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PROGRESS TOWARD SOLAR-TO-PROPELLANT WATER-BASED PROPULSION: PROGRAMMATIC ADVANCES AND PROTOTYPES DEVELOPMENT IN THE GREEN SWAP PROJECT

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ABSTRACT:
Green SWaP (Green Solar-to-Propellant Water Propulsion) is a four-year Horizon Europe EIC Pathfinder project developing the core technologies for a new class of in-space water-based propulsion. Rather than relying on direct water electrolysis into hydrogen and oxygen, Green SWaP co-generates concentrated hydrogen peroxide (H_2O_2) and gaseous hydrogen (H_2) from water using solar energy through photocatalytic, electrocatalytic, and plasma-based conversion approaches. These propellants feed two complementary thrusters: a 200 N bipropellant main engine combining High-Test Peroxide and gaseous hydrogen, and a 1 N solar thermal thruster for attitude control. Since the project kick-off in October 2024, development has progressed from mission analysis and system requirements definition to active prototype design. Both propulsion systems have completed preliminary design, covering materials selection, propellant conditioning, and requirements validation strategies. Component manufacturing and dedicated test bench development are underway. This paper reports the current project status, summarizes the key design choices made during the system definition phase, and outlines the roadmap toward integrated laboratory demonstration.

1. INTRODUCTION

Space propulsion is undergoing a significant transition driven by increasingly diverse mission requirements, growing concerns over the use of toxic propellants, and the long-term ambition to reduce dependence on propellant launched from Earth. Bipropellant systems based on hydrazine derivatives and nitrogen tetroxide have long been the standard for high-performance missions, but their toxicity, cost of handling, and regulatory exposure under frameworks such as the EU REACH regulations are accelerating the search for cleaner alternatives. At the same time, the expansion of on-orbit servicing, satellite relocation, and reusable transfer vehicles is creating demand for propulsion architectures that are both capable and sustainable over extended mission lifetimes.

Water has emerged as one of the most attractive candidates for next-generation in-space propulsion. It is non-toxic, easy to handle, compatible with a wide range of materials, and available on the Moon and several other Solar System bodies, making it a key enabler for In-Situ Resource Utilization (ISRU)-based logistics chains [1]. Water Electrolysis Propulsion (WEP) systems, which split water into hydrogen and oxygen for direct combustion, have been the primary focus of water-based propulsion research to date. However, these systems face well-known limitations: the need for continuous operation, difficulties in storing low-density gaseous propellants, and relatively modest thrust levels [2].

Green Solar-to-Propellant Water Propulsion (Green SWaP) takes a different approach. Funded by the European Innovation Council (EIC) under the Pathfinder Challenges call on in-space solar energy harvesting, and officially started in October 2024 under Grant Agreement No. 101161583, the project aims to produce two storable propellants from water using solar energy: concentrated liquid hydrogen peroxide and high-purity gaseous hydrogen. This propellant combination enables a bimodal propulsion architecture consisting of a high-thrust bipropellant engine and a Solar Thermal Thruster (STT) for attitude control, both sharing the same single-resource supply chain. Compared to conventional water propulsion, this approach offers higher volumetric specific impulse, lower combustion temperatures, and greater mission flexibility, since propellants can be stored after production rather than consumed immediately [3].

A first overview of the project concept and its reference mission scenario was presented at IAC 2025 [3, 4]. Since then, the consortium — comprising the University of Pisa, TU Delft, the University of Turin, KIT, ERIC, and Novaspace — has completed the System Requirements Review and tran-

sitioned into the preliminary design phase for both propulsion subsystems. This paper provides a status update on that development, focusing on the bimodal propulsion system, and covering the key design choices made during the system definition phase, the current state of prototype manufacturing and test bench preparation, and the planned path toward laboratory demonstration at Technology Readiness Level (TRL) 4.

2. HTP/GH2 BIPROPELLANT THRUSTER

The primary propulsive element of the Green SWaP architecture is a bipropellant chemical thruster designed to operate on High-Test Peroxide (HTP) and gaseous hydrogen (GH_2). To effectively manage the complexity and to characterize combustion behaviour of this novel propellant combination, the propulsion system development follows a two-loop design-implementation-test strategy.

The first loop, which is the primary focus of this paper, involves the development of a 100-N subscale, highly modular prototype. This initial system is dedicated to component-level validation (targeting TRL 3), specifically investigating ignition transients, mixing efficiency, and preliminary combustion stability. The downscaling to 100 N represents a programmatic compromise for this initial prototyping phase: it halves propellant consumption, thereby extending the achievable firing duration per test to maximize data collection while minimizing facility downtime.

