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Progress in Iodine Thruster Technology: Key Developments in Project BOOST

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Abstract: The BOOST project (Building bLOcks for iOdine Thrusters), is a research initiative funded by the European Union, aiming at advancing Small satellites capabilities by developing an iodine-compatible RF cathode, a smart propellant storage system for on-orbit refueling, and an improved fluidic subsystem. Additionally, it focuses on upgrading testing facilities and enhancing diagnostics for iodine plasma. Currently, xenon (Xe) and krypton (Kr) are the most commonly used propellants. However, they require pressurized tanks for storage, increasing the mass of the system and introducing safety issues for the launching system. The choice of iodine (I₂) as propellant has the potential to remove these constraints, as it can be stored in solid state at ambient conditions, while further decreasing costs related to space access, as it is cheaper to procure than xenon.



Nomenclature

<i>EP</i>	=	Electric Propulsion
<i>TRL</i>	=	Technology Readiness Level
<i>BOOST</i>	=	Building bLOcks for iO dine Thrusters
<i>RF</i>	=	Radio Frequency
<i>VLEO</i>	=	Very Low Earth Orbit
<i>LEO</i>	=	Low Earth Orbit
<i>SSO</i>	=	Sun-Synchronous Orbit
<i>MEO</i>	=	Medium Earth Orbit
<i>GEO</i>	=	Geostationary Earth Orbit
<i>ROI</i>	=	Return on Investment
<i>EU</i>	=	European Union
<i>KPI</i>	=	Key Performance Indicator
<i>ESA</i>	=	European Space Agency
<i>DRAMA</i>	=	Debris Risk Assessment and Mitigation Analysis
<i>HET</i>	=	Hall Effect Thruster
<i>GIT</i>	=	Gridded Ion Thruster
<i>RAAN</i>	=	Right Ascension of the Ascending Node
<i>SAR</i>	=	Synthetic Aperture Radar
<i>LTAN</i>	=	Local Time of the Ascending Node

I. Introduction

ELECTRIC Propulsion (EP) has become a cornerstone technology for modern space missions, enabling efficient orbit transfer, station-keeping, and constellation deployment at significantly reduced propellant mass compared to chemical propulsion. Among EP propellants, xenon has been the de facto standard due to its high atomic mass, inert nature, and well-established supply chain. However, the exponential growth of satellite constellations and the rising demand for low-cost access to space are creating mounting challenges for xenon affordability [1, 2].

In this context, iodine has emerged as a promising alternative propellant for EP systems [3, 4]. Iodine offers several advantages: it is solid at ambient conditions, eliminating the need for high-pressure storage tanks; it sublimates at moderate temperatures, simplifying feed system design; and it is widely available and inexpensive, with a cost reduction of up to two orders of magnitude compared to xenon [5]. Several in-orbit demonstrations, including CubeSat missions equipped with iodine Hall thrusters and ion engines, have already proven its feasibility. Nevertheless, the technology readiness level (TRL) of iodine EP remains limited, and its broader adoption requires addressing key challenges such as material compatibility, contamination risks, and standardized system architectures [6–8].

The growing deployment of small satellites has raised challenges concerning lifetime, cost efficiency, and sustainability in space operations. Finite propellant reserves limit mission duration, while deorbiting procedures increase the risk of space debris proliferation.

The project BOOST responds to this need by developing modular building blocks for iodine-based propulsion, including an RF cathode, an iodine-compatible fluidic line, and a rechargeable tank for on-orbit refueling. This modular approach aims to establish the foundation for future standardization, scalability, and industrialization of iodine EP across the SmallSat segment. Beyond the development of individual components, BOOST also investigates the strategic implications of iodine refueling technologies for satellite missions.

This paper focuses on two major aspects: the mission analysis for iodine-based refueling concepts and the rechargeable tank design, both considered key enablers for extending satellite lifetimes and improving cost-effectiveness.

II. Mission Analysis Hypothesis

The first objective of the work done within the project has been performed to assess the scenarios where iodine refueling provides the greatest benefits. Specifically, the study evaluates Very Low Earth Orbit (VLEO), Low Earth Orbit (LEO-SSO), Medium Earth Orbit (MEO, e.g., Galileo), and Geostationary Earth Orbit (GEO) missions. For



each regime, propellant requirements, lifetime extension, and servicing strategies were quantified to identify the trade-offs and Return on Investment (ROI) associated with implementing a solid iodine cartridge refueling system.

