design will substantially reduce the mass and power consumption, when compared with conventional Imaging LIDAR systems. The test logic shall include the demonstration of the LIDAR elegant breadboard operation and performance in a representative scenario, with cooperative as well as uncooperative static targets.

- Multispectral Camera: The camera will cover thermal infrared, near-infrared and visual spectral bands. The camera specifications shall be derived from the rendezvous with uncooperative targets. The breadboard shall include the optical head, the proximity electronics and the Image Processing Board and algorithms.
- Far Range Camera: A visual camera used to identify the target satellite from a range of 8 km to 1 km in the visual spectrum. This camera will provide the information to the chaser satellite necessary for the far range approach.
- Close Range Camera: A visual camera used to identify the target satellite from a range of 1 km up to the capture point in the visual spectrum. This camera will provide the information to the chaser satellite necessary for the far range approach.
- Image Processing and Recognition: All algorithms needed for the sensors to perform image recognition will be developed.
- Payload Computer: The image processing, control algorithms from the GNC and robotic control algorithms demand new high performant avionics.

Following consolidation of the GNC system and development of the technologies, all equipment will be tested through hardware in the loop testing (HIL). This will act to verify and validate the equipment, and enable the derivation of the integration and assembly requirements for the e.Deorbit satellite.

The activity will be implemented in two phases with the following tasks:
Phase 1 – Detailed Definition Phase: (3500 k€, 8 months)

- Perform a detailed design of the GNC system including the definition of the software architecture (including FDIR).
- Generate an Engineering Model (EM) for each of the equipment and demonstrate functionality in a relevant environment.
- Provide a test plan to develop each item to EQM, together with the assembly, integration, test and validation plans at both subsystem and system level.

Phase 2 – Validation Phase: (6500 k€, 16 months)

- Generate an Engineering Qualification Model (EQM) for each of the equipment.
- Integrate and test all equipment on a single test bench, demonstrating functionality of the GNC subsystem as a whole.

Deliverables: Design Definition File, Design Justification File, Detailed Design Drawings
LIDAR: Image processing, EM, EQM
Close Range Camera: Image processing, EM, EQM
Far Range Camera: Image processing, EM, EQM
Multispectral Camera: Image processing, EM, EQM
Payload Computer: EM, EQM
GNC Subsystem Fully Integrated and Tested in a Laboratory
Subsystem Software: Control, navigation, FDIR

Current TRL:	3	**Target TRL:**	6	**Duration (months)**	24

Target Application / Timeframe :	2019

Applicable THAG Roadmap: Not related to a harmonisation Subject

5.1 Specific Area: Clean Space - EcoDesign

Domain – Specific Area	*GENERIC TECHNOLOGY – CLEAN SPACE*
Technology Domain	*24- Materials and Processes*

Ref. Number: **G61C-035QT** **Budget (k€): 500**

Title: **Development of a complete Cr-VI anticorrosion system and process scale-up at industrial level**

Objectives: Aluminum alloys are extensively used in space programs for both structural and non-structural applications. As well known, the corrosion resistance of these alloys is quite limited and anticorrosion treatment are needed.
The most used treatment currently used for improving the corrosion resistance of aluminum alloys are usually CrVI-based conversion coating. Due to the high environmental impact of these compounds, the REACH Regulation of the European Union decided to limit/restrict the use of hexavalent chromium. A sunset date of mid-2017 has been already set.
For the time being many chromate-free alternative products are available but they have found to be significantly inferior in terms of corrosion protection performances with respect to the chromate options.
In this regard there is a great need to develop high performance hexavalent chromium-free anti-corrosion coatings.

ESA is currently involved in different projects concerning the development of chromium VI free anticorrosion coatings.
In partnership with NASA Technology Evaluation for Environmental Risk Mitigation (TEERM) a research project focused on the evaluation of alternative pretreatment with primers is currently under development. Possible alternatives for hexavalent chromium-free surface treatments and primers have been evaluated and tested and preliminary, but, promising results have been identified.

