DOI: 10.13009/EUCASS2023-766
Aerospace Europe Conference 2023 – 10TH EUCASS – 9TH CEAS

RELIANCE, an electric pump-fed main engine for ESA's lunar lander

Adrien J. Boiron†, Anthony Haynes**, Henning Josefsen*, Gianluca Liggieri*,*
Nuria Minguez Esteve, Jørn Inge Ruud* and Elliott Worsley***
** Nammo Raufoss AS, 2830 Raufoss, Norway*
***Nammo U.K. Ltd, HP180XB Westcott, United Kingdom*
†Corresponding author: adrien.boiron@nammo.com

Abstract
The RELIANCE engine is an ESA supported development for a new generation bi-propellant electric pump-fed rocket engine in the medium thrust class using hypergolic propellants (MMH and MON-3) that is conducted by Nammo (UK, NO). Its target application is main propulsion as a cluster of engines on Argonaut, ESA's lunar lander. This paper describes the programmatic context for the RELIANCE program and then documents the progress achieved on the engine design definition to this day. It shows how innovative design choices on RELIANCE may enable the first European planetary landings.

1. Programmatic context

1.1 International collaboration on space exploration

In October 2022, the ISECG (International Space Exploration Coordination Group, a group of 27 space agencies worldwide) released a new supplement to the Global Exploration Roadmap first released in January 2018 [1]. The Global Exploration Roadmap reflects an international exploration strategy that begins with the International Space Station (ISS) and extends to the Moon, asteroids, Mars and other destinations. This strategy builds on a shared set of exploration goals and objectives and reflects missions that will provide substantial benefits to the citizens of Earth.

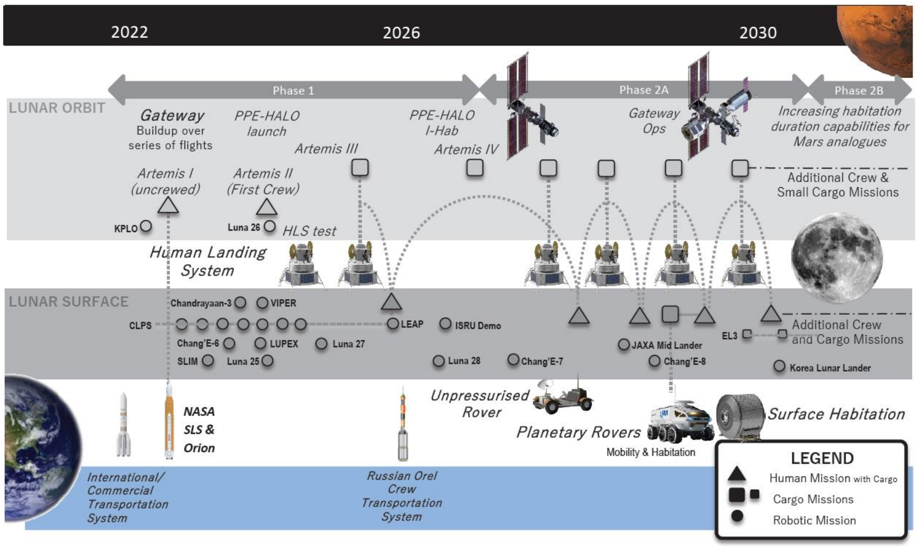

Figure 1: Updated ISECG Lunar Surface Exploration Scenario [1]

This updated supplement describes the latest mission scenario shown on Figure 1 and architecture for human and robotic lunar surface missions, preparatory activities for Mars and scientific priorities for the Moon. Evolved lunar surface exploration and utilisation scenarios reflect plans for a near-term series of robotic missions followed by humans returning to the Moon in this decade.

Copyright © 2023 by Nammo AS. Posted online by the EUCASS association with permission.

DOI: 10.13009/EUCASS2023-766

Rather than looking at individual missions, the ISECG scenario depicts a stepwise development of an increasingly capable lunar transportation system to the lunar surface, traversing systems on the lunar surface, and infrastructure supporting them that will enable cooperative science and human exploration efforts leading toward a sustained presence on the lunar poles and incorporating lunar surface activities as analogues in preparation for human missions to Mars. These efforts emphasise landed downmass to eventually support four crewmembers per mission and mobility systems that dramatically enhance science return and exploration distances around a lunar pole base camp.

The United States is undertaking a new lunar exploration programme—Artemis—that soon will enable human missions to the Moon and in a manner that is sustainable long-term and tests the systems and operations necessary to prepare for future human Mars missions. The National Aeronautics and Space Administration's (NASA) Artemis missions have a goal of enabling human missions to the lunar surface as early as 2025 and target sustainable lunar exploration near the end of the decade. The Artemis missions are enabled by international cooperation with the European Space Agency (ESA), which is providing the European Service Module (ESM) that powers the Orion spacecraft.

In addition to further contributions on the Gateway, ESA also aims to contribute by means of enabling direct cargo delivery to the lunar surface. The European Large Logistics Lander (EL3) program was initially announced at the ESA ministerial conference (Space19+) held in 2019 in Seville. It was then confirmed when ESA released its new exploration roadmap called Terra Novae 2030+ (Latin for new worlds) in June 2022 with a vision of covering low-Earth orbit, the Moon and Mars. This ESA exploration roadmap prepares Europe to implement strategic autonomy in its lunar exploration activities, at the same time strengthening international partnership with the objective to have the first European on the Moon surface by 2030. The EL3 is displayed on the right of the ISECG roadmap on Figure 1. Finally, the ESA lunar lander was renamed from EL3 to Argonaut before it was approved for implementation at the Space22+ ministerial conference held in November 2022 in Paris.

1.2 ESA's lunar lander, Argonaut

Argonaut is Europe's autonomous access to the Moon, allowing Europe to play a major role on the surface of the Earth's natural satellite. The lunar lander is being designed for a series of missions with many options for its payloads – from cargo and infrastructure delivery to scientific operations, a rover or a power station, Argonaut is being designed as a versatile access to the Moon [2].

Argonaut will launch on an Ariane 64 rocket in a direct flight to the Moon. An Argonaut mission from launch to landing could take from a week to a month, depending on orbits and mission design. No area is off-limits for Argonaut as the spacecraft will be able to land at any region on the Moon, and with a high landing accuracy of 50 to 100 meters.

