DOI: 10.13009/EUCASS2025-671
11TH EUROPEAN CONFERENCE FOR AERONAUTICS AND SPACE SCIENCES (EUCASS)

Breadboard Design for 1N Water Electrolysis Propulsion Integrated System

Jeni A. VILAG†, Valeriu A. VILAG*, Cosmin P. SUCIU*, Razvan E. NICOARA*, Daniela ION-EBRASU**, Alin CHITU**, Ana NASTURE*, Nuno FERNANDES***, Olivier HELBIG*** and Geraldine PALISSAT*****

**COMOTI Romanian Research and Development Institute for Gas Turbines, Bucharest, Romania*
***ICSI Energy, National Institute for Cryogenics and Isotopic Technologies ICSI-Rm., Ramnicu Valcea, Romania*
****OMNIDEA-RTG GmbH, Stuhr, Germany*
*****European Space Agency / The European Space Research and Technology Centre, Noordwijk, The Netherlands*
jeni.vilag@comoti.ro, valeriu.vilag@comoti.ro, cosmin.suciu@comoti.ro, razvan.nicoara@comoti.ro, daniela.ebrasu@icsi.ro, alin.chitu@icsi.ro, ana.nasture@icsi.ro, nuno.fernandes@omnidea-rtg.de, olivier.helbig@omnidea-rtg.de and geraldine.palissat@esa.int
† Corresponding Author

Abstract

When it comes to replacing the classical, toxic propellants for long term orbital missions, current candidates still have handling limitations due to their contained chemical energy. Water is the greenest of all possible propellants, with no hazard potential because the energy is added in orbit via solar power. Water electrolysis propulsion has been studied since the 1960s, with a 1990s NASA developed and tested breadboard system, consisting of a 700 W electrolyser and a 1 N thruster. The Water Electrolysis Propulsion (WEP) is a system where gaseous oxygen and hydrogen are produced via electrolysis from pure water over a long period with low electric power and burnt with a high thrust and high specific impulse when needed. Compared to classical Electric Propulsion Systems, in this system the energy generation and usage are decoupled. In the ESA GSTP study that COMOTI is conducting in a consortium involving several entities (OMNIDEA-RTG, ICSI, OMNIDEA – EE), funded by ESA, the preliminary technical requirements of 1-N WEP breadboard have been defined for the main building blocks of the propulsion system. The paper presents the consortium's main steps in designing, developing, and testing the main components: thruster, electrolyser, feed and storage, aiming for achieving functionality, robustness, and performance of the integrated WEP system.

1. Introduction

The pursuit of alternatives to hazardous propellants has led to growing interest in more sustainable and environmentally friendly propulsion technologies for space applications. Conventional propulsion systems historically relying on toxic monopropellants such as hydrazine, which presents challenges related to storage, handling, and environmental impact, the space industry is currently moving toward safer, more affordable, and cleaner propulsion options. Among the emerging options, water has gained considerable attention as a promising green propellant, particularly for small satellite missions. Water stands out as a green propellant due to its intrinsic safety, low cost, and operational versatility. Water-based propulsion systems cover a variety of technologies, including thermal and electric thrusters such as resistojets, microwave electrothermal thrusters, electrolyzed water thrusters, and advanced electric propulsion systems like Hall Effect Thrusters (HET) and Gridded Ion Thrusters. This wide range of applications highlights water's versatility, making it suitable for both chemical and electric propulsion. Key benefits include reduced system mass, easier logistics, and long-term storage capabilities. [1].

One of the most promising developments in this domain is Water Electrolysis Propulsion (WEP), a system in which water serves as the sole propellant and is decomposed into gaseous hydrogen and gaseous oxygen via electrolysis. These gases are then recombined in a combustion chamber or used individually in thermal or electric thrusters, enabling efficient propulsion. WEP offers a scalable and non-toxic alternative to conventional chemical propulsion. Early investigations into such systems have been initiated by NASA in the 1990s [2]. The water electrolysis propulsion has been successfully demonstrated in the United States by Tethers' HYDROS [3], whose technology has flown in orbit, providing early validation of the concept. In Europe, significant contributions have come from the collaboration of ArianeGroup which has developed a prototype system that includes all core propulsion components. Their system has

DOI: 10.13009/EUCASS2025-671

been experimentally validated using a thrust balance, confirming the technical feasibility of water electrolysis-based propulsion [4].