The goal of this work is twofold: to provide a quantitative assessment of the mission classes that stand to benefit most from iodine-based refueling; to frame these findings in the broader context of sustainable space operations, addressing the dual challenges of reducing space debris and improving the economic viability of satellite constellations.

By presenting this mission analysis, the aim is to demonstrate how the adoption of refillable iodine EP systems can contribute to longer-lived, more sustainable, and cost-effective missions in multiple orbital regimes, ultimately supporting the EU's strategic goal of non-dependence in critical space technologies.

A. Mission Analysis Framework

The mission analysis was performed to quantify the benefits of integrating rechargeable solid iodine cartridges into electric propulsion (EP) systems. The analysis considered several representative orbital regimes—VLEO, LEO-SSO, MEO (Galileo-type), and GEO—covering a broad spectrum of applications, from Earth observation and telecommunications to navigation services.

The framework combined analytical estimations and numerical simulations to evaluate the following key performance indicators (KPIs):

- Annual Δv budget, driven by drag, perturbations, and station-keeping requirements.
- Propellant mass consumption for iodine and xenon reference cases.
- Mission lifetime extension enabled by cartridge refueling.
- Servicing architecture feasibility, including number of refueling operations and required cartridges.
- Return on Investment (ROI) through comparison of refueling vs. satellite replacement.

The analysis leveraged the ASTOS software for atmospheric drag modeling and manoeuvre planning in VLEO and higher orbits, as well as analytical formulas for estimating Δv budgets.

B. Target and Servicer Definition

In the BOOST on-orbit refueling concept, two distinct spacecraft classes are defined: the Target Satellite (Client) and the Servicer (Refueling Vehicle). Their complementary roles are central to assessing the technical feasibility and economic viability of a modular iodine cartridge refueling architecture.

Target Satellite (Client).

The Target is a satellite equipped with an iodine-based electric propulsion (EP) system designed to accept additional propellant via in-orbit cartridge exchange. Depending on its mission type and orbital regime, the Target may require refueling for a variety of purposes:

- Drag compensation in VLEO and SSO,
- Collision avoidance manoeuvres in congested LEO orbits,
- Constellation phasing and reallocation
- Drift correction and station-keeping
- End-of-life manoeuvres targeting deorbitation or a graveyard orbit
- Constellation phasing and drift correction in LEO/MEO,
- Extended station-keeping and controlled deorbiting in GEO/MEO.

To enable these capabilities, the satellite must integrate a modular refueling interface (mechanical, thermal, and data-wise), which ensures seamless cartridge replacement during servicing. This design avoids the complexity and risks associated with conventional fluid coupling systems—an important advantage for small satellite classes. Key characteristics of a viable refueling Target therefore include: (i) sufficient mission value and lifetime to justify servicing, (ii) compatibility of propulsion and tank design with the cartridge interface, (iii) predictable orbital elements and servicing windows, and (iv) a high propellant demand profile (e.g., frequent maneuvers or drag compensation).

Servicer (Refueling Spacecraft).

The Servicer is a dedicated or multi-role spacecraft designed to deliver iodine cartridges to one or multiple Target satellites. Its mission profile typically includes orbital transfer, rendezvous, proximity operations, and, when



necessary, robotic or mechanical cartridge exchange. Depending on the servicing strategy, the Servicer may itself employ iodine EP or rely on alternative propulsion solutions: chemical stages provide faster orbital transfers for time-critical scenarios, while EP stages maximize efficiency for multi-target servicing.

Possible mission types include:

- Single-client servicing of a high-value satellite (e.g., in GEO),
- Multi-client constellation servicer, potentially refueling tens of satellites within a single orbital plane,
- A combination of a larger orbital propellant depot and a small servicer for execution of the refuelling task,
- Deployment support missions, where satellites are topped off with propellant immediately after orbital insertion.

The definition of the Servicer architecture is strongly influenced by (i) the orbital regime, (ii) the number and type of Target satellites, (iii) Δv and thrust requirements, and (iv) the cartridge handling and autonomy level.