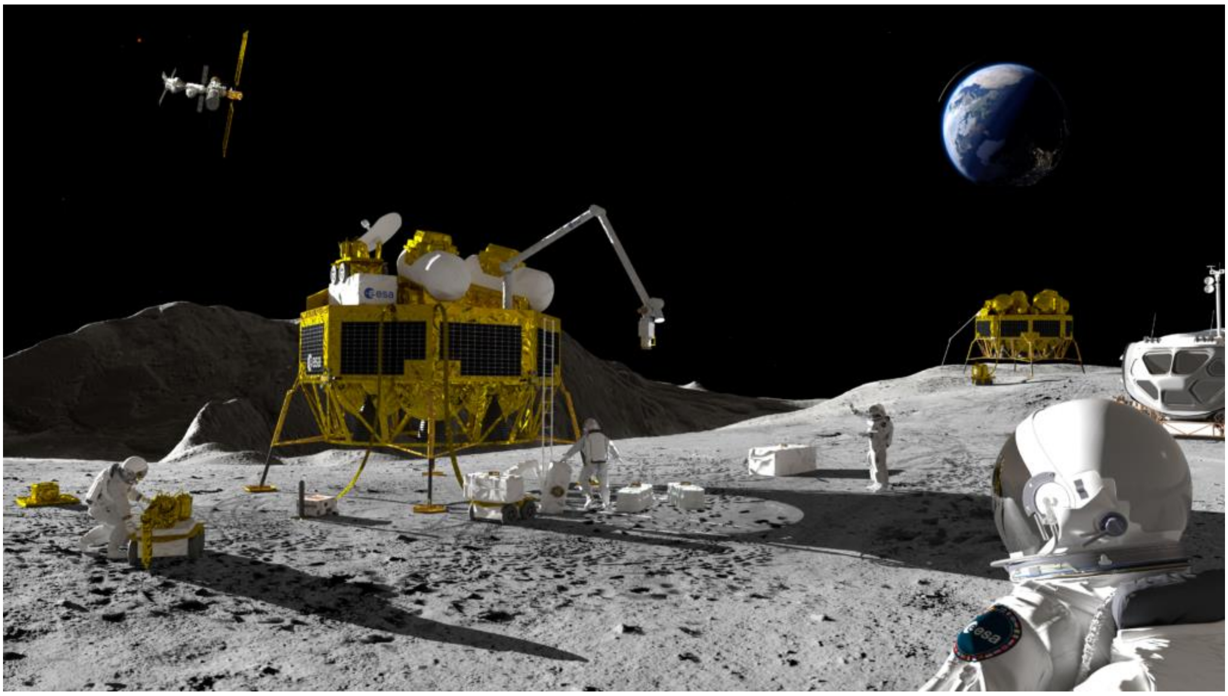

Figure 2: Artistic impression of Argonaut. Image credit: ESA

DOI: 10.13009/EUCASS2023-766

The Argonaut spacecraft has three main components: the lunar descent element that takes care of flying to the Moon and landing on target, the cargo platform element that is the interface between the lander and its payload, and finally, the element that mission designers want to send to the Moon. The Argonaut spacecraft will be 4.5 meters diameter, up to 6 meters tall, weighing about 10 000 kg at launch from Earth and capable of delivering up to 2100 kg of payload to the Moon surface.

Figure 2 shows an artistic impression of Argonaut, integrated in a Artemis human surface exploration scenario. The Argonaut lander has delivered a combination of cargo items, scientific payloads and small robotic assets (rovers). An Artemis crew, including a European astronaut, is unloading the lander assisted by a robotic arm and preparing lunar surface exploration activities. Argonaut is scheduled for a first launch to the Moon in the year 2030, with subsequent recurring missions in the following decade, at a frequency of once every second year, though the mission frequency remains subject to change.

A key technology that has been missing in Europe for many decades to enable lunar landings is the main propulsion, based on a single large engine, or a cluster of smaller engines. Indeed, in order to safely land with very low velocity, engines with deep throttling capability are needed, at least down to 50 to 40% of maximum thrust, and ideally down to 30 to even 20%. Traditionally, Europe used to develop engines for launch vehicles and satellites, and tried to reuse those for exploration missions where possible. When it was not enough, Europe used to rely on international partners such as NASA or JAXA to support with throttleable engines for the landing. As made clear in the recent European exploration roadmaps, ESA aims to change that by achieving autonomous access to the Moon and potentially in the future to other planets as well, and the High Performance Engine plays a critical role to make that happen.

1.3 The High Performance Engine

Well ahead of the EL3 announcement in 2019, the need for a High Performance Engine (HPE) in the medium thrust range has been stated for many years in the ESA Exploration Roadmaps. It was already confirmed by many ESA Phase A/B1 studies for lunar surface missions from as far as the 1990's. Medium thrust range in this case is defined as the range between the classical apogee engines (mainly 400N) and the typical launch vehicles engines (30kN and above).

In this context, high performance means that ESA set the target specific impulse (Isp) to be 340s, as was demonstrated by the Aestus-II engine (55kN), which was based upon the already existing Aestus engine and the existing Rocketdyne turbo pump (RS72), with only moderate adaptations of both systems. Another example of an engine that delivered high specific Impulse is the XLR132 engine also known as the RS-47 (with 16.7 kN thrust). High performance is critical here as it is a key enabler for a multitude of ESA missions, by allowing an increase in payload mass and making new mission architectures feasible.

The HPE requirements defined by ESA were not limited to high performance. Indeed, multiple other requirements and capabilities were also targeted with future exploration missions in mind, such as most importantly:

- Throttleability (down to 50% or even 20% of nominal thrust level) to enable landing as previously discussed;
- Reusability (up to 10 nominal starts) to enable in-space re-fuelling and re-use for longer missions;
- Long life (high throughput and accumulated burn time of up to several thousand seconds) to enable more ambitious deep space missions.

The development of the HPE started at the end of 2018 with the issuance of an ITT for the phase A/B1 of its development as part of the E3P ExPeRT programme, called HPE Phase 1. A consortium led by Nammo with its two sites in Raufoss, Norway and Westcott, U.K., and with Sobriety from Czech Republic as sub-contractor for electric pump system design was selected for this work and kicked-off the activity in April 2019. For more details on this activity, please see [3]. The HPE Phase 1 activity was successfully completed and concluded by Nammo in June 2020.

The HPE concept that won all the trade-offs also against classical turbopump cycles and was selected is the Liquid-liquid E-pump concept. It uses a pintle injector (as developed for NASA LMDE in the Apollo program [4]) with both propellants being injected in liquid phase, which enables engine operation over a large throttle range. It also uses two independent electric pump systems to feed high-pressure propellant into the chamber, increasing the performance and allowing the desired throttleability to be achieved through control of the propellant mass flows. This same e-pump-fed bi-propellant approach was recently shown to provide significant system benefits for a Mars sample return mission [5]. This study laid the groundwork for what would later become the RELIANCE engine development program.

DOI: 10.13009/EUCASS2023-766

2. The RELIANCE Engine System

2.1 Development approach and current status

In September 2021, Nammo (in the United Kingdom and in Norway) kicked-off the High Performance Moon Engine Pre-Development activity with ESA with the goal of bringing the engine concept defined in the previous study to Preliminary Design review (PDR) and Technology Maturity Level (TRL) level of 5 [6]. Nammo held an internal naming contest, which led to the HPE being renamed into RELIANCE, which is an acronym standing for Rocket Engine for Lunar and Interplanetary Anglo-Norwegian Commercial Exploration.

The development approach chosen for RELIANCE is very much in line with system engineering standards used in the space industry, which are notably described by European Cooperation for Space Standardization (ECSS) standards [7]. RELIANCE is currently in its pre-development phase, or Phase B titled “Preliminary definition”, which is to be closed by the Flight Engine PDR (PDR-F). During this phase, the system engineering function according to ECSS is to:

1. Establish the system preliminary definition for the system solution selected at end of Phase A (which has been provided by the previous HPE Phase 1 activity).
2. Demonstrate that the solution meets the technical requirements according to the schedule, the target cost and the customer requirements (this will be performed by means of test at both component and Breadboard level and by means of analysis).
3. Support the System Requirements Review (SRR) (in this case that would be the Baseline Design Review, BDR-F) and Preliminary Design Review (PDR-F), and ensuring implementation of the BDR and PDR actions.
4. Define the development approach and plan of engineering activities (for subsequent phases).