Water propulsion systems have so far been primarily implemented in small satellites, where their non-reactive, low-pressure characteristics are ideal for integration into shared launch configurations. However, ongoing research is expanding their applicability to larger platforms, the feasibility of water-based chemical and hybrid propulsion systems being studied in the context of meeting the more demanding requirements of complex missions [1].

The use of water as a propellant is particularly well-suited to the increasing deployment of satellite constellations in Low Earth Orbit (LEO) and Medium Earth Orbit (MEO), where propulsion systems must be both agile and cost-efficient, with a notable example being the EQUULEUS mission, which successfully executed a lunar flyby using AQUARIUS, a water-based resistojet propulsion system, demonstrating the practical utility of water propulsion in deep-space trajectory manoeuvres [5].

Recent technological advances in water electrolysis have further enhanced the viability of water-based propulsion systems for small spacecraft. By producing high-energy hydrogen and oxygen on demand, electrolysis-based systems eliminate the need for hazardous high-pressure gas storage, thereby improving operational safety. Moreover, such systems support in-situ resource utilization (ISRU), wherein water sourced from extraterrestrial environments—such as lunar or asteroid surfaces—could be converted into usable propellant. This capability significantly broadens the operational range of small satellites, enabling missions beyond Earth orbit and into interplanetary space [6].

2. Water Propulsion System (WPS): design overview

The ELY-ONE activity, led by COMOTI Romanian Research and Development Institute for Gas Turbines, is part of the ESA's Green Propulsion roadmap, which focuses on minimizing environmental impact and simplifying ground operations. The goal of ELY-ONE is to develop a representative breadboard model for a 1 Newton-class Water Electrolysis Propulsion (WEP) system. This initiative supports ESA's objective of deploying hybrid WEP systems for small satellites by 2033, with the first component-level demonstrations expected by 2029.

The primary aim of the project is to design, assemble, and test a simplified water-based electric propulsion system, represented through a breadboard model that incorporates the essential components of the propulsion architecture.

At its core, the ELY-ONE system utilizes an electrolyser cell that splits water into gaseous hydrogen (GH_2) and gaseous oxygen (GO_2). These gases are stored at high pressure and then fed into a thruster to perform orbit and attitude control manoeuvres. Unlike conventional water electrolysis systems, the ELY-ONE electrolyser operates without the need for recirculation pumps or external phase separators, simplifying the system and reducing its mass—both critical factors for small satellite propulsion applications.

The breadboard model will be oriented to meet the specifications typical of an ESA Low Earth Orbit (LEO) mission for 1-ton class spacecraft, capable of performing Attitude and Orbit Control Subsystem (AOCS) manoeuvres with a 1-N thruster. The system, which has already been characterized on a thrust balance, includes a water storage tank, electrolyser cell, gas tanks, valves, piping and a thruster.

The ELY-ONE system design adheres to ESA's future technology roadmaps, which call for demonstration missions at reduced pressure and capabilities prior to the end of the decade. These missions, including the LEO demo outlined in this project, will utilize static water feed/cathode vapor feed technology. The electrolyser is expected to operate at power levels below 1 kW, with pressure levels exceeding those typical of hydrazine (i.e., above 30 bar), ensuring that, when upscaled, the system can provide sufficient delta-v for an AOCS mission of approximately 3-5 years.

Given the relatively low TRL of the breadboard, the project's resources are primarily focused on the development and production of a 35W electrolyser cell. The design philosophy emphasizes the selection of components that are relevant to space applications, ensuring that no bottlenecks arise during system upscaling. However, as the breadboard is not intended for flight, the size and volume of certain components, such as the water tank, may not be mission-representative. For example, the water tank will be small enough for multiple refills during ground testing, as the project lacks the budget for a large, mission-representative 60-80L tank and development of a 500 W electrolyser.

Nevertheless, the selected tank must be space-representative, meeting the structural and environmental requirements for space operations. For example, a bladder or pressurized multi-layer (PMD) tank type will be chosen, ensuring positive expulsion and the ability to withstand typical space environment tests such as vibration, thermal cycling, and shock.

The electrolyser cell is the most critical component of the breadboard, the main objectives including demonstrating the production of hydrogen and oxygen with the appropriate dryness to avoid the need for phase separators, the capability to maintain overall system pressure, and the capability to reach efficiency levels that confirm the viability of the Cathode Vapor Feed (CVF) or Static Water Feed (SWF) concept [7, 8].

TRL 4 is targeted by the conclusion of the project, demonstrating functional verification of the integrated system, with most subsystems anticipated to reach TRL 5, which reflects successful breadboard verification under representative environmental conditions.