Following the successful validation of these core functionalities, a second design loop will begin. This will culminate in a fully integrated, advanced prototype targeted to achieve the project's final TRL 4 demonstration, delivering a vacuum thrust greater than 100 N and a vacuum specific impulse of at least 340 s to ensure efficient propellant consumption.

2.1. Prototype Architecture and Manufacturing

Because the autoignition and combustion performance of the HTP/GH_2 combination are highly sensitive to variables such as injector geometry and nominal chamber pressure, the prototype employs a strictly modular architecture, illustrated in Figure 1. This allows for rapid hardware reconfiguration and iterative parameter isolation. The assembly, shown in Figure 2, is segmented into four distinct subsystems:

- **Catalytic Bed:** Designed to decompose liquid HTP into a high-temperature, oxidizer-rich gaseous stream (steam and oxygen). The baseline configuration utilizes a packed bed of Pt/Al_2O_3 pellets, tightly compressed to ensure structural integrity under severe thermo-mechanical stress.
- **Injection Module:** An interchangeable plate system responsible for mixing the gaseous hydrogen with the hot HTP decomposition products. A 4-on-1 impinging injector faceplate and some shear-coaxial variants have been designed for the initial empirical characterization.
- **Ignition Module:** A redundant module that accommodates a direct spark plug and acts as a failsafe to study ignition reliability alongside thermal autoignition driven by the hot oxidizer.
- **Combustion Chamber and Nozzle:** Designed to contain the stoichiometric combustion and accelerate the exhaust gases. Thermal management currently relies on a passive heat-sink approach, given the short-duration transient firings planned for the initial prototype testing. AISI 310S stainless steel was selected as the baseline material over copper alloys due to its superior oxidation resistance and structural integrity in the highly oxidizing, high-temperature steam environment.

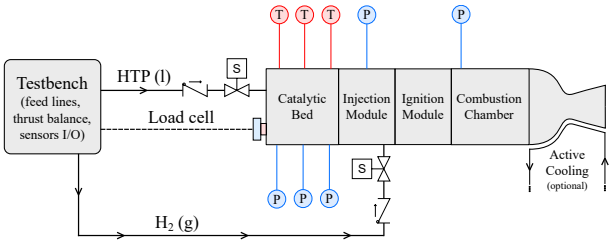


Figure 1. Schematic of the modular architecture of the first bipropellant thruster prototype.

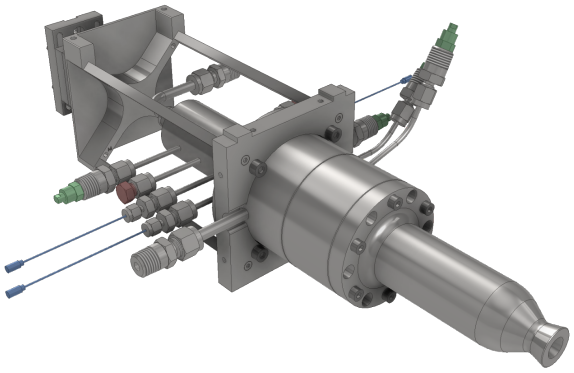


Figure 2. 3D assembly of the HTP/GH_2 thruster fully integrated with the thrust bearing structure. Pressure transducers are shown in green and thermocouples in blue.

2.2. Test Bench and Diagnostics

A critical element for the successful execution of the experimental campaign is the development of a dedicated fluidic test bench and thrust measurement system. The fluidic infrastructure must safely manage liquid HTP and gaseous hydrogen, providing precise control over mass flow rates and injec-