During this pre-development phase, an imbricated “V” system engineering approach will be followed as shown below in Figure 3. It starts with flight engine requirements that allow initiating activities simultaneously both at Breadboard components and Breadboard engine level. During Phase 1, the Breadboard component “V” loop will be completed in order to feed into the Breadboard engine “V” loop and Breadboard engine detailed design delivered at CDR-B. Then during Phase 2, the Breadboard engine “V” loop will be completed to feed into the preliminary design of the flight engine delivered at PDR-F. This approach, kicked-off by the flight engine requirements, allows confidence and validation to be gained through analysis and test of the preliminary flight engine design.

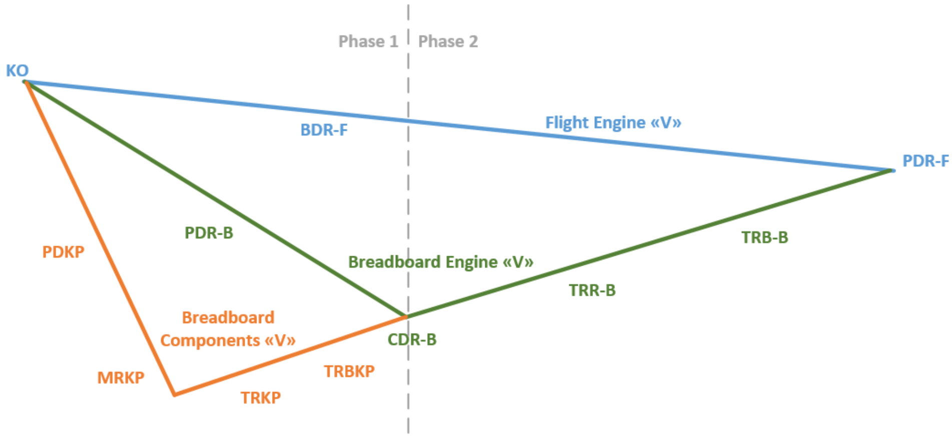

Figure 3: RELIANCE Development Approach

In terms of hardware models, the approach is sequential with first the Breadboard components being tested at representative physical scales, but smaller scales in terms of thrust level, allowing reaching TRL 4. The Breadboard components test campaign was completed in December 2022 and the TRBKP was held in February 2023. Within the span of three weeks, 42 hot fire test were conducted on four different injector configurations and one common chamber configuration called the Heat Load Characterization Chamber (HLCC), which reused hardware parts from the LEROS 4 engine [8]. A picture from one such hot fire test is shown on Figure 4. The conclusion of this test campaign was successful, with Nammo achieving the high combustion efficiency target of 97% in multiple tests, and demonstrating throttling in the full range from 100% down to 50% throttle. A preferred pintle injector design said of “spoke” type was selected for further implementation on the Breadboard engine.

DOI: 10.13009/EUCASS2023-766

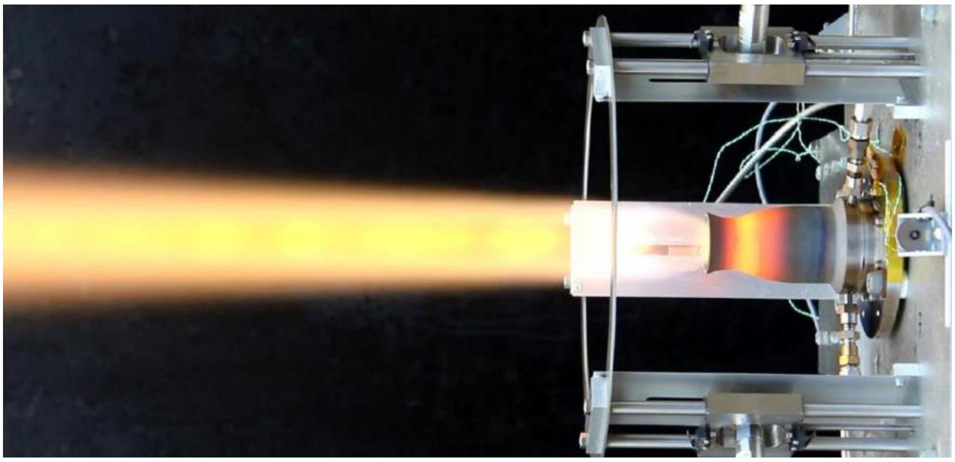

Figure 4: 1.1kN MMH/MON subscale test engine being hot fire tested at sea level in Westcott, UK

The second and main engine hardware model planned in the RELIANCE pre-development is the Breadboard engine. The Breadboard engine is the first full-scale model of the RELIANCE engine to be designed, manufactured and hot fire tested in the RELIANCE development. The goal with Breadboard engine testing is to reach TRL 5 in RELIANCE engine development and provide adequate results and data to feed into the PDR of the flight engine. A dedicated article is written on the Breadboard engine, and it is referred to it for more information [9].

The Critical Design Review for the Breadboard Engine (CDR-B) was successfully completed in May 2023, and the Breadboard engine with all associated test hardware is currently being manufactured. Figure 5 shows the breadboard engine on the test stand; where one can see in red the fuel lines, in blue the oxidizer lines, as well as the large number of sensors that will instrument the engine during hot firing. The Breadboard will be first tested in representative high-pressure conditions without the electric pumps. This is enabled by the test facility at Westcott J4 site, which is being upgraded as part of another ESA contract ongoing in parallel. This test facility will be able to deliver high-pressure propellant at the mass flows needed for RELIANCE and to throttle thanks to throttle valves part of the facility that are able to regulate the mass flows even faster than the current target for throttling with the electric pumps. The J4 test facility is currently nearing completion, and this will be concluded by a hot fire commissioning test set to occur shortly after the summer break. In the fall of 2023, the Breadboard engine will be tested first on its own, then the engine will be removed and the Breadboard electric pump systems will be tested at the same facility with propellant, and finally the engine will the electric pumps will be tested together.

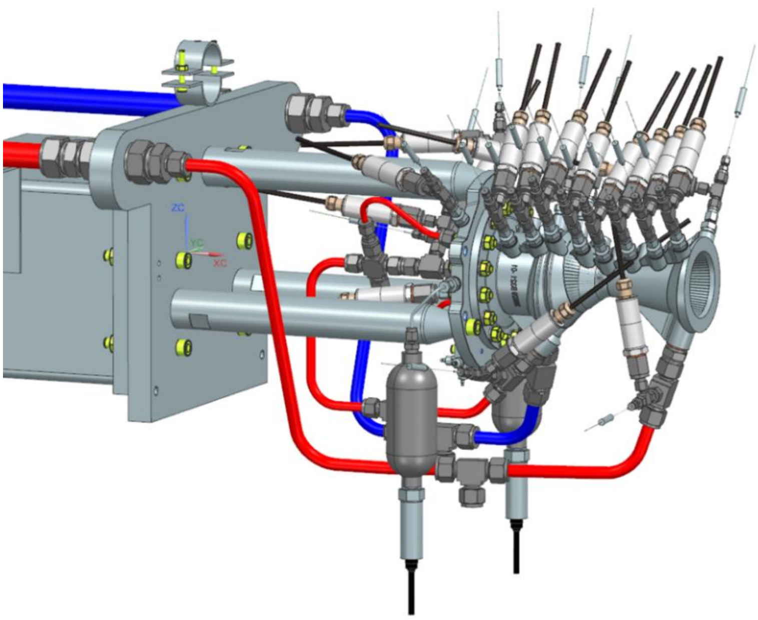

Figure 5: View of the Breadboard Engine CAD Model attached to the Test Stand [9]

DOI: 10.13009/EUCASS2023-766

It is important to mention that RELIANCE is not yet guaranteed a place on Argonaut. Another candidate engine, the SPE-T from ArianeGroup, is being developed in parallel for use on Argonaut. This is standard ESA practice for technological blocks that are on the critical path, such as is the case for the main engine on this Moon mission. In December 2023, at the end of this year, the main engine for Argonaut will be decided in between RELIANCE and the SPE-T at the Key Engine Selection Point (KESP). This decision will be made by the Argonaut prime with supervision from ESA, based on the materials provided and results achieved on both engines up to the KESP. This explains why Nammo is working very hard this year in order to achieve TRL 5, and to be able to show the combined performance of the Breadboard engine with the Breadboard electric pump systems, all in time for the KESP.