By decoupling the propellant supply function (Servicer) from the operational mission function (Target), this architecture provides long-term scalability, mission flexibility, and lifecycle extension across a wide range of satellite classes. This distinction forms the basis of the mission analysis carried out within BOOST, where different orbital regimes and servicing strategies were evaluated to identify conditions in which the Target–Servicer system offers technical and economic benefits.

In the mission analysis carried out within BOOST, the Target satellite was consistently modeled on the *Nebula* platform developed by Tyvak (Terran Orbital), which provides a representative baseline for a small-satellite class equipped with iodine-based EP. *Nebula* features a wet launch mass up to ~250 kg, payload capacity up to ~130 kg, and maximum solar power of ~1 kW.

For the Servicer, different alternatives were considered. The first relies on the same *Nebula* platform, enabling a homogeneous architecture and minimizing development risks. Other options employ larger spacecraft buses such as, for example, the *Ambassador* platform, also developed by Tyvak (Terran Orbital), which accommodates payloads up to ~200 kg and provides higher power availability of up to ~1.5 kW.

The comparison between these architectures allows evaluating the trade-off between scalability and operational flexibility. In particular, while a *Nebula*-class Servicer is well-suited for single-client or technology demonstration missions, *Ambassador* offers enhanced capacity for multi-client servicing scenarios, supporting the refueling of multiple satellites within a single mission.

C. EP thruster characteristics

It is important to underline that the development of a complete thruster unit is not within the objectives of the BOOST project. Instead, the project is focused on the realization of fundamental building blocks of an iodine-based electric propulsion system, namely the rechargeable tank, the iodine-compatible fluidic line, and the RF cathode for plume neutralization. These subsystems constitute the enabling technologies required to advance iodine EP to higher maturity levels, paving the way for future standardization and industrialization.

Nevertheless, in order to carry out a meaningful mission analysis, it was necessary to establish a set of reference parameters for the thruster that would be mounted on both the Target satellites and the Servicer spacecraft. These parameters provide a consistent framework for evaluating mission scenarios and for defining the requirements imposed on the BOOST building blocks. The reference thruster is therefore not a deliverable of the project, but rather a conceptual placeholder that ensures coherence across the system-level studies.

Accordingly, reference values have been defined for key thruster characteristics, such as power input, specific impulse, and thrust level. These values have been selected to be representative of iodine EP systems in the 500–1000 W power class, consistent with the SmallSat market addressed by BOOST. The adopted figures were used as input for sizing the propellant cartridges, defining the fluidic mass flow rate, and assessing the neutralization capability required of the RF cathode.

This approach ensures that, although no integrated thruster is being developed within BOOST, the project outcomes remain mission-driven and aligned with realistic performance expectations for future iodine-based propulsion systems.



Table 1: Properties of the propulsion system

Property	Value and Unit
Thrust	45.8 mN
Isp	1800 s

The above thruster performance, typical of a HET of the 1 kW class [9, 10], has been selected based on the thrust requirements of a VLEO mission to compensate for drag, allowing, considering a propellant mass of 3.5 kg, for a maximum velocity impulse of 169.6 m/s. Using a thrust of 25 mN and an Isp of 2500 s, typical of a GIT [11], a maximum velocity change of 235.6 m/s could have been achieved, a value which is more attractive for long orbit raising manoeuvres.

D. Mission Profiles and Operational Phases

The mission analysis carried out within BOOST was structured around the definition of representative mission profiles and their corresponding operational phases, in order to capture the range of scenarios in which iodine-based refueling may provide significant advantages. These mission profiles were selected to reflect the most relevant orbital regimes for current and future satellite operations, including Very Low Earth Orbit (VLEO), Sun-Synchronous Orbit (SSO), Medium Earth Orbit (MEO), and Geostationary Orbit (GEO). For each case, both single-client servicing and constellation-support missions were considered.

