DOI: 10.13009/EUCASS2023-470
Aerospace Europe Conference 2023 – 10TH EUCASS – 9TH CEAS

RELIANCE - Design, Manufacturing and Testing of the Breadboard Engine

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

Abstract

RELIANCE is a 6kN liquid rocket engine using hypergolic propellants (MON-3 and MMH). Its first target application is as main propulsion for ESA's lunar lander, Argonaut. New technologies such as electric pumps, additive manufacturing, advanced physics modelling and high precision control will provide an engine with completely new capabilities.

The Breadboard Engine is the first full-scale model of RELIANCE to be designed, manufactured and tested. It will validate critical functions such as high performance and stability at all operating points, wide throttleability, full control and high precision in thrust regulation and ignition in vacuum. The goal is to reach TRL5 in 2023.

1. Introduction

1.1 Background

Within the framework of the European Exploration Envelope Programme (E3P) of the European Space Agency (ESA), Nammo (UK, Norway) is in charge of the RELIANCE (Rocket Engine for Lunar and Interplanetary Anglo Norwegian Commercial Exploration) pre-development.

RELIANCE is an ESA supported development of a new generation bi-propellant rocket engine in the medium thrust class (6kN nominal vacuum thrust) using classical hypergolic propellants (MON-3 as oxidiser and MMH as fuel). Its target application is main propulsion as a cluster of engines on ESA's Argonaut mission, previously named the European Large Logistics Lander (EL3).

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 electric-pump driven cycle will provide:

- High performance (higher than 330s of Isp at the 6kN 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 fixed 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.

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The RELIANCE engine 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 safely perform a large number of restarts (at least 10) and also be stored for long durations of time in space at low temperatures, without risk of the propellant freezing.

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 of the Breadboard Engine testing is to reach TRL5 in RELIANCE engine development and provide adequate results and data to successfully perform the Preliminary Design Review of RELIANCE (PDR-F) at the end of the pre-development phase of this activity.

The scope of the Breadboard Engine is limited to the thrust chamber assembly, including the injector and regeneratively-cooled combustion chamber. It is designed so that its main characteristics will be representative of the RELIANCE flight model, including the (additive) manufacturing process.

The Breadboard Engine is designed for 45 bar chamber pressure as in the flight model, corresponding to about 4700N of thrust at sea level for an expansion ratio of 4.95:1 and to an Isp at the nominal point of 249s at sea level.

In terms of design, the Breadboard engine includes a liquid-liquid fixed pintle injector that will provide good performance and stable operation over all the wide throttle range. The combustion chamber will be regeneratively cooled by axial channels running along the walls of the chamber in a dual configuration (both oxidizer and fuel are used along different portions of the thrust chamber). In addition, part of the fuel will be injected through specific holes to provide film cooling to the chamber. A fully regeneratively cooled nozzle will be designed for atmospheric testing (no vacuum testing is planned at Breadboard-level). The radiatively-cooled nozzle extension, needed for the vacuum design, is therefore not included in the Breadboard Engine.

The Breadboard Engine testing will not include electric pumps in the first instance. The E-pump system will be developed and tested separately before being included in the engine system testing. In the meantime, to allow Breadboard Engine testing at the right conditions without E-pumps, a high-pressure and high thrust test facility is being built at Nammo UK: the J4 test site. The test facility will be able to provide both hypergolic propellants to the Breadboard with the same mass flows (delivering up to 7kN thrust) and pressures (up to 90 bar) as would come at the outlets of the electric pumps. Throttle valves will be also included, enabling the testing of the throttleability of the engine. This approach helps manage risk and progress faster, by being able to test the Breadboard Engine in high-pressure-fed mode without the E-pumps first, and to progress safely to E-pump testing afterwards. Moreover, it should be mentioned that this test facility will also include throttle valves, capable of throttling the engine without the E-pumps. Finally, the test facility will also include a purging system to test and demonstrate the purging procedure as is planned to use on-board the Flight Engine.