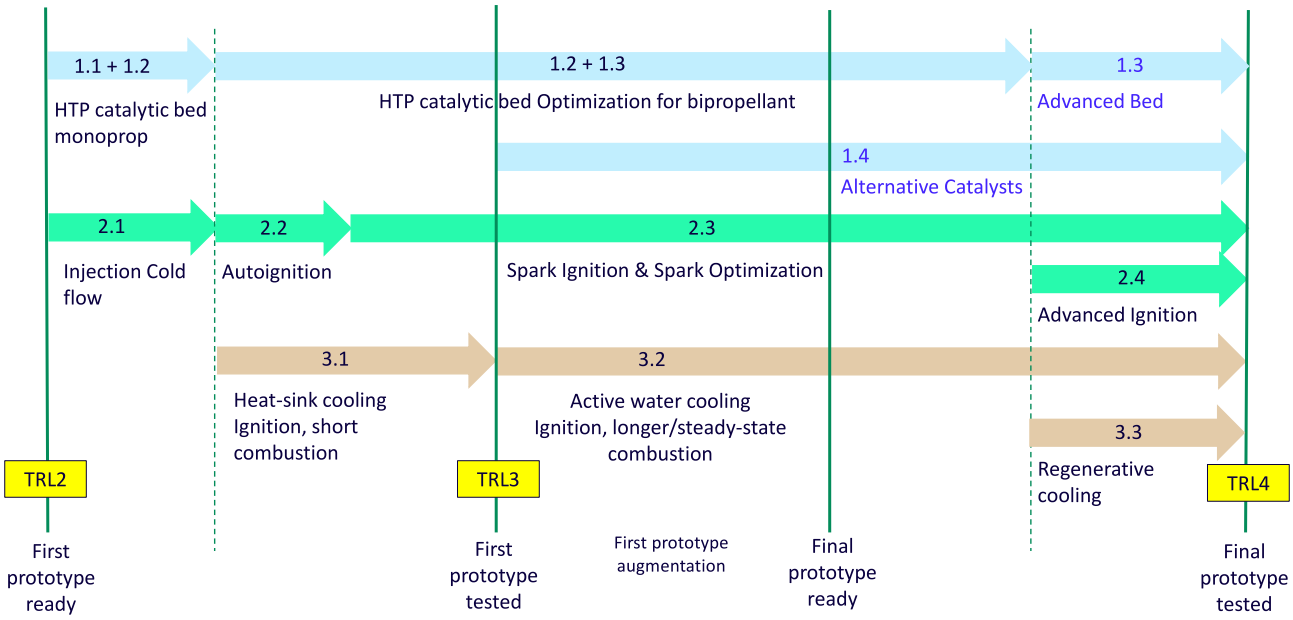


Figure 3. Testing roadmap and TRL assessment strategy for the HTP/GH_2 bipropellant prototype.

tion pressures to decouple feed system dynamics from potential acoustic instabilities.

The test bench is currently under development, with the P&ID fully defined and the procurement of sensors and fluidic components underway. To provide operational flexibility, the entire system is mounted on a mobile structure, facilitating the transfer from the assembly workshop to the outdoor test site within the University of Pisa. The bench hosts a stainless steel tank to store and pressurize liquid HTP using gaseous nitrogen, regulated by valves and pressure regulators. To guarantee safe operation, the fluidic circuit integrates critical passive safety elements, including relief valves and burst disks, alongside dedicated pressure transducers and thermocouples to continuously monitor tank and line conditions. All sensors and automated pneumatic valves are managed by a centralized Data Acquisition (DAQ) system, which enables full remote control of the facility to ensure operator safety during hot-fire testing. Furthermore, to ensure accurate performance characterization (specifically c^* and I_{sp}), propellant mass flow rates are measured using a Coriolis mass flow meter for the dense liquid HTP stream and a thermal mass flow meter for the low-density GH_2.

Axial thrust measurement is provided by a custom-designed thrust balance originally developed during the PulCheR project [5]. The assembly integrates a 200-N load cell aligned with the engine's thrust vector. For this experimental campaign, the balance has been upgraded with a modified flange interface to accommodate this larger prototype.

Finally, to accurately capture transient performance, autoignition delays, and combustion stability, the engine itself is heavily instrumented. Type-K thermocouples (1-mm Inconel-sheathed) measure the HTP decomposition profile along the catalytic bed. Furthermore, miniaturized high-temperature piezoresistive pressure transducers record the dynamic pressure response in the catalytic bed and the combustion chamber. To ensure survivability in the severe thermal and oxidizing environment, these pressure sensors are deliberately recessed via 1/8-inch capillary tubes, protecting their sensitive membranes from direct contact with the hot combustion gases.

2.3. Test Strategy and TRL Assessment

The chemical thruster follows an iterative, component-level testing roadmap designed to advance the engine from its current conceptual design phase (TRL 2, achieved at the Preliminary Design Review) to a fully integrated laboratory prototype (TRL 4) by the end of the project's development cycle. As shown in Figure 3, rather than a strictly sequential process, the experimental campaign progresses along three concurrent development tracks to optimize schedule and resource allocation:

- **Track 1: Catalytic Bed Validation.** Initial testing utilizes the fluidic test bench to evaluate the baseline Pt/Al_2O_3 catalyst in a monopropellant configuration. This phase assesses packing quality, decomposition efficiency, pressure drops, and operational stability before transitioning to optimization for bipropellant operations and exploring advanced, non-Critical Raw Material (CRM) alternative catalysts.
- **Track 2: Injection and Ignition.** Developed in parallel, the injection module first undergoes cold-flow testing with inert gases to characterize flow dynamics and mixing efficiency. Subse-

quent hot-fire tests map the autoignition boundaries and characteristics. Should autoignition fail or prove unreliable, testing will shift to optimizing spark ignition reliability and investigating alternative ignition methodologies.