The objective of this activity is to evaluate the anticorrosion behaviour of the different alternative pre-treatments applied to the most used aluminum alloys (2024 in T3 and T8 treatment, 6061, 7075 in T73 treatment and 5083). The outcome of this activity will be the identification and the optimization of the most promising anticorrosion pre-treatment.
At this point, a natural continuation of this project would be beneficial to define the most promising pretreatment/primer combinations and to build a complete and performant anti-corrosion system. Furthermore an industrial upscale of the process will be one of the major target of this new activity.
The sunset date of the 2017 defined by REACH regulation is imminent and consistent efforts are needed in order to build a robust a reliable industrial process for space applications.

Description: The proposed activity will consist of the following steps:
- Identification of the most promising substrate/pre-treatment/primer combination
- Test campaign at sample level in order to set-up a reliable and robust process
- Identification of representative case-study in order to build a strategy to scale-up the process at industrial level
- Test campaign a prototype level in order to improve the robustness and reliability of the process

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Agence spatiale européenne

Deliverables:	Breadboard				
Current TRL:	3	**Target TRL:**	4	**Duration (months)**	18
Target Application / Timeframe :	2017				

Applicable THAG Roadmap: Not related to a Harmonisation Subject

Domain – Specific Area	*GENERIC TECHNOLOGY – CLEAN SPACE*
Technology Domain	*24- Materials and Processes*

Ref. Number: **G61C-044QT** **Budget (k€): 500**

Title: **Alternatives to processes affected by REACH for the manufacture of PCBs**

Objectives:
- Inventorise materials and processes for the manufacture of PCBs that are impacted by REACH legislation.
- Survey alternatives products that can be used as drop-in technology using the same process flow and survey alternative process flows.
- Evaluate the manufacturability and reliability of PCBs with alternative process, compared to the existing process.

Description: The REACH legislation deals with Registration, Evaluation, Authorisation and Restriction of Chemical substances. The law entered into force on 1 June 2007. The aim of REACH is to improve the protection of human health and the environment through the better and earlier identification of the intrinsic properties of chemical substances. REACH office maintains lists of chemical substances of concern (SVHC) and define restriction for their use.
The ESA qualification of PCBs is, in parts, a process qualification, as detailed in ECSS-Q-ST-70-10 Qualification of PCBs. The Product Identification Document PID of each PCB manufacturer specifies the processes involved. Significant changes to the process flow can be subject to delta qualification before they are approved.
This activity aims to inventorise affected processes by defining impact factor and priority. This is followed by testing selected alternative processes for PCB manufacturability and reliability.

The following processes have already been identified to be impacted by REACH:

1) Electroless copper
   All current processes contain formaldehyde which is a CMR (Carcinogen, Mutagen or Reprotoxic) product. Some processes contain a salt of mercury as a stabilizer, which will be banned around 2017 according to a European Directive on quality of water.
   Chemistry suppliers are developing drop-in electroless copper processes, which need to be evaluated. In addition, it may be possible to use other process flows to metallise the through-hole, by using direct metallisation (e.g. using palladium).

2) Tin-lead surface finish
   One process uses lead-methanesulfonate, which is CMR and in the SVHC list. Another fluoroborate process uses boric acid, which is CMR and in the SVHC list. Tin-lead processes are under threat of obsolescence due to a general ban under RoHS regulation.

3) ENEPIG surface finish
   This finish is candidate as a substitute for tin-lead and ENIG finish. The process flow uses nickel-sulfate which is CMR, but not yet included in the SVHC list.

4) Electrolytic nickel-gold finish
   Process flow uses boric acid, which is CMR and in the SVHC list.

5) Surface treatment on copper foils
   This process commonly uses chromates. Cr (VI) is on the SVHC list.

Deliverables: Study Report

Current TRL:	3	**Target TRL:**	5	**Duration (months)**	24

Target Application / Timeframe : TRL 5 by 2017.