The Breadboard test campaign aims to validate the critical functions of the engine such as performance and stability at all operating points, throttleability capabilities and ignition in vacuum.

The following chapters will present the status of the RELIANCE Breadboard Engine; its design, with focus on the key components (pintle injector and the regeneratively-cooled chamber), its manufacturing process and all the steps that will lead to its hot fire test campaign in Q4 2023.

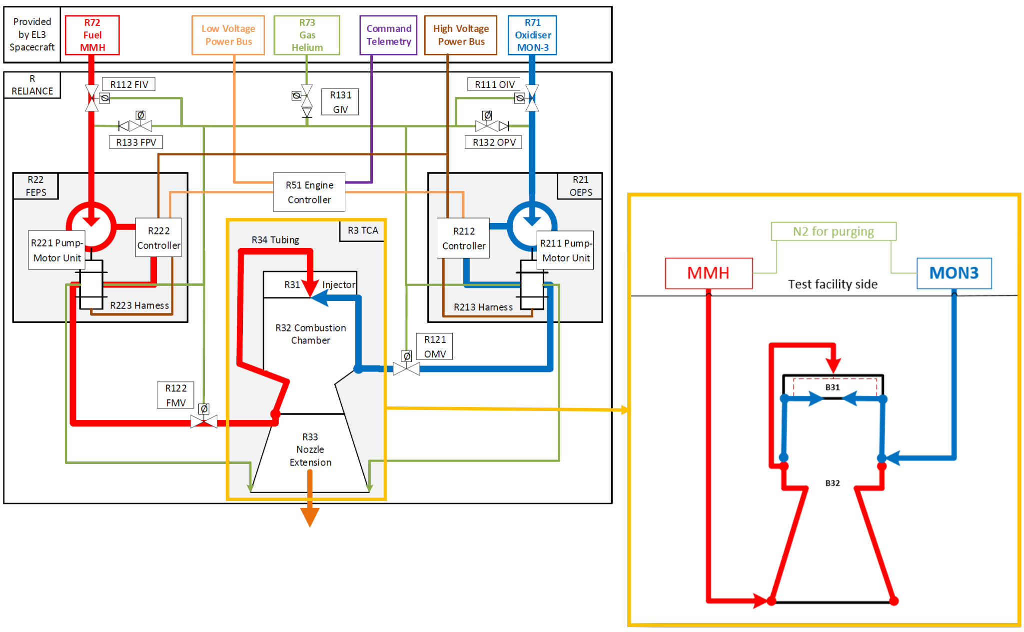

Figure 1: Breadboard Engine Schematic (right) Extracted from RELIANCE Engine Schematic (left)

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1.2 RELIANCE Development Approach

The development approach for RELIANCE is very much in line with system engineering standards used in the industry, which are notably described by ECSS. RELIANCE is now 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 covered by a previous 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 SRR 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 is followed as shown below in Figure 2. It starts with Flight Engine requirements, which allows the initiation of activities simultaneously both at Breadboard component-level and Breadboard Engine-level. During Phase 1, the Breadboard component "V" loop was 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.

In terms of hardware models, the approach would be as follows:

- Phase (B)1: Component hardware models manufacturing and testing => Reach TRL4
- Phase (B)2: Breadboard Engine hardware model manufacturing and testing => Reach TRL5

RELIANCE has successfully passed the Critical Design Review of the Breadboard Engine (CDR-B) in May 2023 and is moving towards Breadboard testing by the end of 2023.