- **Track 3: Combustion and Cooling.** Occurring concurrently with the early ignition tests, the integrated hot-fire campaigns begin with passive heat-sink cooling for short-duration firings to evaluate maximum allowable firing times and thermal limits. As the other tracks mature toward steady-state combustion, this track will sequentially incorporate active water cooling, ultimately evaluating the feasibility of regenerative cooling using the hydrogen fuel flow.

The successful experimental validation of the initial components across these concurrent tracks will mark the achievement of TRL 3, effectively concluding the first design-test loop of the propulsion system development.

Following this milestone, the empirical data and component characterizations obtained will drive the critical design of the second-generation prototype. The ultimate objective of the project's experimental campaign is the hot-fire demonstration of this completely integrated, second-loop prototype under relevant operational conditions. Reaching this final milestone will formally elevate the main engine technology to TRL 4 by the end of the project.

3. SOLAR THERMAL THRUSTER

The Solar Thermal Thruster relies on the integration of three principal subsystems: the Receiver–Absorber Cavity (RAC), which converts incident radiation into thermal energy; the Heat Exchanger (HEX), which transfers that thermal energy to the hydrogen propellant; and the nozzle, which accelerates the heated gas to generate thrust. It is worth noting that the solar concentrator is outside the scope of this project, and radiation is assumed to be already incident on the cavity via an external optical system that will be manufactured based on the State-of-the-Art (SoA).

The TRL 4 demonstration target requires the fully integrated prototype to deliver a vacuum thrust of at least 1 N and a specific impulse of at least 500 s, using hydrogen as propellant and a light source (simulated or concentrated solar radiation) as the heat input.

3.1. Test Strategy

Development and testing follow a "fail cheap" philosophy, structured in three sequential test campaigns of increasing fidelity, complexity, and cost. Each subsystem is tested independently before integration, allowing focused development, faster iteration, and early risk mitigation.

- Test Campaign 1 uses inexpensive surrogate materials and inert gases (nitrogen, helium) at ambient pressure. The goal is model validation and early-phase design iteration, without incurring the cost or safety constraints of high-temperature materials and hydrogen hazards and handling criticalities.
- Test Campaign 2 transitions to final or near-final materials and introduces hydrogen flow where applicable. Testing may include controlled vacuum conditions. This campaign focuses on performance refinement, material compatibility, sealing strategies, and integration readiness before final assembly.
- Test Campaign 3 is the final system test. The fully integrated STT prototype is tested with hydrogen and light heating under relevant environmental conditions, with the explicit goal of demonstrating TRL 4 performance (1 N / 500 s).

The test campaigns are structured to allow independent, parallel progress on each subsystem during the first two campaigns, converging on the integrated prototype in the third. The overall timeline is illustrated in Figure 4.

The first test campaign is expected to conclude around October 2026, at which point the STT technology should reach TRL 3, with all core functionalities validated at the individual subcomponent level. At this stage, one or more thruster assemblies manufactured in surrogate materials may also be tested with non-hazardous propellants. The final integrated prototype is targeted for full performance validation by the end of the project, upon which the system will be considered to have reached TRL 4. The tests numbering will be explained in the following sections.

Two test benches are under development to support this experimental campaign. A first thermal test bench will provide the capability of heating up the RAC to assess materials and geometry properties. The second one will consist of a thrust stand, used to validate the thruster performances in terms of I_{sp} and F. After validation, these capabilities will be incorporated into a single test bench for the performance evaluation of the fully assembled thruster.

3.2. Absorber Testing

The absorber is responsible for converting incident light into thermal energy, and its performance directly determines whether the propellant can be heated to the temperatures required for the target specific impulse. The absorber test campaign pursues four objectives: verifying the ability to reach high temperatures under lamp illumination, optimising cavity geometry for efficient light trapping, verifying material performance under vacuum and high-