2.2 Selected concept

In order to deliver on the requirements set by ESA, RELIANCE makes use of new technologies notably in the fields of electric-driven pumps, additive manufacturing, advanced physics modelling and high precision control to provide an engine with completely new capabilities. Its innovative electric-pump driven cycle shown in Figure 6 will provide:

- High performance (at least 330 seconds of specific impulse at the 6 kN nominal vacuum thrust point) thanks to higher chamber pressure than conventional pressure-fed engines.

- Large throttle range (from 117% down to 50%, potentially lower) thanks to the use of a pintle injector, a modernized technology from the Apollo era, and of additive manufacturing on the regeneratively-cooled chamber, maximizing the use of both propellants for efficient and high performance chamber wall cooling.

- Full control and high precision in thrust regulation throughout the entire throttle range, thanks to high fidelity electric pump rotational speed control.

RELIANCE also includes a Helium gas system to provide sealing to the electric pumps and a purge function for the engine in space. This on-board purge will enable the engine to perform a large number of restarts (at least 10) and to be stored for long durations of time in space at low temperatures, without risk of the propellant freezing.

A key characteristic of this engine system, which makes the chosen engine cycle possible, is the use of two independent electric pumps. Such a configuration allows for high performance without coupling between propellants, nor use of energy from the propellants (as would classically be the case in a turbopump-fed engine). Each propellant feed line is planned to run independently, with matching done at engine controller level between oxidizer and fuel e-pump commands in order to make sure the needed mixture ratio is achieved. This allows for the highest achievable flexibility in throttling, both following the nominal mixture ratio, but also the off nominal mixture ratio if so desired.

Electric pumps also provide the highest precision in throttling, as mass flow control through control of the rotary velocity of the motor and pump is very predictable, reproducible, and much more precise than throttleable valves can achieve. This allows a very tight control of the mixture ratio throughout the entire throttling range of the engine. Electric pumps are therefore very important elements of this engine cycle, as they provide both the high specific impulse performance (through feed pressure increase and therefore chamber pressure increase) and the wide range but precise thrust regulation capability.

Last but not least, electric pumps also lower the engine propellant inlet pressure down to 7 bar or lower. This provides important mass savings on the spacecraft pressurization system compared to pressure-fed engines, which often contributes to a lower overall engine mass, even when accounting for the battery mass. The associated battery mass is of course mission dependent, it may be recharged in flight, and may serve other mission objectives such as surviving the lunar night. The battery mass budget is also expected to reduce as battery technology improves in the coming years.

Another aspect of RELIANCE is the use of dual propellant cooling, made possible by additive manufacturing technology. Dual cooling makes use of both propellants, the MMH fuel and the MON-3 oxidizer to cool the combustion chamber. MMH is injected at the end of the regen section of the nozzle and flows up along the chamber until the end of the chamber cylindrical section. MON-3 is itself injected at the end of the chamber cylindrical section and flows up in the chamber wall until the head-end. This solution makes the engine cycle feasible at this medium thrust scale. It provides sufficient chamber wall cooling while not overheating the propellants beyond their boiling point, throughout the wide throttling range of the RELIANCE engine, down to the most demanding point at lowest throttling.

DOI: 10.13009/EUCASS2023-766

2.3 System schematic

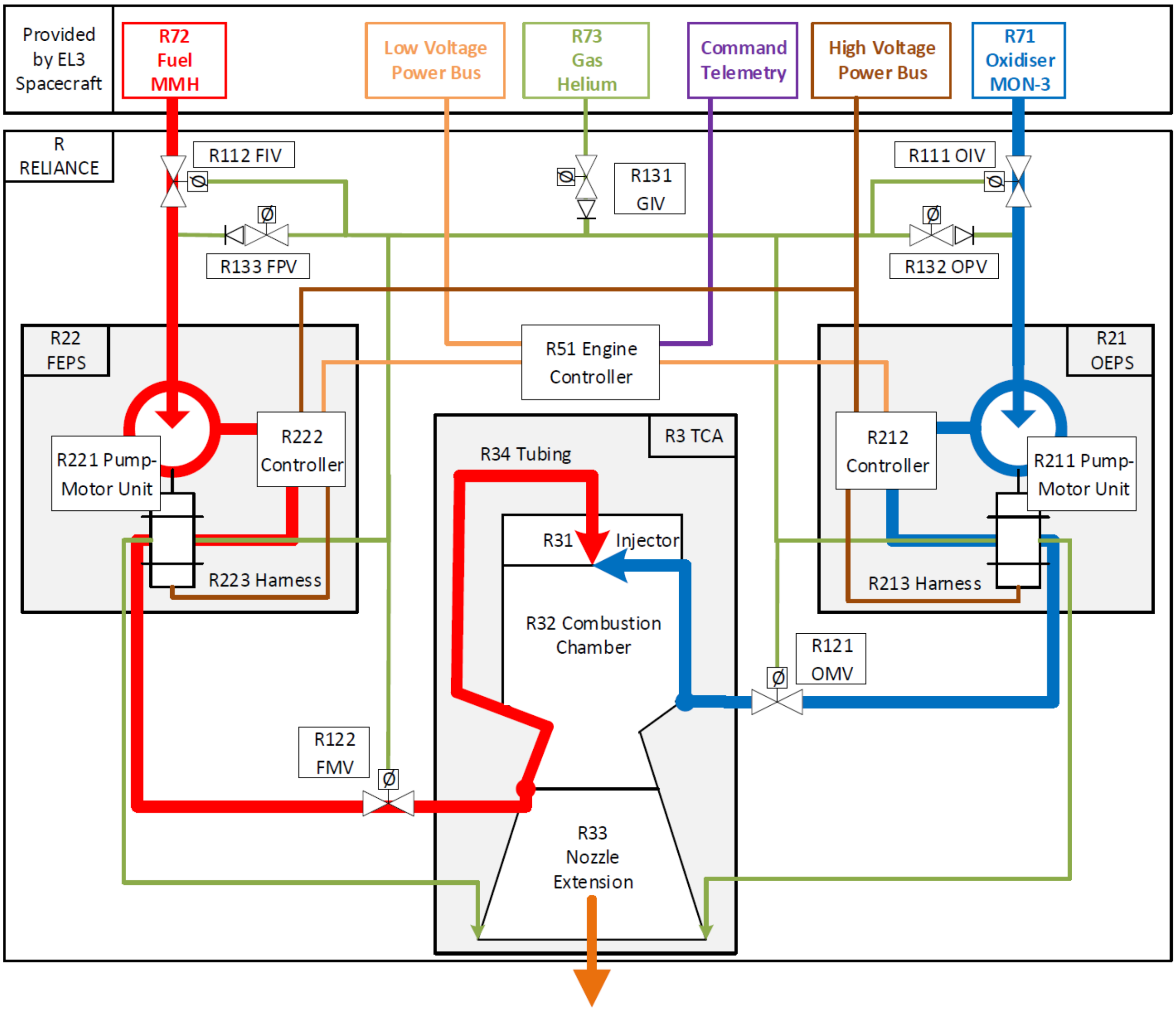

Figure 6: RELIANCE engine system schematic

The schematic for the RELIANCE flight engine in Figure 6 focuses on the fluidic layout and does not display all power and communication lines for simplification, including those leading to valves and sensors. It only includes selective lines to the engine and e-pump controllers. The abbreviations used are explained by the product tree in Table 1.