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The ELY-ONE breadboard system is designed to integrate a series of key components, such as: a water storage tank for onboard feedstock, a 35 W compact electrolyser cell for in-situ hydrogen and oxygen production, gas storage tanks for GH_2 and GO_2, and a 1N thruster for precise AOCS manoeuvres. This setup forms a closed-loop, self-sufficient propulsion module, designed for long-duration LEO missions, with a particular emphasis on AOCS functionality.

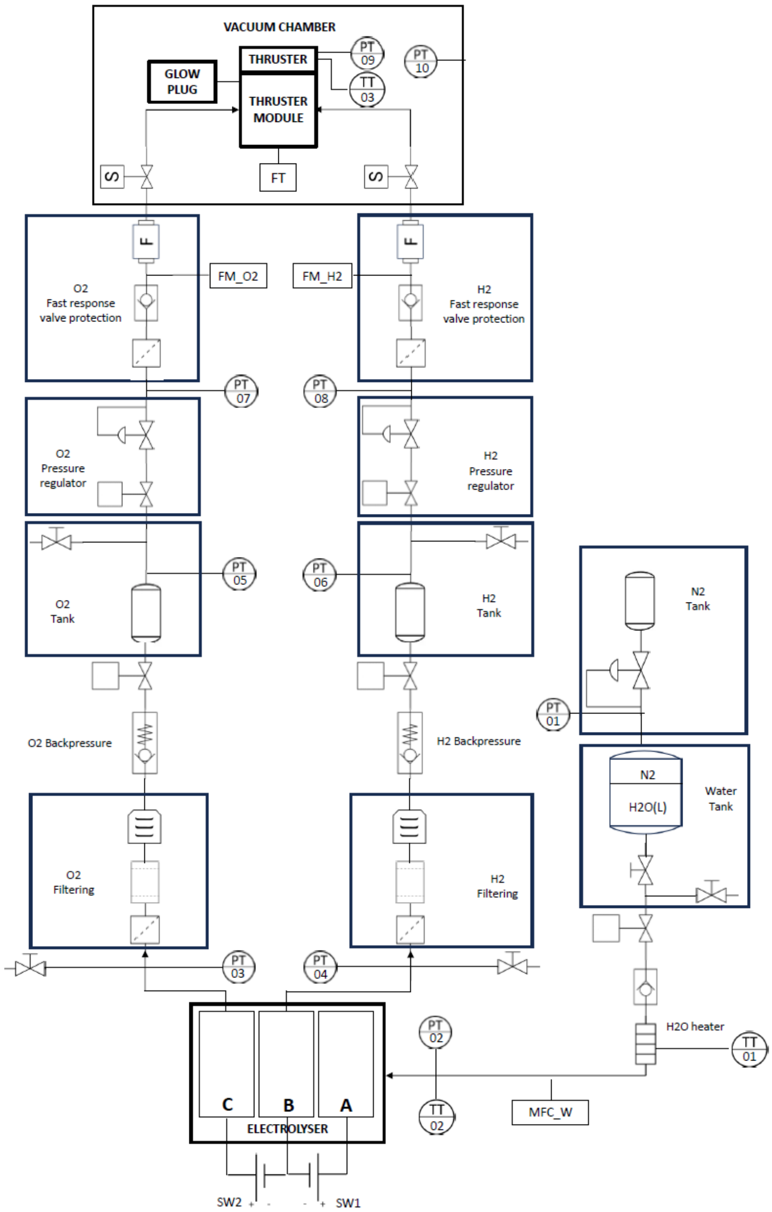

Figure 1: Instrumentation diagram – Integrated ELY-ONE ground breadboard

The system is designed to operate in four distinct phases:

- System Standby, with the system inactive, all components in a dormant state;
- Electrolyser cell activation and Gas Storage, the electrolyser cell splitting water into hydrogen and oxygen, and the gases stored at high pressure (30 bar);
- Standby with Filled Tanks, while the system remains idle, with gas storage tanks filled and ready for use;
- Thruster Firing, the stored gases being fed into the thruster, enabling precise manoeuvres.

This decoupling of the energy input (electrolyser) and propulsion output (thruster) provides flexibility in system design and enhances minimum impulse bit (MIB) control via fast-response valves. Unlike direct gas feeding from the electrolyser, the system stores pressurized gases (30 bar), ensuring sufficient thrust operation at pressures above the minimum requirement of 14 bar. This configuration is necessary because operating at low power (35 W) would not yield the required gas flow or pressure for effective propulsion.