The operational phases of a typical servicing mission were broken down into distinct elements:

1. **Orbit transfer of the Servicer**, either from the launcher drop-off orbit or from a parking orbit, to the operational orbit of the Target(s). Depending on the scenario, this transfer may be performed using electric propulsion alone or with a hybrid chemical/EP strategy.
2. **Rendezvous and proximity operations**, during which the Servicer approaches the Target satellite, ensuring precise alignment for cartridge exchange. This phase requires particular attention to safety aspects, including robust relative navigation, collaborative docking strategies, collision-avoidance protocols, and adherence to keep-out zones, supported by fail-safe retreat manoeuvres and plume-impingement mitigation.
3. **Refueling operation**, consisting of the removal of the depleted iodine cartridge from the Target's tank and the insertion of a fresh cartridge delivered by the Servicer. This phase assumes the availability of a modular mechanical/thermal interface.
4. **Post-refueling operations**, including the possible disposal of empty cartridges, reconfiguration of the Servicer for the next Target, and potential orbital transfer to another client satellite.

To enable quantitative analysis, a set of simplifying assumptions was adopted. For instance, it was assumed that both the Servicer and Target are equipped with iodine EP thrusters in the 500–1000 W power class, consistent with BOOST's technology development focus. Propellant resupply was modeled as an instantaneous operation from a Δv perspective, with no penalties for robotic handling time. In constellation scenarios, Target satellites were assumed to be distributed within a single orbital plane, enabling sequential servicing with limited plane-change requirements. Furthermore, it was assumed that orbital mechanics perturbations (e.g., drag or J2 effects in SSO) are known and predictable, such that servicing windows can be scheduled in advance.

This structured decomposition into mission profiles and operational phases allowed for the identification of key drivers in the economic and technical feasibility of in-orbit refueling, including the Δv requirements for the Servicer, the frequency of refueling events, and the lifetime extension achievable for the Target satellites.

III. Target Scenario Description

The Target was assumed to operate in different orbital regimes, depending on the mission profile under investigation: Very Low Earth Orbit (VLEO, below 450 km), Sun-Synchronous Orbit (SSO, around 500–700 km), Medium Earth Orbit (MEO, ~20,000 km), and Geostationary Orbit (GEO, 35,786 km). Each regime poses distinct challenges and propellant demands, as described in the following paragraphs.

VLEO Scenario

Very Low Earth Orbit (VLEO) missions, typically defined at altitudes below 450 km, provide unique advantages for Earth observation and communication applications. The proximity to Earth enables higher spatial resolution for



imaging sensors and lower latency for communication links. However, these benefits come at the cost of significantly increased atmospheric drag, which drives rapid orbital decay if not actively compensated. For small satellites equipped with electric propulsion and limited propellant capacity (e.g., 3.5 kg of iodine), continuous station-keeping in circular VLEO orbits is therefore not feasible over long durations.

To address this limitation, the BOOST mission analysis explored an elliptical orbit strategy as a means to combine the performance benefits of VLEO with improved fuel economy and extended lifetime. In this approach, the satellite does not remain in a circular VLEO orbit. Instead, it follows a repetitive elliptical cycle in which:

- (i) The spacecraft periodically descends to a VLEO perigee (≈ 300 km) to perform high-resolution imaging or sensing operations.
- (ii) The apogee is maintained at a higher altitude (≈ 500 – 600 km), reducing the average drag load and propellant consumption.
- (iii) At the end of the perigee operational phase, or once the allocated propellant is depleted, the satellite circularizes at apogee.
- (iv) A dedicated Servicer spacecraft rendezvous with the Target at this higher altitude, where drag effects are minimal, and delivers a fresh iodine cartridge via on-orbit refueling.
- (v) After refueling, the Target resumes its elliptical dive toward VLEO, initiating a new operational cycle.

This strategy enables satellites to “dip” into VLEO when required, rather than attempting continuous operation in a drag-dominated environment. The result is a mission architecture that preserves VLEO’s performance advantages while mitigating its main drawback: limited mission lifetime.

The VLEO elliptical cycle concept introduces several operational requirements:

- **Servicer role.** A one-to-multi servicing scheme is assumed, with the Servicer synchronizing with one or more Targets during the circularized apogee phase after each VLEO dive.
- **Timing and operations.** The mission must tightly coordinate perigee operations with refueling events. Accurate drag modeling and orbit prediction are critical, particularly under high solar activity, which increases atmospheric density and drag variability. Due to natural orbital drifts the orbital planes of Target and Servicer need to be synchronized.
- **Fuel management.** The majority of propellant is consumed during perigee drag compensation and re-entry into elliptical cycles. This directly determines the length of each operational phase and the frequency of refueling intervals.
- **Suitability of EP and iodine.** Electric propulsion provides efficient orbit modulation, while iodine’s solid-state storage and cartridge-based refueling concept are especially well-suited for modular, cyclical mission designs of this type.