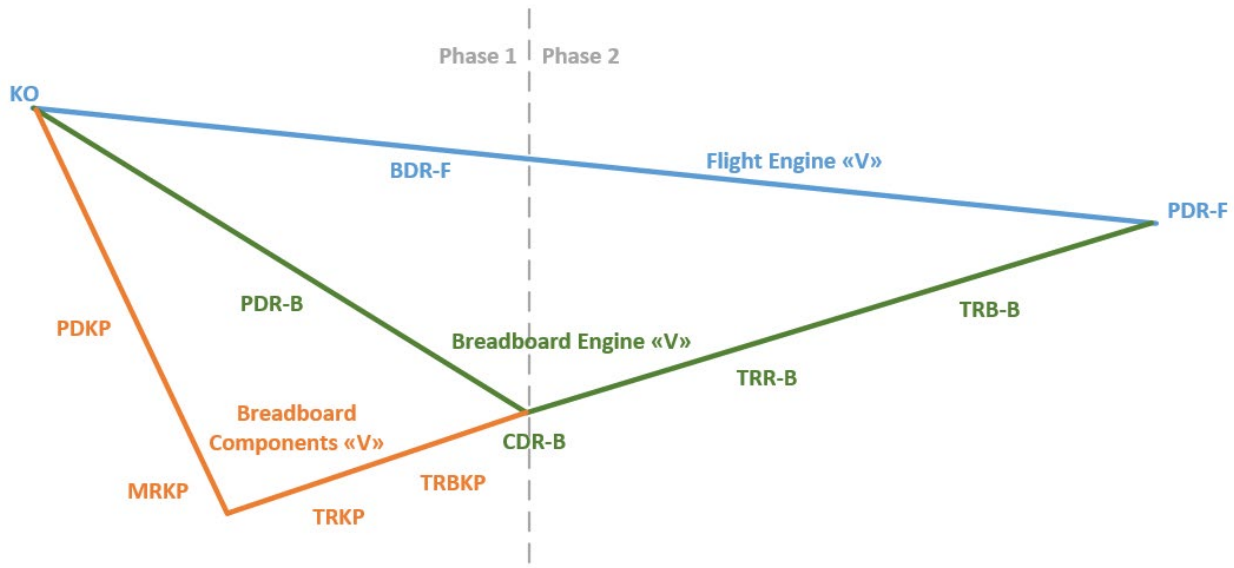

Figure 2: RELIANCE Development Approach

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2. Breadboard Engine

2.1 Main Requirements

Table 1 outlines the main specifications extracted from the Breadboard Engine Technical Specification.

Table 1: Main Requirements for the Breadboard Engine

Reference	Title	Text
B-001-D	Fuel	The engine shall use MMH as fuel in accordance with standard MIL-PRF-27404D.
B-002-D	Oxidizer	The engine shall use MON-3 as oxidizer in accordance with standard MIL-PRF-26539G.
B-003-F	Nominal Chamber Pressure	The engine shall have a chamber pressure of 45 ± 5% barA at the nominal operating point (NOP). Note: 45 bar is the chamber pressure at NOP chosen for the Breadboard and baseline design of the Flight Engine.
B-004-F	Up throttleability	The engine shall be able to throttle up in the full range from 100% of NOP (B-003-F) to 117% of NOP (53 ± 5% barA) (TBC). Note: 53 bar is the chamber pressure at maximum thrust point for the Breadboard and baseline design of the Flight Engine.
B-006-F	Nominal mixture ratio	The engine shall operate with a nominal mixture ratio (oxidizer to fuel ratio) of 1.82 ± 0.05 at NOP.
B-007-F	Down throttleability	The engine shall be able to throttle down in the full range from 50% of NOP (23.4 ± 5% barA) to 100% of NOP (B-003-F) (TBC). Note: 23.4 bar is the chamber pressure at minimum thrust point for the Breadboard and baseline design of the Flight Engine.

2.2 Selected Concept

The Breadboard Engine is a bolt-up sea level liquid-liquid "high-pressure fed" engine (fed from the test facility where it will be tested), where both propellants are used to regeneratively cool the combustion chamber and nozzle. This is shown in Figure 3.