This schematic illustrates the following elements of interest:

- Dual propellant cooling is in use for the regeneratively-cooled chamber;
- The two independent electric pump systems (one on each propellant line) are controlled by a common engine controller;
- The engine controller will have a central role in communicating with the spacecraft, collecting engine sensor data and commanding the engine's electrical components;
- Within each electric pump system, first the controller and then the electric motor are cooled by the propellant before it leaves the electric pump system assembly;
- Helium gas has multiple uses: propellant purging downstream of the isolation valves and through the electric pumps, electric pump sealing and propellant valves actuation;
- Helium sealing gas and small quantities of propellant may leak from electric pumps during operation and would be collected and discarded close to the nozzle exhaust;
- Gas valves include a check valve function to avoid propellant contamination in the upstream gas system.

DOI: 10.13009/EUCASS2023-766

2.4 Product Tree

Table 1 shows the product tree for the RELIANCE. The product codes were used to refer to engine components in Figure 6 and the table below also explains the abbreviations used in many instances. The Reliance product tree shown here is at a quite high level, and it displays both the complexity and the architecture of the engine system.

Table 1: RELIANCE Product Tree

Level 1 System	Level 2 Sub-system	Level 3 Assembly or Component Group	Level 4 Component	Level 5 Sub-component
R	**RELIANCE**			
	R1	**Valves**		
		R11	Isolation Valves	
			R111	Oxidizer Isolation Valve
			R112	Fuel Isolation Valve
		R12	Main Valves	
			R121	Oxidizer Main Valve
			R122	Fuel Main Valve
		R13	Gas Valves	
			R131	Gas Isolation Valve
			R132	Oxidizer Purge Valve
			R133	Fuel Purge Valve
	R2	**Electric Pump Systems**		
		R21	Oxidizer Electric Pump System	
			R211	Pump-Motor Unit
			R212	Controller Unit
			R213	Harness
		R22	Fuel Electric Pump System	
			R221	Pump-Motor Unit
			R222	Controller Unit
			R223	Harness
	R3	**Thrust Chamber Assembly**		
		R31	Injector	
		R32	Combustion Chamber	
		R33	Nozzle extension	
		R34	Tubing	
	R4	**Structures**		
		R41	Thrust structure	
		R42	Fixtures	
		R43	Brackets	
		R44	Sensors	
	R5	**Electronics**		
		R51	Controller	
		R52	Fixtures	

DOI: 10.13009/EUCASS2023-766

		R53	Harness	
		R54	Sensors	
	R6	**Tubing**		
		R61	Oxidizer Tubing	
		R62	Fuel Tubing	
		R63	Gas Tubing	
	R7	**Fluids**		
		R71	MON-3	
		R72	MMH	
		R73	Helium	
	R8	**Ground Support Equipment**		

2.5 Industrial consortium

The industrial procurement plan for RELIANCE includes three main sub-contractors and three main manufacturing suppliers. The sub-contractors concern the following products:

- **R1 Valves:** Safran Aero Boosters (SAB) in Belgium will develop propellant valves for RELIANCE based on their extensive expertise and an already existing design at TRL 5. They will do so with a high level of commonality between oxidizer and fuel, and between isolation and main valves items. A similar approach is foreseen for the gas valves, where SAB also has a component that would require some delta-development.

- **R2 Electric Pump Systems:** Inpraise Systems (INS) in Czech Republic and Thales Alenia Space (TAS) in Italy are both already under contract with Nammo to develop electric pump systems for the RELIANCE engine. Concerning the high criticality of this new technology for the RELIANCE engine, the decision was made here as well to place two candidate suppliers in contract. They both are aiming to provide Breadboard electric pump systems in time for the pump testing at Westcott to occur this fall. The first to be ready to ship its electric pump systems for testing in the UK will most probably be the first to test them with the Breadboard engine. Same as for the engine, an electric pump system Supplier Selection Point will be organized by Nammo and ESA and be held in order to decide which electric pump system supplier will be chosen and allowed to continue for the remaining of the RELIANCE engine development and exploitation.

- **R51 Engine Controller:** An announcement was published and was opened on esa-star during April and May 2023 for identifying interested parties to be the engine controller supplier for RELIANCE. The Engine Controller Request for Proposal (RFP) data pack is currently under review by Nammo and ESA and will be soon released to the many firms that expressed their interest on the ESA platform. After a few weeks of proposal response time, Nammo will conduct under ESA's supervision a Tender Evaluation Board in order to assess all proposals and identify the preferred supplier for the Engine Controller.

The three main manufacturing suppliers concern the following products:

- **R31 Injector & R32 Combustion Chamber:** Alloyed in the United Kingdom supports the manufacturing of critical injector and combustion chamber parts with its expertise and production facilities for additive manufacturing. Nammo further makes use of a special high-strength and high-temperature capable nickel-based alloy called ABD-900AM that was originally developed by Alloyed for jet engine turbine applications.

- **R33 Nozzle Extension:** Nammo will utilise its established network of suppliers for manufacturing nozzle extension cones, using the same manufacturing suppliers and methods as for the LEROS engines. The LEROS 4 [8] nozzle extension cone for example is very close in size to the extension cone needed for RELIANCE.

- **R41 Thrust Structure:** Norsk Titanium in Norway supports the manufacturing of the main engine support structure in Titanium. Norsk Titanium is a well-recognized supplier in wire additive manufacturing (WAM) made components for the aerospace industry, a production method that fits well the needs of RELIANCE.

DOI: 10.13009/EUCASS2023-766

2.6 Main characteristics

Table 2: Main characteristics of the RELIANCE engine

ENGINE CHARACTERISTIC	VALUE
Typical Application	Exploration (lunar and deep space) Main delta-V, ascent and descent engine
Typical Operating Mode	Long duration steady-state burn(s) Advanced throttling
Propellants	MON-3/MMH
Thrust @NOP[1] (N)	6000
Thrust range[2] (N)	3000 to 7000
Throttle rate (N/s)	≥2000
Throttle precision (N)	±60
Mixture Ratio @NOP (Ox/Fu)	1.82
Oxidizer Mass Flow Rate @NOP (kg/s)	1.198
Fuel Mass Flow Rate @NOP (kg/s)	0.658
Chamber Pressure @NOP (barA)	45.0
Vacuum Specific Impulse @NOP (s)	≥330.0
E-pumps Power[3] @NOP (kW)	≤22.0
E-pumps Power[3] @OTP[4] (kW)	≤28.0
Single Firing Time (s)	≥700
Accumulated Firing Time (s)	≥2400
Restarts	≥10
Nominal Inlet Pressure (barA)	7.0 ±0.5
Length Flange to Exit[5] (mm)	880
Diameter at Nozzle Exit[5] (mm)	499.4
Nozzle Area Ratio[5]	258:1
Thrust vector alignment (deg)	±0.25
Interface Flange Diameter (mm)	140
Upper Envelope Outer Dimensions (H x L x W mm)	350 x 540 x 400
Engine mass without EPS[6] (kg)	27.7
Engine mass with EPS[6] (kg)	47.3
Clustering[7]	YES (100 mm nozzle-to-nozzle distance)
TVC compatible[8]	N/A
Other fluidic needs	Helium gas
Helium mass flow while firing (g/s)	≤0.02
Helium mass flow while purging (g/s)	0.5
Purge duration (s)	30
Operating Temperature (°C)	0 to 30
Propellant Temperature (°C)	0 to 30