The VLEO scenario thus represents a niche but valuable application of on-orbit refueling. It is particularly relevant to high-value Earth observation and sensing missions requiring periodic access to ultra-low altitudes without sacrificing overall mission lifetime. The proposed elliptical orbit strategy, combined with iodine-based electric propulsion and a Servicer–Target refueling architecture, provides a technically feasible and sustainable pathway to long-duration VLEO operations.

SSO Scenario

Sun-synchronous orbits (SSO) maintain the right ascension of the ascending node (RAAN) locked to the Sun, enabling consistent illumination conditions for optical imaging and fixed geometries for synthetic aperture radar (SAR) missions. Typical inclinations vary between 97.4° and 98.9° , depending on altitude in the range 500–900 km. These orbits are therefore the preferred choice for Earth observation systems, but they also represent one of the most congested orbital environments.

The propulsive demand in SSO arises from three main sources:

- Drag compensation, depending on altitude and solar activity, typically 8–15 m/s per year [12].
- Collision avoidance maneuvers, frequent in the crowded SSO belt, requiring 3–8 m/s per year [13].
- Agile operations, including rapid retargeting or formation flying for imaging constellations, with requirements up to 5–20 m/s per year.

From these values, two reference budgets were defined: ≈ 15 m/s per year for a standard Earth observation satellite and ≈ 30 m/s per year for highly agile systems. A representative 300 kg optical satellite, launched with ~ 40 kg of xenon, exhausts its Δv capacity after approximately six to seven years. By contrast, a single 3.5 kg iodine cartridge



would extend the operational life by an additional three to seven years, highlighting the value of refueling for long-lived Earth observation missions.

Optical systems with ~ 0.5 m resolution payloads are valued in the range €18–24 M, while X-band SAR systems (0.5–1 m) require more massive platforms and powerful payloads, with total mission costs of €23–35 M. In both cases, the extension of operational lifetime by several years via iodine refueling represents a cost-effective strategy compared to full replacement. Despite its economic potential, in-orbit refueling in SSO faces specific challenges. Large inter-plane maneuvers are prohibitive due to their high Δv requirements, and the natural RAAN drift is strongly altitude-dependent ($\approx 0.9^\circ$ per month at 500 km, $\approx 0.5^\circ$ per month at 800 km). As a result, reaching satellites distributed across multiple planes may take several months, rendering refueling sorties inefficient.

Constellation designs exacerbate this difficulty. Optical EO systems often cluster satellites in single-LTAN shells to maximize uniform lighting conditions, while SAR constellations (e.g., ICEYE, Capella) deliberately spread satellites across multiple LTANs to optimize temporal coverage. According to the UCS satellite catalog (May 2023), there are 231 satellites >40 kg in SSO, including:

- CartoSat (India): 7 satellites, LTAN 9:29–9:37, altitudes 450–640 km.
- SkySat (Planet): 20 satellites in two LTAN groups (13:30 at 500 km and 22:30 at 507–600 km).
- ICEYE (Finland): 44 satellites distributed over LTANs 2:00, 21:00, and 22:00.

These examples illustrate the strong heterogeneity of the SSO environment. Efficient refueling services are therefore viable only when a sufficiently large number of compatible satellites (>10) share common orbital shells. This highlights the need to synchronize constellation design with servicing concepts, ensuring that orbital mechanics constraints do not offset the potential cost savings of refueling.

LEO Constellation Scenario

Large broadband constellations, such as those designed for global internet access, typically deploy hundreds of satellites per RAAN plane at altitudes around 550 km and inclinations of 53° or 43° . The high density of satellites within each plane simplifies servicing logistics: a Servicer can be launched directly into a selected orbital plane and remain there for the duration of its sortie, without the need for costly inter-plane transfers.