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The ELY-ONE breadboard system is designed to meet specific mission and operational requirements for Low Earth Orbit (LEO) Attitude and Orbit Control Subsystem (AOCS) missions. Key mission requirements include a 1 N thrust capability, a minimum impulse bit of less than 0.1 Ns, and a total impulse and duty cycle that are suitable for LEO AOCS operations. These parameters ensure that the system can perform the necessary orbital and attitude control manoeuvres over extended mission durations, with particular attention to the precise and efficient management of propellant for long-term operations.
In terms of technical specifications, the breadboard system is focused on demonstrating critical performance metrics such as thrust, specific impulse, energy input, and duty cycle. The system includes a single-cell electrolyser (49 cm²) operating at a nominal power of 35 W to generate the required hydrogen and oxygen for propulsion. For the thruster, a minimum operational pressure of 14 bar is required to ensure effective thrust production. Additionally, the system is designed with modular and scalable components, enabling future upscaling to meet more demanding mission profiles.
To guide the development of the ELY-ONE breadboard and ensure that each subsystem meets both technical performance and integration criteria, a comprehensive list of requirements has been established. These requirements are divided into hard (mandatory) and soft (desirable but non-critical) categories, based on their importance for achieving the intended system functionality within the current phase of the project.

3. Equipment Design: Requirements Consolidation and Trade-Off Evaluation

3.1 Electrolyser

The electrolyser cell is a critical component of the WPS, responsible for generating gaseous hydrogen (GH_2) and gaseous oxygen (GO_2) in-situ. The selected configuration for the WEPE1 project is the Cathode Vapor Feed (CVF) electrolyser integrated with an Electrochemical Hydrogen Compressor (EHC). This configuration was chosen for its ability to produce dry, pressurized gases, its scalability for future mission needs, and its strong compatibility with microgravity environments. The key performance requirements for the electrolyser include a minimum operating pressure of 14 bar, with a nominal power consumption of 35 W. The electrolyser is designed to have an active area of 49 cm² and a typical cell voltage of 2 V to ensure efficient operation and gas production.
The electrolyser's design was informed by a thorough trade-off analysis, comparing four different electrolyser types based on complexity, durability, efficiency, microgravity compatibility, and cost. The CVF with EHC configuration emerged as the optimal choice due to its ability to meet the dry gas production requirement while also offering feasibility for upscaling to higher power levels in future missions. Additionally, this configuration ensures compatibility with the space environment, particularly in terms of performance in microgravity.
The electrolyser subsystem must satisfy both hard and soft requirements to ensure effective integration into the WPS and overall system performance. The hard requirement is the ability to sustain a pressure of $\geq$ 14 bar, which is essential for ensuring adequate thruster operation. The remaining requirements are considered soft and serve to guide the design toward operational feasibility, scalability, and efficiency. These include factors such as the electrolyser's active area, cell voltage, and nominal power. The hydrogen and oxygen production rates are also key to meeting the mission's refuelling needs, while ensuring the system operates within the required stoichiometric balance.
To ensure that the most effective solution is selected, a comprehensive trade-off analysis was conducted across four candidate electrolyser configurations. These configurations included the Liquid Anode Feed Electrolyser (LAF), Liquid Cathode Feed Electrolyser (LCF), Cathode Vapor Feed Electrolyser with Vapor Generator (CVF-VG), and Cathode Vapor Feed Electrolyser with Electrochemical Hydrogen Pump (CVF-EHP).
The evaluation was based on a series of criteria essential for system performance and suitability for space applications. These criteria included constructive solution complexity, which considered the overall complexity of the design and its integration with other subsystems. Robustness and durability were crucial, given the challenging space environment and the need for long-lasting components. Power density and efficiency were examined to ensure that the electrolyser cell could operate effectively while maintaining low power consumption. The technological limitations of each system were assessed to understand how each design would perform under real-world conditions. The humidity of exhaust gases was another consideration, as excessive moisture could impact downstream components. Material requirements were evaluated to ensure the availability of suitable materials that could withstand space conditions. Overall mass was considered to keep the propulsion system lightweight, while electrical performance was analysed for its efficiency in converting electrical energy to chemical energy. Additionally, gas production rate was reviewed to ensure that the electrolyser could generate sufficient hydrogen and oxygen at the required rate for mission operations. Finally, 0g/microgravity operation was essential, given the intended operation in space environments, particularly with small satellites, which would require a system capable of functioning effectively in weightless conditions.
The analysis concluded that the CVF-EHP configuration emerged as the optimal solution. This was largely due to its ability to function efficiently in microgravity, its robust design, and the integration of an Electrochemical Hydrogen Pump (EHP). In this configuration, water vapor diffuses through the Nafion membrane toward the anode, where

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electrolysis takes place, producing pressurized hydrogen at the cathode and oxygen at the anode. The CVF-EHP's ability to generate pressurized gases in a microgravity environment, combined with its efficient gas production and robust construction, made it the most suitable choice for the project.