DOI: 10.13009/EUCASS2023-766

Storage Temperature (°C)	-20 to 80
Lifetime on ground (years)	4
Lifetime in space (years)	6
Reliability[9]	≥0.9993 at 60% confidence
Engine Qualification Date	Engine under development. Due for Qualification in 2026.
Man Rating[10]	N/A
First Flight	2030
Quantity Delivered	N/A – In development

[1]*NOP: Nominal Operating Point (6000 N)*
[2]*The current target is for the High Performance Engine to achieve at least 50% of thrust decrease from the nominal thrust, with also an overthrust capability to 7000 N.*
[3]*This value represents the cumulated power need for both the fuel and oxidizer e-pumps*
[4]*OTP: Over Thrust Point (7000 N)*
[5]*This corresponds to option 1 in the nozzle selection.*
[6]*EPS stands for Electric Pump Systems, and their mass corresponds to all components highlighted under R2 in the product tree. See Table 1.*
[7]*RELIANCE is designed to be compatible with clustering of multiple engines – feasible engine-to-engine distance TBC by nozzle option selection and thermal analysis.*
[8]*Thrust Vector Control (TVC) has not yet been part of the design, but could be later implemented.*
[9]*Reliability is defined here as the reliability to have a single engine out, not functioning for example when it is operated within a cluster of multiple engines.*
[10]*Man-rating has not yet been part of the design, but could be later implemented.*

The main characteristics of the RELIANCE flight engine provided in Table 2 illustrate the current expectations in terms of future RELIANCE flight engine characteristics and performance, based on the design effort completed for Baseline Design Review (BDR), which was held in October 2022. Many of these numbers may still evolve in the upcoming phases of the engine development and the upcoming PDR; hence, most of them should be understood at this stage with To Be Confirmed (TBC) status. These numbers are valuable input to Argonaut system design and to the finalization of the RELIANCE specifications to be performed at the PDR.

2.7 Design

At BDR, Nammo chose to design the engine system in a modular way, with a tubular outer structural frame in Titanium holding all the engine components separately, as a first step towards the flight model (left picture on Figure 7). In doing so, all the component models could be progressed separately and in parallel, and later included in a common assembly. That was the first time that all components are included in the CAD design. This significant step provided a first validation of the overall system integration and highlighted the specific design constraints for this engine design.

Since the Baseline Design Review (BDR) and on the path to the Preliminary Design Review (PDR), Nammo has been working on a new evolution of the flight engine design (right picture on Figure 7). This new design is more compact (smaller occupied volume), more integrated (displaying a higher degree of design integration between internal parts and components), and is designed to achieve the system mass target outlined at BDR.

The main change is that instead of a tubular frame structure built outside in, Nammo has designed a singular support structure built inside out. The new structure, colored in yellow on the right picture in Figure 7, has multiple roles. It is responsible for mechanical interface with the spacecraft at the top. It also interfaces structurally with thrust chamber assembly, valves and control boxes. The piping is currently still free floating at this stage, but will be attached to this structure by means of small brackets soon to be designed as well. The position of the main external interfaces such as the fluidic interfaces for example located at the top, have not changed. It should be mentioned that this latest design of the engine is ongoing, which has yet to be validated by a complete analysis loop. Nammo is still gathering dimensional and mechanical environment requirements at this stage, and is planning to perform multiple analysis loops later this year in preparation for the PDR, where several iterations of this design are foreseen.

DOI: 10.13009/EUCASS2023-766

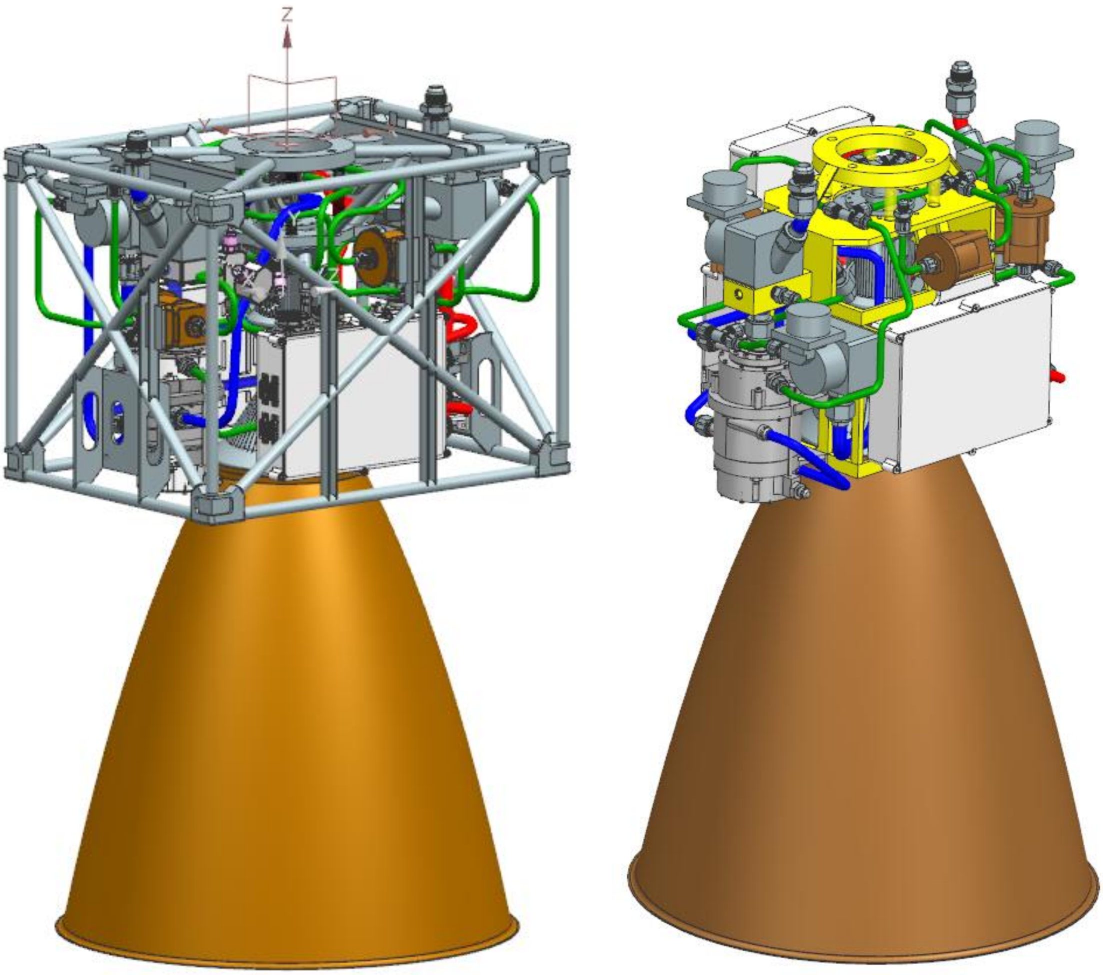

Figure 7: BDR design (left) and latest design (right)

The main improvement, apart from the lower mass and improved stiffness, is the reduced volume occupancy of this new design. There is still some further room for improvement, which will be exploited at a later stage in a more detailed integration effort, in the lead up to the PDR.