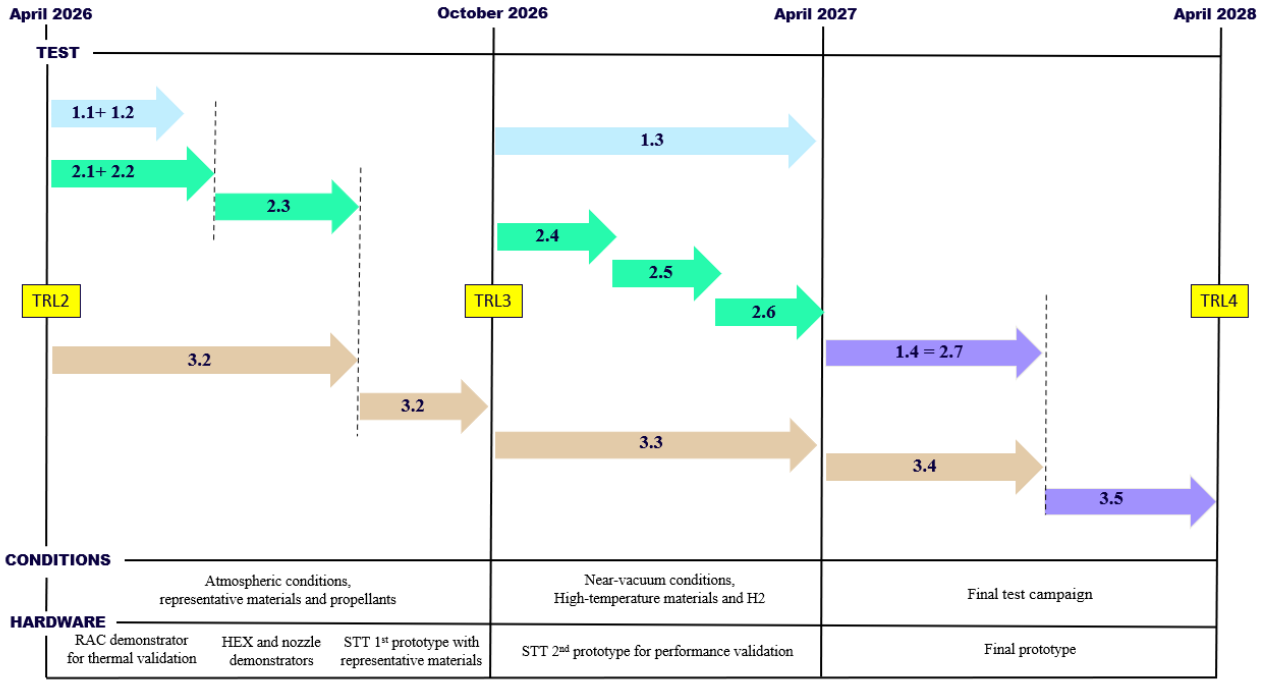


Figure 4. STT development and test campaign timeline.

temperature conditions, and assessing integration with the final HEX design.

Tests 1.1 and 1.2 use inexpensive materials (e.g., copper, steel) at ambient pressure, heated to increasingly higher temperatures using cartridge heaters. Test 1.1 establishes baseline heating capability and input power level, while Test 1.2 compares multiple insulation strategies. Together, these two tests validate the thermal setup and the accuracy of the thermal models before committing to more expensive hardware.

Test 1.3 introduces a xenon lamp as a heating element to identify the cavity configuration with the best light-trapping and heating efficiency, providing the first realistic assessment of the selected material's thermal behavior and radiative losses. Test 1.4 then validates the fully assembled HEX under the same conditions, confirming that the complete structure can be heated to the target operating temperature range of 1400-2000 K and identifying any hot spots or failure points before hot-flow testing begins.

3.3. Heat Exchanger Testing

The heat exchanger shall efficiently transfer the absorbed heat to the propellant flow, raising propellant temperature to the range needed to achieve the specific impulse requirement. In addition to thermal performance, the HEX must maintain structural integrity, meet hydrogen-compatibility requirements, and comply with demanding leakage standards, given hydrogen's low molar mass. The HEX test campaign is therefore structured to evaluate four aspects in parallel: heat transfer efficiency across different geometries, thermal performance of the selected materials, sealing and leakage behaviour under high-temperature and hydrogen conditions, and experimental validation of the thermal and fluid models.

The early tests (2.1 and 2.2) use inexpensive, low-melting-point materials without flow. Their purpose is to verify the mechanical assembly of the HEX and to investigate sealing strategies under thermal stress, with particular attention to leakage due to thermal expansion and mechanical deformation. Test 2.3 then introduces inert gas flow (nitrogen or helium) through HEX variants of different geometries, still using inexpensive materials. This test characterises heat exchange efficiency across configurations and establishes early performance correlations. It also serves to optimise the temperature measurement strategy for small flow rates and high gradients.