The Δv budget for these spacecraft is dominated by atmospheric drag, which is strongly modulated by the solar cycle. Flight data from first-generation fleets indicate annual reboost requirements between 5–12 m/s, to which collision avoidance maneuvers add an additional 2–5 m/s per year. For propellant budgeting, a reference value of ≈ 12 m/s per year is adopted.

Within this framework, the availability of on-orbit refueling represents a valuable option: docking a single 3.5 kg iodine cartridge restores approximately 170 m/s of Δv , extending satellite lifetime by 3 to 10 years depending on the mass of the satellite.

Operationally, the Servicer can exploit small semi-major axis offsets (~ 5 km) to generate along-track drift, enabling sequential rendezvous with multiple satellites. Using this strategy, a Servicer could visit ~ 20 satellites within a few weeks, minimizing propellant expenditure and avoiding large plane-change maneuvers

MEO Scenario

Medium Earth Orbit (MEO) is primarily populated by navigation constellations, such as Galileo, which deploy satellites in three RAAN planes at an altitude of approximately 23,200 km, with eight spacecraft per plane. In MEO the main drivers of propellant consumption are resonant and secular perturbations: the 2:1 tesseral resonance at the GPS altitude induces long-term drifts of the orbital elements, while higher inclinations, as used by GLONASS, amplify J₂-driven node and inclination variations. These effects typically require several meters per second of yearly station-keeping Δv if tight control of the orbital plane is enforced. In contrast, optimized designs such as Galileo deliberately avoid strong resonances and exploit a suitable choice of inclination and RAAN, such that the secular drifts nearly cancel. As a result, the annual Δv demand for routine station keeping can shrink to the millimeters-per-second level [14]. For that reason we exclude the MEO regime from further analysis.

GEO Scenario

Geostationary Orbit (GEO) remains the cornerstone for global telecommunications, broadcasting, and meteorological services. Satellites in GEO can be categorized into three representative platform classes:



- Standard platforms (~5.8 t), designed for conventional communication missions,
- Agile platforms (~6.3 t), incorporating enhanced pointing agility and relocation capabilities,
- Compact SmallGEO buses (~3.3 t), such as the OHB all-electric platform.

The dominant propellant demand in GEO arises from North–South inclination control, required to counter lunar and solar gravitational perturbations. For standard platforms, this results in ~40–55 m/s annually, while agile platforms—subject to stricter pointing and relocation requirements—demand 80–90 m/s per year. Including East–West station keeping and operational margins, the total annual Δv budget amounts to approximately 50 m/s for standard GEO missions and 100 m/s for agile systems.

Within the BOOST refueling concept, these propellant demands could be partially alleviated by modular iodine cartridges: ~70 kg for standard platforms, ~110 kg for agile platforms, and ~40 kg for SmallGEO buses, each providing sufficient Δv to extend the mission by approximately three to four years.

IV. Economic Analysis

This section evaluates the economic viability of orbital refuelling by combining cartridge value, target platform economics, and servicing mission costs. While the technical feasibility was addressed in previous sections, this section builds the economic logic behind cartridge sizing, servicing frequency, and return on investment (ROI). The analysis includes both individual satellite value (in terms of replacement cost or EBITDA) and servicing architecture (including launch and operations).

Two classes of servicing vehicles are considered:

- Compact servicer based on the NEBULA platform, which supports up to 50 kg of cartridge payload, e.g. five cartridges of 3.5 kg iodine. Current production cost is estimated at €2 million per unit, not yet reflecting serial manufacturing.
- Large-scale servicers with no upper payload limit, but with constraints on precision docking and mission complexity. These are treated as economically scalable but technically constrained.

The economic model focuses on ROI per sortie, defined as the net cartridge revenue across all targets divided by total servicing costs. For a servicing mission to be considered viable, a target ROI threshold of factor 15 is set, based on industry analogues for on-orbit risk and capital return. This framework also supports a sensitivity analysis with varying launch prices, platform classes, and Δv budgets.

Subsequent sections elaborate on target value (replacement cost or revenue per extended year), cartridge value per orbit type, mission cost models, and ROI estimations.

Cartridge Design and Life Extension per Orbit

Cartridge value depends on three interconnected parameters:

- the Δv budget of the target satellite,
- the specific impulse (Isp) of the propulsion system, and
- the monetary value associated with extending operational life.