The MMH fuel is first injected into a manifold located at the Breadboard Engine nozzle exit. The fuel then flows upwards along the nozzle divergent, throat section and nozzle convergent until another manifold located at the beginning of the chamber cylindrical section. It exits the manifold and a pipe section then brings it to the top of the head end.

The oxidiser inlet manifold is located next to the fuel exit manifold, where MON oxidiser enters and flows upwards along the chamber cylindrical wall. At the top of the chamber, it reaches a manifold inside the engine head-end, flows along the top of the chamber providing additional cooling, and is then directed towards the pintle injector.

The fuel coming in at the top of the head end is separated in two; a small percentage goes to a series of holes along the chamber wall to provide fuel film cooling (FFC) and the remaining and majority of the flow, called the core flow, is then injected by the pintle injector, impinging against the incoming oxidiser.

The Breadboard Engine design is fully modular, allowing the exchange and inspection of parts between firings and the possibility to adjust the fuel film cooling or pintle injector parameters if necessary. To enable this, spare blanks, particularly of the injector assembly, will be produced beforehand, leaving only the critical injector surfaces unfinished. If any of the test campaigns conclude that any dimensions need urgent alteration, then a blank can be used and quickly modified in less time than is required to start from the un-machined stock material.

Another specificity of the Breadboard Engine is its rather long and low angle conical nozzle. This concept was chosen to have a representative cooling channel length on the Breadboard that provides the same heat to the fuel as in the Flight Engine, hence resulting in the same propellant injector inlet temperatures and cooling jacket performance. It also provides more room for instrumentation and manifolds without causing structural concerns.

Figure 3 shows the CAD model of the Breadboard Engine without any fitting, tubing or instrumentation. Down to the right of the motor, at the nozzle exit, the inlet of the MMH to the cooling jacket is visible. In the middle, there are two

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rings that surround the engine; these are the MMH outlet from the cooling jacket (lowest) and the MON-3 inlet to the cooling jacket (upper) respectively.