Applicable THAG Roadmap: Not related to a Harmonisation Subject

Domain – Specific Area	*GENERIC TECHNOLOGY – CLEAN SPACE*
Technology Domain	*26- Others*

Ref. Number: **G61C-045SW** **Budget (k€): 350**

Title: **REIM - Resource Efficiency through Improved Methods for treatment of recycling products**

Objectives:

1. Assessment and analysis of the impacts of the treatment and recycling processes of scrap material during the production phase of space hardware
2. Assessment and analysis of the impacts of the treatment and recycling processes for non-accepted components during the manufacturing and assembly of space hardware
3. Identification of methods to reduce material waste and of alternative treatment of scrap material and non-accepted components, reducing overall resource consumption and impacts of the processes.
4. Update of current environmental impact models based on primary data for waste material and component acceptance rates.

Description:

The traditional manufacturing route for many space applications involves the procurement of large aluminium and titanium plates and forgings which are subsequently machined into the final structure; for example for the production of a 1 m3 titanium tank of 58 kg, 921 kg of titanium are needed. Due to the significant amount of machining that is required to produce the final shape, the associated manufacturing costs and environmental impacts are considerable, in particular on resource depletion and use of Critical Raw Materials.

Studies on the environmental impacts of space activities show that the treatment of the waste material thus becomes an important factor, but in the same time is a major uncertainty, since the buy-to-fly ratio of a product depends on the material, machining operation and the final product shape.

In the aerospace industry protocols are already in place which allow some of the chips (machined material) which are produced during the manufacturing of wing spars and ribs to be recycled by the aluminium and titanium supplier to form new products.

Although the volume of machining in the space industry is much less than that of the commercial aircraft industry, there is still an opportunity to recycle as much material possible, thus reducing the associated environmental impact and making cost savings. The use of specialised materials also makes dedicated methods necessary in order to separate different alloys and retain their specific properties, to maximise the benefit of the recycling process and the re-use of critical alloying elements.

Similar considerations apply to acceptance tests of components and equipment. The acceptance rates and the treatment of the failed products present a major gap in the current models, but are also identified as a promising field of increasing resource efficiency and reducing overall impacts.

Consequently this study assesses the loss and fail rates of a representative number of manufacturing processes and acceptance tests and investigates the treatment of waste material and failed products in a subset of these cases. With the results the current environmental models can be updated based on the primary data obtained and subsequently potential methods to increase the efficiency in the use of resources and to improve the treatment of waste materials and failed products are developed.

This way, the study aims at providing monetary and environmental benefit to industry through the more efficient use of resources and to decrease the dependence on Critical Raw Materials (CRMs), identified by the European Commission as raw materials of special value and high risk associated to their supply.

In this activity the following tasks will be performed:

1. A number of aluminium and titanium products will be selected for possible study, based on the amount of usage and their associated environmental impacts as identified in earlier studies. Their fly-to-buy ratio and/or acceptance rate will be determined and the traditional waste treatment assessed.
2. Based on the precursor activities, eco-design principles will be applied to determine the most appropriate methodology for recycling. Recycling routes will be proposed, either based on traditional casting methods or by using 3D printing.
3. The existing LCA models will be updated based on the results of the study and potentially additional cradle-to-gate LCAs will be performed to compare the overall environmental impact of the recycled products to existing ones.
4. Lessons learned and suggestions for improvement of waste materials will be issued.

Deliverables: Report, LCA models

Current TRL: 3 **Target TRL:** 5 **Duration (months)** 12

Target Application Timeframe : 2017

Applicable THAG Roadmap: Not related to a Harmonisation Subject

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ANNEX I
List of activities in
GSTP-6 E1 Work Plan/Procurement Plan

6 ANNEX I - ACTIVITIES IN GSTP ELEMENT 1 "DEVELOP" WORK PLAN / PROCUREMENT PLAN (ACTIVITIES APPROVED BY IPC)

Specific area: Clean Space

TD 3- Spacecraft Electrical Power

GSTP-6 Reference	Title	Budget(k€)
G61C-021EP	Spacecraft power system passivation at end of mission	400
	Total	**400**