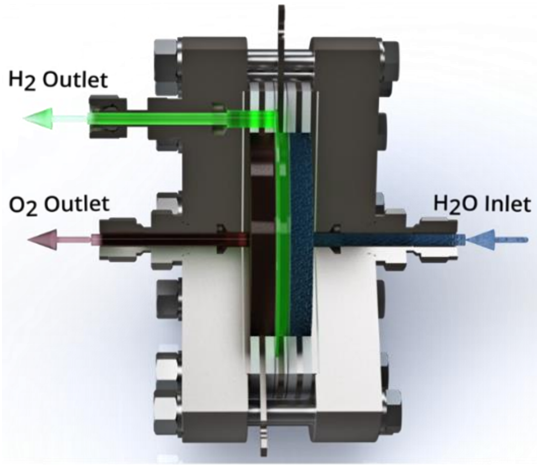

Figure 2: CVF electrolyser cell section view

3.2 Feed and Storage

The Feed and Storage are integral to the WPS, ensuring the safe and efficient handling, storage, and transport of water and gas, therefore the effective operation of the electrolyser and thruster subsystems. The design of these subsystems focuses on maximizing reliability while minimizing mass and complexity, in alignment with the project's goals for small satellite propulsion. The storage system includes both the water tank and the high-pressure gas tanks for hydrogen (H_2) and oxygen (O_2). While scaled down for ground testing, these tanks must simulate the performance characteristics of their space-compatible counterparts, as the final design will be deployed in future missions. For the water tank, a membrane tank is selected due to its capability for positive expulsion, which is essential for simulating operational conditions in a ground test environment. This design choice is based on the unavailability of suitably sized Pressure-Matched Diaphragm (PMD) tanks. For the gas storage tanks, fully metallic tanks are considered, taking into consideration the availability.

The feed system controls the transport of water to the electrolyser and directs gases to the storage and thruster units. A comprehensive trade-off analysis was conducted between different pipe sizes, in order to minimize pressure loss while maintaining manageable mass. Solenoid valves were chosen for their fast actuation, simple design, and enhanced cycling endurance over alternatives such as ball and piezoelectric valves.

The storage system components must meet a set of functional and safety requirements that ensure operational readiness. Critical parameters for the water tank include its ability to sustain a minimum operating pressure and maximum pressure to simulate realistic operational conditions. The inner pressurant volume is another hard requirement, as it is critical for proper feed system operation, ensuring continuous and reliable propulsion. The selection of membrane type (e.g., bladder or PMD designs) and materials is vital for ensuring positive expulsion and resistance to typical space environment stresses such as vibration, shock, and thermal cycling.

The gas storage tanks are selected to support pressures above 30 bar, with proof pressures and minimum burst pressures to ensure structural integrity and safety during operation. Both tanks must meet stringent cleanliness levels to prevent contamination, particularly with oxygen and hydrogen, which require careful handling due to their reactive nature. The vacuum resistance and vibration resistance of the gas storage system are also key considerations for in-space compatibility and environmental durability.

The feed system plays a crucial role in safely transporting water to the electrolyser and directing the resulting gaseous hydrogen and oxygen to the storage and propulsion components. The feed pipes must be made of corrosion-resistant and gas-compatible materials to prevent any leaks or contamination during operation and ensure proper functionality over the system's operational lifetime. Furthermore, the system must tolerate thermal cycling and vibration during space operations, ensuring it can endure the environmental conditions encountered during launch and in orbit.