Tests 2.4 and 2.5 mark the transition to final materials and geometry. Test 2.4 validates the assembly's thermal behaviour and mechanical integrity at high temperature without flow, while Test 2.5 introduces hydrogen to assess sealing performance and material compatibility under operationally representative conditions. Test 2.6 is arguably the most critical test of the campaign. It flows high-temperature hydrogen through the final HEX geometry and material to directly measure propellant exit temperature, which is the quantity most closely tied to specific impulse performance. Optical heating is deliberately excluded at this stage to allow the absorber subsystem to be developed in parallel and to limit the number of variables during this technically demanding

test.

Tests 2.7 and 2.8 then bring the two subsystems together. Test 2.7 integrates the absorber with the final HEX under vacuum conditions but without propellant flow, verifying optical heating behaviour, assembly stability, and the absence of material vaporisation effects. Test 2.8 is the final heat exchange validation, combining light-based heating, hydrogen flow, and the final HEX configuration to confirm that the subsystem can achieve the required exit temperature and thermal efficiency and to support final thruster design decisions.

3.4. Nozzle Testing

The nozzle converts the thermal energy of the heated hydrogen into thrust. Its test campaign is designed to validate geometry, material compatibility, and performance under progressively realistic conditions. Tests 3.1 and 3.2 compare candidate nozzle geometries using inert gases and inexpensive materials at ambient pressure. Test 3.1 uses cold gas to assess geometric effects on thrust and to validate the thrust measurement system on the test bench. Test 3.2 introduces heated inert gas to evaluate the influence of temperature on nozzle performance and to refine the thermal and thrust models. Test 3.3 transitions to the final nozzle material and introduces vacuum conditions, providing a near-space environment for evaluating nozzle expansion characteristics, and establishing correlations between geometry, expansion ratio, and thrust under low back-pressure conditions. Test 3.4 then introduces hydrogen or an equivalent propellant as the working fluid to characterise material compatibility, fluid dynamic behaviour, and real-gas effects associated with propellant flow through high-performance nozzles. Test 3.5 is the final validation for the nozzle subsystem. It combines the final geometry, final material, and vacuum conditions to reproduce the most realistic operating environment and to directly verify whether the 1 N thrust and 500 s specific impulse requirement can be met.

3.5. Test bench status

A dedicated thermal test bench will be developed to characterize the transient and steady-state response of the system under controlled heating conditions. The experimental approach is structured in successive phases, increasing in complexity and control capability. In the initial configuration, a resistive cartridge heater with an integrated thermocouple will be employed as the heat source. The heater is driven by a Solid State Relay (SSR) operating in zero-cross mode and controlled by a commercial Proportional–Integral–Derivative (PID) controller. In this configuration, the PID controller regulates the temperature by means of time-proportional control, modulating the duty cycle of the SSR. Although this approach does not allow direct specification of the electrical power supplied to the heater, it provides a simple and robust closed-loop temperature control suitable for preliminary testing and system validation.

In a second phase, direct control of the input power will be introduced to enable systematic studies of the thermal response as a function of known heat input. For this purpose, a variable autotransformer Variable Autotransformer (Variac) is integrated into the setup to manually adjust the RMS voltage supplied to the heater, and consequently the electrical power. This configuration allows quasi-continuous control of the heater power, enabling the imposition of specific power levels (e.g., fixed fractions of the nominal power) and the observation of the resulting temperature evolution.

Subsequently, the test bench will be upgraded to allow programmable and automated power control. The heater will be driven through a data acquisition Data Acquisition (DAQ) system interfaced with a laptop running a custom control environment (e.g., LabVIEW). In this configuration, the SSR will be actuated via a digital output channel, implementing time-proportional (burst-fire) control to achieve a prescribed average power level. This approach enables fine control of the input power, reproducible test conditions, and synchronized acquisition of temperature data from multiple thermocouples distributed throughout the system.

The initial phase of the campaign conducted without fluid flow, focuses on validating the numerical model for the relevant heat transfer mechanisms, including conduction through the wall and heat exchange at internal and external surfaces. In this context, the required input power $\dot{Q}_{in}$ to achieve a prescribed wall temperature T_w is determined experimentally, enabling direct comparison with model predictions. In particular, under steady-state conditions, heat transfer through the cylindrical wall is governed by radial conduction and can be expressed as:

$$\dot{Q} = \frac{2\pi k L}{\ln\left(\frac{R_1}{R_2}\right)} \left(T_1 - T_2\right) \tag{1}$$

with the corresponding radial temperature profile given by:

$$T(r) = \frac{\dot{Q}}{2\pi k L} \ln\left(\frac{r}{R_x}\right) + T_x \tag{2}$$

In the electrically heated configuration, the heat input is provided by the cartridge heater. Temperature measurements are acquired at multiple radial and axial locations (e.g., T_1, T_2, T_3, T_4, T_c, $T_{w,f}$, $T_{w,l}$, and $T_{w,b}$, see Figure 5) in order to reconstruct the thermal field and assess the validity of the analytical and numerical models. The radial temperature distribution is expected to follow a logarithmic trend,

while axial gradients are assumed to be limited under steady-state conditions, thus providing a consistent framework for comparison. Particular attention will be given to the role of insulation materials and thickness in limiting conductive and radiative losses, as well as to the assessment of material degradation under repeated thermal cycling.

In the final phase of the experimental campaign, the electrical heater will be replaced by a high-flux xenon lamp coupled with an optical concentrator, in order to reproduce radiative heat flux conditions representative of the target application. This setup will be used to size and validate the absorber cavity under realistic irradiation conditions. The thermal characterization obtained with the cartridge heater will be used as a reference to estimate the effective power delivered by the radiative source. Specifically, equivalent thermal states will be identified by matching temperature distributions and steady-state values between the electrically heated and optically heated configurations. By correlating the known electrical power input required to reach a given temperature with the temperature achieved under radiative heating, it will be possible to estimate the effective power absorbed within the cavity.

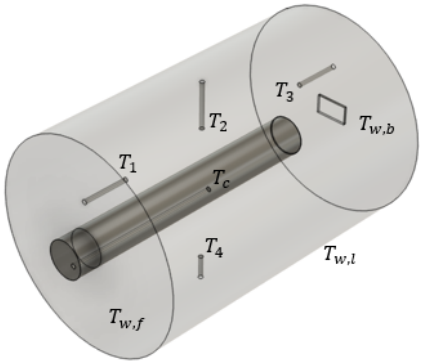


Figure 5. Proposed thermocouples configuration for the test thermal test bench validation phase.

To verify that the STT meets the required performance targets, a custom-designed thrust stand is necessary to experimentally validate the nozzle thrust and specific impulse. The thrust stand will initially be used for testing during the nozzle development phase and will later be integrated with a thermal test bench to enable testing of the complete STT prototype.

The thruster prototype is designed to deliver a nominal vacuum thrust of 1 N, with a throttleable range between 30% and 120%, and a minimum specific impulse of 500 s. The challenges associated with testing the Green SWaP STT arise from the required thrust measurement range, which varies both due to operational requirements and environmental test conditions (vacuum or ambient). In addition, typical challenges of STT testing must be addressed, including thermal shielding and accessibility during testing.

These factors necessitate the development of a dedicated thrust stand specifically tailored to the requirements of solar thermal propulsion experiments. The thrust stand currently under development at TU Delft represents the first European test bench explicitly designed for STT characterization, marking a significant advancement in dedicated ground testing capabilities for this propulsion technology.

The proposed thrust stand integrates load cells with an adjustable leverage system, enabling scalable measurement capability across a wide thrust range. The target measurement range spans from 0.01 N to 2 N, with an absolute accuracy of 5%, which satisfies the requirements for STT development. To validate and demonstrate the stand's performance, reproducibility, and accuracy, a calibration system based on a pulley mechanism will be employed during a dedicated commissioning campaign.

A key advantage of the proposed design is its ability to accurately measure a broad range of thrust levels while maintaining low cost and operational simplicity. Compared to conventional load-cell or pendulum-based configurations, the new design offers improved versatility and cost efficiency. Furthermore, due to its simplicity, affordability, and ease of operation, the thrust stand is also suitable for testing cold gas thrusters, enabling cost-effective experimental campaigns that can reduce development time and effort, ultimately contributing to more accessible space technologies.

Following the commissioning of the thrust stand and completion of the nozzle development phase, the facility will be upgraded to incorporate solar simulation capabilities of the thrust stand used for the heat exchanger/absorption cavity test campaign. This enhancement will enable representative testing of STT prototypes under realistic operational conditions.

3.6. Manufacturing approach

The manufacturing strategy for the solar thermal thruster is structured in two complementary phases, aimed at progressively increasing the geometric complexity and thermal performance of the absorber and heat exchanger components.