These relationships are used to size cartridges, estimate mass and cost, and compare expected revenue to servicing investment. For a given Δv requirement and satellite mass, the propellant mass can be estimated using the rocket equation. Assuming electric propulsion systems with Isp=1800 s and full cartridge utilization, the cartridge characteristics and the life extension for serviced satellites may be summarized through the following table:

Table 2: Cartridge size and satellite life extension per Orbit

Orbit	Cartridge Mass	Years Gained
LEO	3.5 kg	3–7 years
SSO	3.5 kg	2-10 years
GEO	95–145 kg	4-6 years

Servicer Mission Model

The servicing cost per sortie is a critical factor in determining economic viability. It depends on vehicle architecture, refill capacity, launch cost, and operational complexity. Two classes of servicers are distinguished in this analysis:



- NEBULA-class compact servicer: accommodates up to 50 kg of cartridge mass (e.g. 5 cartridges × 10 kg), at a manufacturing cost of approximately €2 million. With launch and operations, a full sortie cost is estimated at €8–12 million.

- Heavy-duty servicer: scalable to >300 kg cartridge capacity. These may be economically efficient for large GEO campaigns or mass LEO replenishment but face challenges with precise docking, TRL, and cost of system integration. Estimated sortie cost is €15–25 million for LEO deployment. For missions delivered to MEO or GEO, higher launch costs apply, increasing the total sortie cost to €20–30 million depending on vehicle architecture and delivery profile.

The number of targets per sortie is orbit-dependent due to satellite distribution, RAAN dispersion, and Δv logistics. For systems like Galileo, clustered targets within a single orbital plane allow for servicing of up to 8 satellites per sortie, limited primarily by propellant mass and sortie duration.

Table 3: Targets serviced per sortie

Orbit	Typical Targets per Sortie	Notes
LEO	5	Single-plane drift campaigns; 3.5 kg fuel per cartridge
SSO	5	Clustered RAANs needed; 3.5 kg fuel per cartridge
GEO	2-8	Direct servicing; long transfer arcs; cartridges >90kg

The cartridge mass carried per sortie determines the maximum number of serviced satellites. For NEBULA-class vehicles, this typically limits LEO campaigns to 5 clients (50 kg total payload), while a full heavy-duty sortie may support up to 20–30 small cartridges in ideal conditions.

Profitability Analysis

To assess the economic viability of orbital refuelling, we calculate the return on investment (ROI) per sortie as: $ROI = \text{Total Cartridge Revenue} / \text{Total Sortie Cost}$

This analysis uses the cartridge revenue values, the sortie cost estimates, and typical sortie efficiencies per orbit type.

Table 4: ROI Estimates per Orbit

Orbit	Revenue per Target	Targets per Sortie	Sortie Cost (M€)	Total Revenue (M€)	ROI ×
SSO	€4 M (avg)	5	3.7 – 4.7	20	3 – 26×
LEO	€3.5 M (avg)	5	3.7 – 6.1	17.5	2 – 14×
LEO Heavy duty	€3.5 M (avg)	20	6.1	70	15 – 46×
GEO	€40 M (avg)	8	30 – 60	40–80	5 – 13×

LEO and SSO missions achieve limited ROI under current NEBULA-class sortie constraints (5 cartridges max). Profitability could improve through lower-cost launches, modular reuse, or future cartridge miniaturization. An alternative is the use of a compact heavy-duty servicer in LEO targeting larger next generation satellites carrying more than 20 cartridges (3.5 kg Iodine each), raising total cartridge payload to 200 kg. This configuration increases target count per sortie to 20, enabling ROI values above 15× while remaining compatible with current docking infrastructure.

GEO targets offer high cartridge value, but the low number of targets per sortie and long transfer durations limit ROI unless future architectures reduce sortie cost or increase cartridge density.

V. Mission Analysis Outcomes

The mission analysis carried out within BOOST highlights that the most promising scenarios for iodine-based cartridge refueling are VLEO and large LEO constellations, where the balance between propellant demand, servicing feasibility, and economic return is most favorable.