TD 5- Space System Control

GSTP-6 Reference	Title	Budget(k€)
G61C-016EC	GNC for drag augmentation devices	450
G61C-018EC	Rapid Assessment of Design Impact on Debris Generation	500
G61C-029EC	Image Recognition and Processing for Navigation	600
	Total	**1,550**

TD 11- Space Debris

GSTP-6 Reference	Title	Budget(k€)
G61C-024GR	Optical In-Situ Monitor	1,200
G61C-025GR	Enhancement of S/C Fragmentation and Environmental Evolution Models	300
G61C-026SY	Phase B1 of an Active Debris Removal mission (2 parallel studies)	1,600
G61C-034GR	Debris Attitude Motion Measurements and Modelling	600
	Total	**3,700**

TD 13- Automation, Telepresence & Robotics

GSTP-6 Reference	Title	Budget(k€)
G61C-032MM	Harpoon characterisation, breadboarding and testing for Active Debris Removal (ADR)	700
	Total	**700**

TD 16- Optics

GSTP-6 Reference	Title	Budget(k€)
G61C-028MM	Miniaturized Imaging LIDAR System (MILS) for Rendezvous & Docking operations between spacecraft	1,200
	Total	**1,200**

TD 19- Propulsion

GSTP-6 Reference	Title	Budget(k€)
G61C-005MP	Hydrogen Peroxide Storability/Compatibility Verification	1,000
G61C-017MP	De-orbit motor Engineering Model Manufacturing and Testing	1,300
	Total	**2,300**

TD 20- Structures & Pyrotechnics

GSTP-6 Reference	Title	Budget(k€)
G61C-012MS/ G61C-039MS	Bio-composite structure in space applications	500
G61C-014MS	Deployable Membrane	400
G61C-015MS	Architectural design and testing of the Sub-system boom-sails	600
	Total	**1,000**

TD 24- Materials and Processes

GSTP-6 Reference	Title	Budget(k€)
G61C-007QT	Surface Engineering for parts made by Additive Manufacturing (Step 1)	600
G61C-008QT	Verification methodology for parts made by Additive Manufacturing	500
G61C-010QT	Sustainable, green ancillary materials for structure manufacturing	200
G61C-036QT	Development and test of Additive Manufactured space hardware	1,300
	Total	**2,600**

26- Others

GSTP-6 Reference	Title	Budget(k€)
G61C-001SY	Space propellants Life Cycle Assessment (LCA)	300
G61C-002SY	Life Cycle Assessment (LCA) of manufacturing processes and space materials	400
	Total	**700**

ANNEX II
List of withdrawn activities from the previous Compendia

7 ANNEX II - ACTIVITIES WITHDRAWN FROM THE PREVIOUS COMPENDIA

Specific area: Clean Space

TD 5- Space System Control

GSTP-6 Reference	Title	Budget(k€)
G61C-027EC	Breadboard of a Multi-Spectral Camera for Relative Navigation	800
G61C-040EC	GNC design and performance validation for active debris removal with RIGID capture	300
G61C-041EC	GNC design and performance validation for active debris removal with FLEXIBLE capture	300
	Total	**1,400**

TD 13- Automation, Telepresence & Robotics

GSTP-6 Reference	Title	Budget(k€)
G61C-030MM	Net-Winch-Tether design and breadboard development	450
G61C-042MM	Capture of space debris with throw nets: Engineering Qualification Model development and sounding rocket testing	3,000
	Total	**3,450**

TD 15- Mechanisms & Tribology

GSTP-6 Reference	Title	Budget(k€)
G61C-031MS	Breadboard development of the throw-net ejector mechanism	400
G61C-033MS	Breadboard of a clamping based capture mechanism	450
	Total	**850**

TD 18- Aerothermodynamics

GSTP-6 Reference	Title	Budget(k€)
G61C-003MP	Hot gas plume characterisation in vacuum	500
	Total	**500**

These activities have been absorbed by e.Deorbit mature phase proposed developments