2.8 Nozzle options

Nammo has analyzed multiple nozzle design options at BDR, at the request of ESA. Nammo has included option 1 (the smaller one) in the main engine characteristics Table 2 as it is the one based on current ESA requirements. Two other larger nozzle options have then been designed and evaluated: option 2 for larger nozzle at 1000 mm, and option 3 for an even larger nozzle reaching an engine length of 1100 mm. The three options are compared side-by-side on Figure 8. Nammo will continue to analyze with primes which nozzle option is to be preferred based on the evolving constraints in terms of engine length, diameter and performance targets.

Table 3: Overview of the three nozzle profile options analysed for RELIANCE at NOP

Nozzle profile	Area ratio	Exit OD (mm)	Engine length (mm)	Isp delta (s)	Mass delta (kg)
Option 1	258	499.4	880	0.0 (ref.)	0.0 (ref.)
Option 2	356	583.5	1000	+2.1	+1.2
Option 3	438	645.3	1100	+3.4	+2.4

DOI: 10.13009/EUCASS2023-766

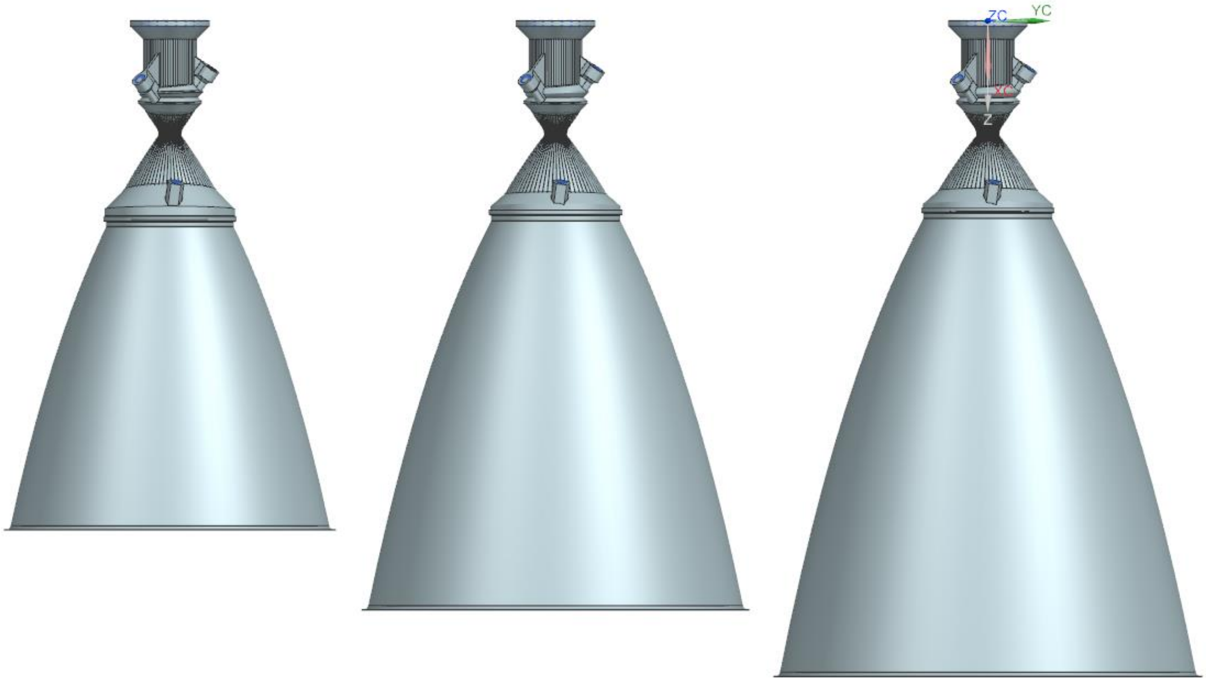

Figure 8: Comparison of RELIANCE nozzle options (from left to right: 1, 2 and 3) side view

2.9 Control architecture

What sets apart RELIANCE from other traditional engines, is the fact that the propellant feed power generation has been fully electrified. Two electric pump systems are responsible for raising propellant pressures and controlling the propellant mass flows in order to deliver both the high performance and the large throttling range. That demands a new electrical control architecture, and the introduction of a centralized engine controller. As is shown on Figure 9, the engine controller receives low voltage unregulated 28V power and communicates with the MIL1553 standard with the spacecraft on-board computer (OBC) on the one hand, and directly controls all electrical equipment within the engine system (electric-pump systems, valves and sensors) on the other hand.

In traditional engines, both turbopump-fed and pressure-fed, the thermodynamic balance in temperature and pressure regulates the operation of the engine and dictates its achievable performance. In electrified engines, it is rather the electronics that drive performance and define which engine characteristics can be achieved. In the case of RELIANCE, the way in which power available from batteries can be delivered to the propellant by the electric pumps controller and motor is the limiting factor for engine performance and sets the achievable specific impulse, throttle rate and throttle precision targets. Any future improvement in electronics, whether in battery design, controller (inverter) design or electric motor design will be able to be directly transformed into improved engine performance through lower mass or other improved performance metrics (response times, stability, controllability, etc.).

The RELIANCE engine controller, built of both hardware and software, is in many ways the heart of the engine system. It must manage the operational modes of the engine and make sure the system can pass through multiple gates in order to perform its mission. It must receive commands from the OBC in almost all situations and be able to understand and implement them, which often means a complex choreography of valves and pumps movements. It must monitor the engine is performing as intended at all times, remaining within the desired mixture ratio range, stability parameters, thrust targets, pressure and temperature limits, etc. It must collect data from all sensors, use it to perform its functions, and send a telemetry package to the OBC at regular intervals like a heartbeat, to show the controller is still running. It must finally be able to handle failure detection, isolation and recovery, avoiding at all costs an unwanted engine shutdown, which would mean in the Moon landing scenario, the terrible outcome that is overall mission failure. For all these reasons, the engine controller is an integral part of the engine system, and it will be developed and qualified together with the overall engine system.

DOI: 10.13009/EUCASS2023-766

As of now, the control approach for reaching the targeted thrust is in open loop. It means that a look-up table will have to be generated through engine testing on ground and then introduced as data in the engine controller. Based on the thrust command, the engine controller will then read in the look-up table what parameters it must enforce throughout the system (such as for example pump rotational speeds) to achieve the targeted thrust. Combined testing with the Breadboard engine and electric pumps will show whether this approach can yield satisfactory precision for the mission.

In case the thrust precision needs to be further improved, a closed loop approach is also being envisaged by Nammo. The engine controller would then use each propellant feed pressures, measured as close to the injector as possible, to direct the rotational speed of the electric pumps. These engine pressures (or the chamber pressure itself if it can be made available in flight, which is not guaranteed) would then function as the closest indicator to engine thrust. Closed loop system bring an added level of complexity, which should not be underestimated, but is expected to provide, when it is well-tuned, improved levels of precision while requiring less extensive testing on ground to collect data. In theory, the engine would itself be able to learn and adapt better than any calibration would.

As previously mentioned, the MIL1553 standard has been defined for communications between the engine controller and the OBC. The context and interface diagram in Figure 9 makes clear what is within the scope and perimeter of the RELIANCE system in terms of electronics, as well as the various interfaces being considered and discussed for this engine. For higher reliability, it is expected that each of the external interfaces for power and communication between the RELIANCE system and the spacecraft will have to have both a nominal and a redundant connection.