The water storage system was designed with the primary decision point being between membrane tanks and Propellant Management Device (PMD) tanks. Although PMD tanks provide better functionality for space applications, they are not commercially available at the small scale required for this development phase. Membrane-type tanks, however, offer several advantages: they are widely available, have proven flight heritage, and are capable of simulating the

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positive expulsion mechanisms necessary for space operations. Given these benefits, the membrane-type tank was selected as the most practical and suitable solution for the current development phase.
The gaseous storage system focused on the trade-off between fully metallic tanks and Composite Overwrapped Pressure Vessels (COPVs). Fully metallic tanks were selected based on cost and availability.
The feeding system, responsible for transporting water to the electrolyser cell and directing gases to storage and thruster units, was carefully analysed to ensure optimal performance. Two key components, the piping and the valves, were evaluated to determine the best configurations. A comparison was made between two different dimension tubing, taking into account factors such as mass, procurement availability, pressure losses, and ease of assembly. The ¼″ tubing was chosen for its ability to minimize pressure loss while ensuring ease of integration into the system. This provided the best balance between performance and practical considerations. Three types of valves were evaluated: solenoid valves (plunger/latch type), ball valves, and needle (piezo-driven) valves. The evaluation criteria included mass and volume, actuation durability, opening characteristics, minimum impulse bit (MIB) capability, thermal behaviour during continuous operation, space qualification, and power consumption. Solenoid valves emerged as the optimal choice due to their excellent impulse response, proven cycling capability, existing space qualification heritage, and simpler control interface. These features make solenoid valves the most suitable for the breadboard configuration.

3.3 Thruster

The Thruster is a critical component of the Water Propulsion System (WPS), responsible for delivering the required thrust for Attitude and Orbit Control System (AOCS) manoeuvres. The design of the thruster focuses on ensuring the efficient conversion of stored gaseous hydrogen (GH_2) and oxygen (GO_2) into thrust, with a particular emphasis on performance, reliability, and integration with other system subsystems, including the electrolyser.
The thruster is designed to operate in a pulsed mode, with an emphasis on high repeatability and compatibility with the gases produced by the electrolyser. A comprehensive evaluation of cooling methods for the thruster was conducted, considering no cooling, radiative cooling, regenerative cooling, and film cooling. While radiative cooling thrusters showed the best performance, the no-cooling configuration was ultimately selected. This choice was driven by its simpler design, which offers advantages in terms of cost and ease of integration, without significantly compromising performance based on prior experience.
The integration of the thruster with the electrolyser output is streamlined to maximize system efficiency. The selected no-cooling design supports lower mass and simplified integration with the storage and feed systems, ensuring that the gases are efficiently fed into the thruster for precise AOCS manoeuvres.
The thruster has several key requirements that are essential for ensuring its functionality within the mission parameters. The Specific Impulse (Isp) requirement is classified as hard and must meet or exceed 300 seconds, ensuring that the system can deliver the necessary Δv for orbital adjustments. The thrust must be maintained between 0.9 and 1.1 N, which is essential for precise AOCS manoeuvres. Additionally, the Minimum Impulse Bit (MIB) must be less than 0.1 Ns to enable high-precision attitude control, which is critical for the stability and accuracy of small satellite missions. Other specifications, such as the operating pressure (between 14 and 30 bar) and repeatability of operation, are classified as soft requirements, with values reflecting the operational range of the system and the need for consistent performance across the mission. The thruster's fluid compatibility with pure GH_2 and GO_2 is also emphasized, as it must handle the propellants produced by the electrolyser without degradation in performance.
The thruster subsystem underwent a thorough evaluation of four candidate designs: a thruster without cooling, a radiative cooling thruster, a regenerative (channel) cooling thruster, and a film cooling thruster. The assessment of these options was based on nine criteria, each reflecting key performance and integration factors: system complexity, robustness and reliability, maximum theoretical specific impulse, thrust response, self-cooling capacity, technological limitations, material demands, overall mass, and relative cost.
The results of the evaluation showed that the radiative cooling thruster emerged as the top performer, closely followed by the thruster without cooling. The small performance difference between these two options indicated that both could deliver similar thrust capabilities. However, the regenerative cooling and film cooling thrusters scored lower due to their higher complexity and increased mass, which introduced challenges related to integration and overall system efficiency.
A secondary analysis, where equal weightings were applied to all criteria, reaffirmed the robustness of the rankings, confirming that the radiative and non-cooling thrusters outperformed the more complex cooling designs. Despite the radiative cooling thruster offering marginally better performance, the thruster without cooling was selected for the project. Several factors contributed to this decision: the team's proven experience with such systems, which minimizes development risks, the simplicity of implementation during the Engineering Model (EM) development stage, and the fact that the pulsed operational regime of the thruster provided sufficient thermal tolerance without the need for active cooling.