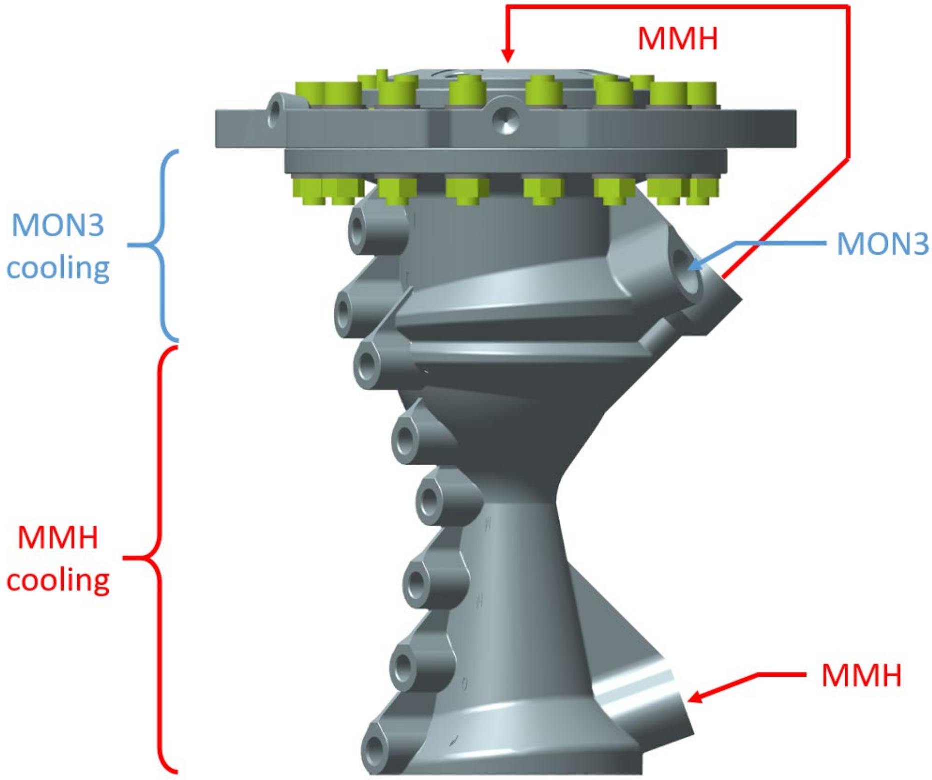

Figure 3: View of the Breadboard Engine without Tubing or Instrumentation

2.3 Main Characteristics

Since the Breadboard Engine is built to be representative of the Flight Engine, the main characteristics and design parameters are very similar to those of the flight model:

- **Liquid-liquid pintle injector:** as with the Flight Engine, the baseline for the Breadboard Engine is a fixed pintle injector. The wide throttleability will be explored through testing of the Breadboard Engine at different thrust levels.
- **Regeneratively-cooled combustion chamber:** as with the Flight Engine, the chamber will use axial cooling channels running along the walls of the chamber and will be additively manufactured.
- **Nozzle skirt:** the Breadboard Engine will make use of a sea level 'expansion cone', which is a part of the chamber, and will therefore not make use of a nozzle skirt.
- **E-pumps:** the Breadboard Engine will be tested first in a pressure-fed configuration, and later with the two Breadboard E-pump systems.
- **Propellant valves:** the test facility is responsible for providing different mass flow and pressure levels to throttle the engine. The Breadboard Engine will not have any valves within its perimeter, the main valves have been transferred to the test facility for easier interface control.
- **Chamber pressure:** the Breadboard Engine is designed for 45 bar chamber pressure at the nominal operating point.
- **Thrust level:** the Breadboard Engine will target 6000N vacuum thrust level as the nominal point, which would correspond to about 4600N of thrust at sea-level for an expansion ratio of 4.95:1 (to limit separation in throttling down conditions).
- **Isp level:** the calculated delivered sea level Isp at the nominal point is 249s.

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The performance of the Breadboard Engine has been derived from an equivalent 6000N vacuum thrust engine design, keeping propellant mass flows, chamber pressure and chamber/injector design identical, while adjusting the nozzle design and expansion ratio due to the atmospheric firing environment.

The nozzle of the Breadboard has been designed with an expansion ratio of 4.95:1, which will allow to potentially test the Breadboard chamber and nozzle down to about 25% of NOP without incurring any nozzle separation.

It should be noted as well that the test facility is foreseen to be able to deliver propellants to the Breadboard Engine in line with its technical requirements (mass flows, start-up, throttling).

A summary of the main characteristics, including performances, size and mass of the engine, is given in Table 2.

Table 2: Breadboard Engine Data Sheet

ENGINE CHARACTERISTIC	VALUE
Typical Application	Testing
Operating Modes	Ramp-up, Screening, Comprehensive tests
Propellants	MON-3/MMH
Thrust @NOP (N)	4584
Thrust range (N)	2292 to 5399
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
Chamber Pressure Range (barA)	22.2 to 53
Vacuum Specific Impulse @NOP (s)	249
Single Firing Time (s)	≤240s
Accumulated Firing Time (s)	≥1010
Restarts	≥10
Nominal Inlet Pressure (barA)	70.9/75.3
Length Flange to Exit (mm)	531.8
Engine Length (mm)	426.1
Thrust Chamber Assembly (TCA) Length (mm)	245.8
Outer Diameter Head End Flange (mm)	202
Outer Diameter at Nozzle Throat (mm)	34.9
Diameter at Nozzle Exit (mm)	95
Nozzle Area Ratio	4.95
TCA Envelope Outer Dimensions (mm)	426.1 x 202 x 202
Engine mass (kg)	33.23
TCA mass (kg)	15.17
Other fluidic needs	Nitrogen gas
Purge duration (s)	10 to 30
Propellant Temperature (°C)	20 ± 5
First Test	Q4 2023

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3. Design

3.1 Injector Assembly

The injector to be used in the Breadboard Engine is a pintle injector. Figure 4 shows a section of the Injector assembly with all its different components. The main parts are described hereafter.