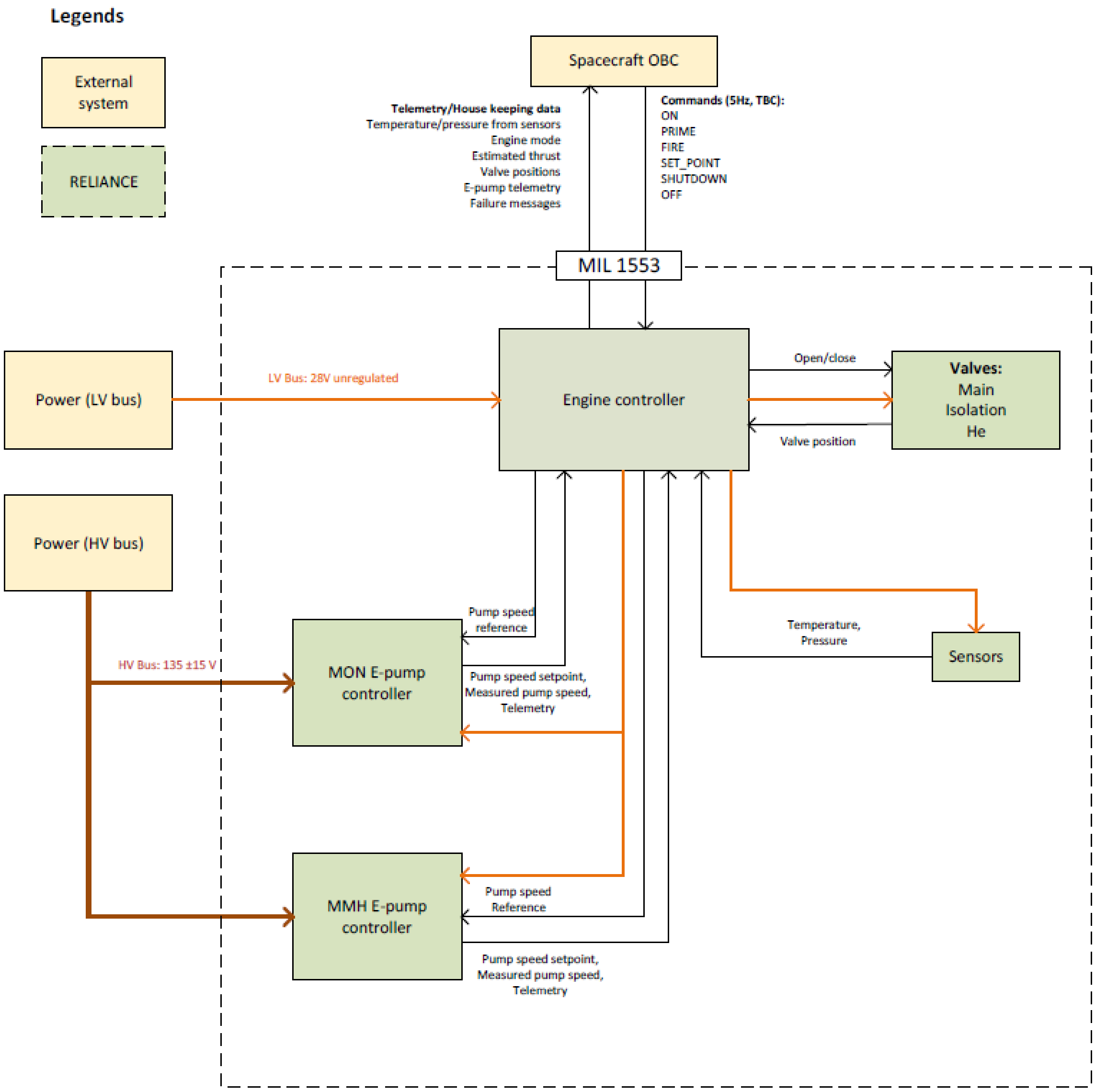

Figure 9: RELIANCE electrical context and interface diagram

DOI: 10.13009/EUCASS2023-766

3. Acknowledgements

The work discussed in this article was conducted under a programme of and funded by the European Space Agency. Nammo would like to thank the European Space Agency (ESA) for their financial, managerial and technical support on this program, as well as for the confidence they place in Nammo to lead this program to success.

Nammo would like to thank also the involved national space agencies UKSA, NOSA, ASI and the Czech Space Office for providing financial support to the RELIANCE engine development program.

Nammo would like to thank the two candidate primes for Argonaut, Airbus Defence and Space (ADS) and Thales Alenia Space (TAS) for their continuous collaboration and technical guidance to ensure the success of the RELIANCE development program.

4. Conclusion

In this article were presented first the programmatic context of the RELIANCE engine development program, starting from the international collaboration, presenting Argonaut, ESA's lunar lander and the High Performance Engine. Second, Nammo presented the RELIANCE engine system: development approach and status, selected concept, system schematic, product tree, industrial consortium, main characteristics, design, nozzle options and control architecture.

RELIANCE is a groundbreaking new engine development in the medium thrust class, which aims to enable the first European lunar lander vehicle, Argonaut. It makes use of multiple innovative European technologies such as electric pumps, additive manufacturing and pintle injector in order to deliver an engine with completely new capabilities to ESA's exploration program.

The RELIANCE development is progressing as planned. The Breadboard engine will be hot fired in the fall in 2023, and shortly followed by combined tests with Breadboard electric pumps and engine. The Key Engine Selection Point will take place in December 2023, deciding whether the program can proceed to subsequent Phases C, D and E. The RELIANCE Preliminary Design Review will be held in Q2 2024, and it will be another very important milestone towards a first Moon landing that Nammo hopes will be powered by RELIANCE in 2030.

References

[1] International Space Exploration Coordination Group, The Global Exploration Roadmap supplement, Oct. 2022, https://www.globalspaceexploration.org/wp-content/isecg/GER_Supplement_Update_2022.pdf
[2] European Space Agency web page on Argonaut https://www.esa.int/Science_Exploration/Human_and_Robotic_Exploration/Exploration/Argonaut
[3] Boiron et al., RELIANCE, a throttleable and e-pump-fed bi-propellant engine for exploration missions, Presented at Space Propulsion Conference 2022 in Estoril, Portugal, SP2022_146
[4] Elverum, G. TRW – Lunar Descent Engine. Remembering the Giants: Apollo Rocket Propulsion Development, Document ID 20100027320, November 2009
[5] Vaughan, D., Nakazono, B. & Preudhomme, M. Propulsion system options for a Potential Mars Sample Return Lander (SRL) for Mars. Presented at Space Propulsion Conference 2018 in Seville, Spain. SP2018_00401.
[6] ECSS-E-AS-11C – Adoption Notice of ISO 16290, Space systems – Definition of the Technology Readiness Levels (TRLs) and their criteria of assessment (1 October 2014)
[7] ECSS-M-ST-10C Rev.1 – Project planning and implementation (6 March 2009)
[8] LEROS 4 Interplanetary Engine web page on the Nammo web site https://www.nammo.com/product/leros-4/
[9] Liggieri et al., RELIANCE – Design, Manufacturing and Testing of the Breadboard Engine, Presented at Aerospace Europe Conference 2023 in Lausanne, Switzerland. ID 501.

Disclaimer:
The view expressed herein can in no way be taken to reflect the official opinion of the European Space Agency.