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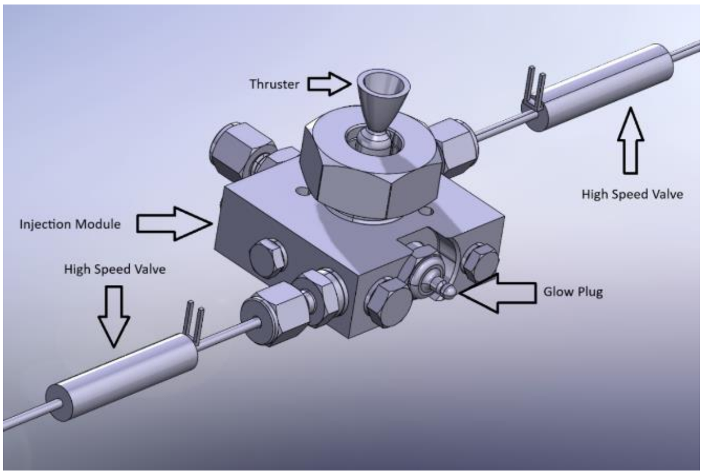

Figure 3: Thruster assembly isometric view

Table 1: Water Electrolysis Propulsion System hard requirements

Parameter	**Subsystem**	**Description**
Pressure	Electrolyser	Must sustain ≥ 30 bar to supply gas to the thruster
Min. Operating Pressure	Storage (H_2O tank)	Minimum functional pressure during operation
Max. Pressure	Storage (H_2O tank)	Maximum allowed operating pressure
Proof Pressure	Storage (H_2O tank)	Verification pressure for structural integrity
Inner pressurant volume	Storage (H_2O tank)	Critical for feed system operation
Cleanliness level	Storage (H_2O tank)	Fluid compatibility and contamination prevention
Min./Max. Operating Pressure	Storage (H_2/O_2 tanks)	Must support operational envelope, thruster needs
Proof Pressure, Min. Burst	Storage (H_2/O_2 tanks)	Critical for safety and certification
Cleanliness level	Storage (H_2/O_2 tanks)	Required for safe oxygen and hydrogen handling
Vacuum resistance	Storage (H_2/O_2 tanks)	Essential for in-space compatibility
Min./Max. Operating Pressure	Feed	Ensures reliable flow during all operational phases
Proof Pressure, Min. Burst	Feed	Guarantees structural integrity and safety
Specific Impulse (Isp)	Thruster	Must achieve required Δv with given propellant mass
Thrust	Thruster	Nominal 1N output for AOCS manoeuvres
Minimum Impulse Bit (MIB)	Thruster	Enables high-precision attitude control

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4. System Integration and Breadboard Assembly

The operating cycle of the WEP integrated system provides a comprehensive framework for managing the production, storage, and utilization of propellants, hydrogen and oxygen, produced through water electrolysis. The cycle is designed to optimize system performance while ensuring effective control over key propulsion parameters such as fuel generation, tank filling time, impulse delivery, and operational endurance.

Electrolysis and Propellant Production involves the electrolyser's task of converting water into gaseous hydrogen and oxygen, producing hydrogen at a rate of 0.66 g/h and oxygen at a rate of 5.28 g/h. The cycle accounts for the total water mass processed (3 l), which results in a total of 332.33 g of hydrogen and 2658.67 g of oxygen.

The relatively low hydrogen production rate reflects the inherent inefficiencies of the electrolyser, but the system's design compensates by optimizing storage and propulsion to match the mission's operational demands. The cycle also estimates the total mass flow rates for the stored hydrogen and oxygen gases, which are essential for assessing the propulsion subsystem's performance. The electrolysis process is structured to achieve a full tank filling at 30 bar pressure within a 9.37-hour timeframe.

Once the gases are produced, the cycle evaluates the storage and filling times for the hydrogen and oxygen tanks. These tanks are modelled to operate at a pressure of 3 MPa (3000 kPa) with respective volumes of 2 litres for hydrogen and 1 litre for oxygen. The system can hold 4.21 g of hydrogen and 33.65 g of oxygen, which is sufficient to generate the necessary propulsion power for the mission. The 6.37-hour electrolyser operation time, required to fill the tanks, is a key parameter for understanding the system's refuelling efficiency.

These storage parameters are crucial for mission success, as the tanks' size and filling time directly affect the total mission duration and the number of pulses achievable by the propulsion system. The relatively modest tank sizes indicate a focus on short-duration manoeuvres typical for small satellite missions.

The mass flow rates of hydrogen (0.026 g/s) and oxygen (0.210 g/s) directly translate to the thruster's ability to generate thrust. The nominal thrust of 1 N is targeted for attitude and orbit control subsystems (AOCS). The thruster is capable of firing for 159.92 seconds per tank, delivering a total impulse of 159.92 Ns per fuel tank.