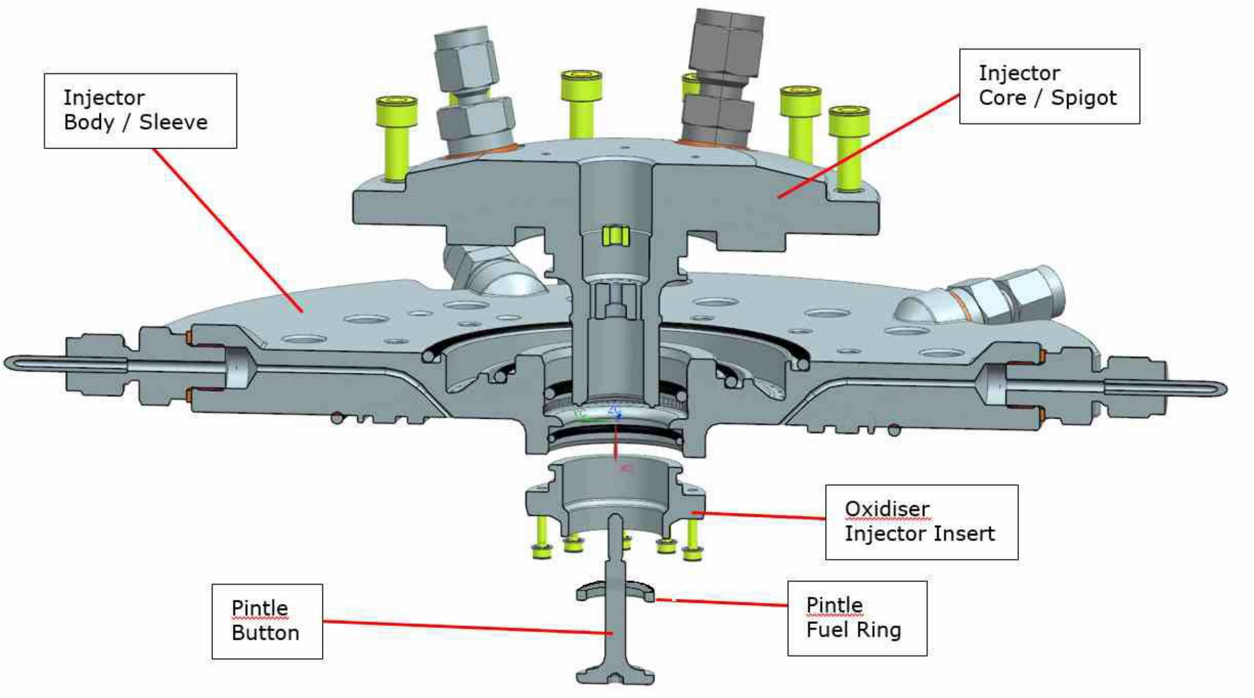

Figure 4: Exploded View of the Injector Assembly

Button - its purpose is to create, together with the spigot and the fuel ring, the flow passage for the fuel in the injector. The fuel injection area is very important for the achieved performance of the engine, since it determines the fuel pressure drop and injection velocity. This part is not movable, and is fixed on the top by a lock nut. Given its simplicity, this part will be conventionally machined. The lower end of the button will be subject to high temperatures coming from the combustion and needs therefore to be made of a material that is highly resistant to heat.

Fuel Ring – its purpose is to define the spoke injection area. This part is locked between the button and spigot, leaving openings that define the fuel injection areas. This part will also be conventionally machined.