In VLEO, atmospheric drag drives substantial and continuous Δv requirements, which cannot be satisfied with conventional onboard propellant reserves. The adoption of small 3.5 kg iodine cartridges enables satellites to sustain



periodic elliptical “dives” into very low altitudes while relying on refueling to extend their operational lifetime. This represents a transformative opportunity for high-value Earth observation and sensing missions requiring ultra-low altitude access.

For LEO constellations, servicing economics depend primarily on sortie efficiency. While NEBULA-class Servicers may only be marginally viable when addressing a few targets, larger platforms capable of delivering and exchanging multiple 3.5 kg cartridges per sortie (20 or more) significantly improve return on investment. Dense orbital planes at ~550 km, such as those used by broadband mega constellations, provide favorable conditions for along-track servicing campaigns. However, first-generation lightweight communication satellites with minimal propellant budgets are not considered viable candidates for refueling.

By contrast, SSO and GEO missions present more challenging conditions. While agile SSO assets, particularly high-value SAR satellites, may benefit from cartridge refueling, the heterogeneous distribution of orbital planes complicates sortie logistics and reduces economic attractiveness. GEO platforms, despite their high annual service value, suffer from limited sortie density and the dominance of launch-to-GEO costs, which constrain profitability.

In summary, the optimum cartridge sizes identified are 3.5 kg for VLEO and LEO servicing missions. These values strike a balance between feasible servicing logistics, scalable hardware design, and tangible lifetime extension benefits. The outcomes of this analysis reinforce the strategic potential of iodine cartridge refueling in supporting long-lived, modular, and economically sustainable satellite infrastructures..

VI. Rechargeable Iodine Cartridge and Tank Development

Within the BOOST project, the rechargeable iodine tank and cartridge represent a cornerstone building block towards enabling modular and serviceable electric propulsion systems. While the mission analysis provided the rationale for cartridge sizing (3.5 kg for VLEO/LEO), the practical realization of a laboratory prototype has offered insights into the challenges and opportunities of iodine storage.

The subsystem consists of three key elements (Figure 1): (i) the tank platform, (ii) the removable cartridge, and (iii) the tank–fluidic line interface. The cartridge, fabricated primarily from Inconel 625 and stainless steel AISI 316L for iodine compatibility, can store up to 3.5 kg of solid iodine. Electrical heaters, integrated on the cartridge surfaces, drive sublimation, while insulation minimizes radiative heat losses. A spring-loaded piston and perforated plate maintain stable contact with the iodine and prevent solid grains from entering the fluidic system.

The tank platform is designed around a modular aluminum 7075-T6 frame, integrating guiding rails for precise cartridge insertion, as well as actuators to operate a quick-disconnect mechanism. The tank–fluidic interface employs a PTFE tube and stainless-steel push-in fittings, both heated to prevent condensation. This quick-disconnect design ensures straightforward cartridge replacement during servicing missions.

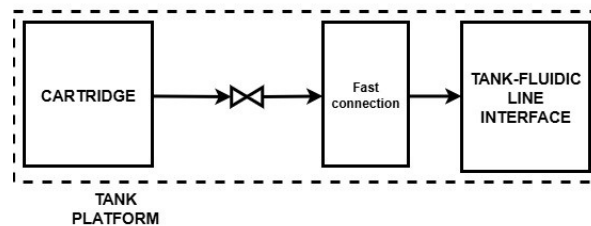


Figure 1: System design: scheme of the developed subsystem

A series of laboratory tests were conducted to validate the subsystem: (i) heating tests under vacuum, demonstrating the role of shielding and emissivity in determining thermal performance, (ii) iodine mass flow experiments, which confirmed stable sublimation rates of ~0.1–0.3 mg/s depending on temperature, and (iii) leakage tests of the pneumatic fittings, which showed leakage rates on the order of 0.2 $\mu\text{g/s}$ – not critical for intended operations. These results confirm the feasibility of the cartridge-tank approach while highlighting the importance of thermal uniformity and continuous heating of all vapor-exposed components.



Future work will address long-duration compatibility tests, vibration testing to simulate launch environments, and refinement of mass flow control strategies. Together, these developments support the BOOST objective of delivering a fully serviceable, modular iodine reservoir system for next-generation electric propulsion architectures.

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