One of the critical figures in the thruster's operational cycle is the specific impulse, which stands at 431 s, a key performance metric that ensures efficient use of propellant. This specific impulse value is suitable for small satellite missions, which often require high efficiency for small, precise manoeuvres. The system also demonstrates the capability for a high total number of pulses (126,362) and total impulse per water tank (12,636 Ns), indicating substantial endurance over the course of the mission, especially for longer-duration AOCS tasks.

The system’s ability to perform a substantial number of pulses while maintaining a high specific impulse reflects its capacity for sustained performance, making it a promising solution for long-term AOCS manoeuvres. Moreover, the total firing time per water tank (3.51 hours) ensures that the system can perform manoeuvres for extended periods, which is critical for mission longevity in Low Earth Orbit (LEO).

The integrated WEP system encompasses all the key equipment, connecting elements, and subsystems. The instrumentation diagram in Figure 3 details the system components and their interconnections. To ensure safe operation during testing, several safety devices have been incorporated, although certain elements, such as H2 and O2 filtering and dehumidifiers, may become redundant once the moisture content of the produced gases is analysed. The water tank filling and storage process is designed to operate in a stepwise manner, starting with the filling of the tank via a fill and drain valve, followed by the charging of water into the heater and electrolyser once the isolation valve is opened. Gaseous O2 and H2 produced by the electrolyser are directed to their respective storage tanks, where pressure transducers and test ports are installed to monitor and purge the gases if necessary. The gases are filtered and routed through non-return valves into their respective tanks, with safety isolation valves closing once the tanks are full and the electrolyser powered down. For firing, the downstream isolation valve is opened, filling the flow control valves of the thruster assembly, which includes a pressure regulator to ensure constant pressure. The gas is filtered and passes through a flame arrester to protect the system, while flowmeters monitor consumption during thruster operation.

The system operates through a series of well-defined sequential steps, with intermittent start/stop cycles for the subsystems, including the electrolyser cell, which are synchronized with the energy availability based on the sun/shadow ratio during orbit. The process begins with the initial state, followed by system startup, and then proceeds with filling the gas tanks. After reaching the desired gas levels, the system enters a stand-by state, maintaining nominal conditions for thruster operation. Thruster operation follows, after which the system returns to stand-by. The cycle repeats with periodic restarts for gas tank filling before returning to stand-by. The entire sequence is designed to optimize energy usage and ensure efficient system operation, responding to the varying conditions in orbit. This cyclical process provides an efficient and controlled method for managing the water electrolysis propulsion system, balancing gas production, storage, and thruster utilization to meet mission requirements.

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5. Conclusion and Future Work

The ELY-ONE breadboard system marks a significant milestone in the development of water-based electrolysis propulsion systems for small satellite missions. The project's primary objective is to demonstrate a fully integrated, functional propulsion system that aligns with the European Space Agency's (ESA) strategic roadmaps for green propulsion technologies. By providing critical performance data, the system will offer valuable insights into the design and operational requirements for hybrid Water Electric Propulsion (WEP) systems, facilitating their eventual deployment in operational missions by 2033.

The comprehensive set of requirements established for the ELY-ONE system forms the backbone for both its design and testing. These specifications ensure that the system will meet the essential criteria for reliable performance in space, while also offering the flexibility necessary for future mission adaptations. With a focus on scalability and seamless integration, each subsystem is developed to be readily adaptable for integration into flight models. The breadboard will validate these parameters in a ground-based environment, with the goal of reaching functional readiness (TRL 4) by the conclusion of the project.

The analysis of the operating cycle highlights the system's efficiency, with carefully optimized parameters for electrolysis, fuel storage, and propulsion. The balance between hydrogen and oxygen production rates, effective gas storage, and adequate propulsion capability demonstrates the system's potential to meet the demands of attitude and orbit control for small satellite missions. The specific impulse and total impulse values confirm the system's ability to support mission-critical manoeuvres, while the endurance analysis suggests it is well-suited for longer-duration missions requiring precise propulsion capabilities.

Having completed the design, fabrication, and preliminary testing of the subsystems, the project is now entering a phase focused on detailed subsystem testing according to approved plans. The final phase will involve system integration followed by comprehensive ground validation testing, paving the way for the next steps toward the deployment of water-based propulsion systems for future space missions.

Acknowledgements

The activity has been carried out under the GSTP of, and funded by, the European Space Agency (contract number: 4000143031/23/NL/GLC/ces).

The view expresses by the paper can in no way be taken to reflect the official opinion of the European Space Agency.

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