In the first phase, the thruster is manufactured using conventional machining techniques and well-established heat exchanger configurations. This approach relies on standard fabrication processes such as drilling, milling, and assembly of metallic components to realize geometries that are robust, reproducible, and compatible with high-temperature operation. Classical heat exchanger layouts are adopted, ensuring predictable thermal behavior and facilitating comparison with analytical and numerical models. This initial configuration enables rapid prototyping and validation of the thermal design under

controlled conditions, while minimizing manufacturing risks and costs. Representative configurations considered in this phase are shown in Fig. 6.

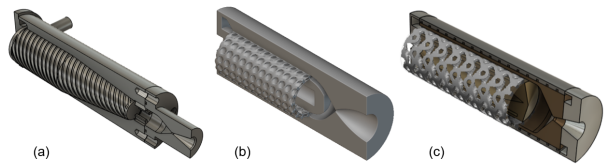


Figure 6. Comparison of manufacturing approaches for the solar thermal thruster: (a) conventionally machined configuration with internal helical channel, (b) fully additively manufactured design featuring a lattice-based heat exchanger, and (c) hybrid approach combining a machined outer casing with an additively manufactured porous insert.

In the second phase, the manufacturing approach shifts toward additive manufacturing techniques, with particular focus on refractory metals and high-temperature ceramics. This transition enables the realization of geometries that are not achievable through conventional machining, including highly complex internal structures designed to enhance heat transfer. In particular, lattice-based and Triply Periodic Minimal Surfaces (TPMS) architectures are investigated to maximize surface area while reducing the pressure drop. The use of additive manufacturing also allows for greater design flexibility, enabling the integration of multiple functionalities within a single component and reducing the need for assembly. Preliminary investigations are underway to confirm the printability of the candidate configuration. As illustrated in Fig. 7(b), fully additively manufactured concepts enable intricate internal geometries, while hybrid solutions (Fig. 7(c)) combine the structural reliability of machining with the thermal advantages of engineered porous media.

This dual approach ensures a progressive development pathway, where initial designs are validated using conventional manufacturing before advancing toward high-performance configurations enabled by additive manufacturing technologies.

4. CONCLUSIONS

This paper has reported the current development status of the Green SWaP project, a four-year Horizon Europe EIC Pathfinder initiative aimed at establishing the core technologies for a new class of in-space water-based propulsion. Since the project kick-off in October 2024, the consortium has advanced from the initial concept definition and mission analysis phase through the System Requirements Review, and has now entered the preliminary design phase for both propulsion subsystems.

For the HTP/GH_2 bipropellant thruster, a highly



Figure 7. Stereolithography (SLA) 3D printed thrusters. On the left, the helical HEX configuration, on the right the TPMS alternative.

modular 100-N subscale prototype has been designed to enable systematic component-level validation at TRL 3. The architecture is segmented into four interchangeable subsystems – catalytic bed, injection module, ignition module, and combustion chamber – allowing rapid reconfiguration and iterative parameter isolation. AISI 310S stainless steel was selected as the baseline structural material for its superior oxidation resistance in the high-temperature, oxidizer-rich steam environment. A dedicated fluidic test bench and thrust measurement system are currently under development at the University of Pisa, with the P&ID fully defined and component procurement underway. Testing will proceed along three concurrent tracks addressing catalytic bed validation, injection and ignition characterisation, and combustion and cooling performance. Successful completion of these tracks will mark the achievement of TRL 3 and initiate the second design loop, targeting a fully integrated prototype with vacuum thrust greater than 100 N and a vacuum specific impulse of at least 340 s, to be demonstrated at TRL 4 by project end.

For the Solar Thermal Thruster, development follows a three-campaign “fail cheap” philosophy of increasing fidelity, beginning with surrogate materials and inert gases and progressing toward final materials and hydrogen flow under vacuum conditions. The three principal subsystems – the Receiver-Absorber Cavity, the Heat Exchanger, and the nozzle – are being developed and tested independently before integration. A dedicated thermal test bench is under development for absorber and heat exchanger characterisation, while a custom thrust stand is being developed at TU Delft. This stand will cover a measurement range of 0.01–2 N with 5% absolute accuracy. The manufacturing strategy progresses from conventional machining in the first phase to additive manufacturing techniques in the second phase. The first test campaign is expected to conclude around October 2026, achieving TRL 3, with the final integrated STT prototype targeting TRL 4 performance of at least 1 N thrust and

500 s specific impulse by the end of the project.

Overall, both the propulsive subsystems in the Green SWaP project have completed preliminary design, and their manufacturing is underway. Additionally, the experimental infrastructure is currently being put in place. The results obtained in the coming test campaigns will provide the empirical foundation for the critical design of the second-generation prototypes and pave the way toward the integrated laboratory demonstrations planned for the final phase of the project.

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