Spigot – one of its primary purposes is to, together with the sleeve and the oxidiser insert, create the flow passage for the oxidiser in the injector. The oxidiser injection area is also very important for the achieved performance of the engine, since it determines the oxidiser pressure drop and injection velocity. It includes the interface for the tube that brings the fuel to the injector from the cooling jacket. The fuel will enter a gallery where it will pass through holes that will distribute the fuel around the pintle locking nut before being directed via the button and fuel ring out in the combustion chamber. Moreover, when mounted with the sleeve, it creates the FFC gallery, where fuel tapped off the main propellant line enters before passing through the FFC holes.

Sleeve Assembly – its main purpose is to create the flow passage for the oxidiser from the combustion chamber to the injector along with the oxidiser insert. This part is planned to be additively manufactured given its complexity. When the AM process is concluded, it will be further machined.

Oxidiser Insert – this part has been separated out for the Breadboard Engine design to allow more rapid injector iterations. Its primary purpose is to form the annular oxidiser injector flow-path (both oxidiser restrictor and injector) in conjunction with the spigot when connected to the sleeve. The part will be also be additively manufactured.

Sealing - due to the bolt-up configuration of the Breadboard Engine, sealing elements are needed. Since there are two hypergolic propellants flowing, the first goal of the seals is to prevent unwanted mixture of the two propellants before they enter the combustion chamber. The second goal is to prevent leakage to the surroundings. In addition, sealing

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elements are needed between the injector and combustion chamber to prevent leakage of the combustion gasses to the surroundings.

When designing a pintle injector. Some key parameters have to be taken into account. These are summarized below.

Fuel or Oxidiser Centred – Given the flow rates and densities of the propellants being used, a Fuel centred pintle has been selected.

Total Momentum Ratio (TMR) – For the slotted type pintle injector a TMR value of 1 provides optimum performance according to literature and is used to define the injector dimensions. However, the Breadboard testing will still allow testing of multiple TMR.

Injection Velocities – This is the velocity at which the propellants are injected into the chamber. Literature suggests the propellant injection velocities should be in the range of 10m/s to 50m/s. This is a parameter that contributes and affects the achieved TMR of the engine. Injection velocities should be high enough to encourage good mixing of the two propellant flows. In the case of the fuel centred propellant flow, a higher fuel injection velocity may help to promote break-through and the persistence of fuel out towards the chamber wall. This is beneficial from a chamber cooling perspective.

Chamber ID to Pintle OD Ratio – Literature suggests that this value should be between 3 to 5, and biasing this value towards 5 should help reduce the heat flux on to the chamber wall.

Slotted Radial Injection Vs Spoke Radial Injection – Tests performed at subscale level showed a better performance of a discretised “spoke” design. As a result, the spoke design has been adopted for the Breadboard injector design.

Pressure Drop – Pressure drop across the fuel and the oxidiser sides of the pintle injector is a critical parameter when considering feed system coupled instability and particularly relevant when the engine is in its throttle down condition. A generally agreed rule is that the pressure drop across the injector should be ≥20% of the chamber pressure i.e. if the chamber pressure is 10 bar then the pressure drop across the injector should be ≥2.0 bar. Liquid injector pressure drops tend to reduce almost proportionally to throttle setting. Therefore, for a fixed injector geometry, and to stay within stability guidelines, for this engine to be capable of throttling down to 50%, the design pressure drop across the injectors at 100% should be around 40% of chamber pressure, which should maintain 20% of Pc drop at the lowest throttle.

Skip Distance – The skip distance is the length that the annular flow (i.e. the outer propellant) must travel before impacting the radially injected flow divided by the pintle diameter. A typical value for this parameter is around 1x Pintle Diameter. Subscale test results has suggested that this time of flight could adversely link with the longitudinal mode of the chamber if not carefully selected.

In order to appropriately size these key parameters, extensive use of results obtained at subscale level and CFD analysis has been made to converge on the final Breadboard injector baseline. Nevertheless, as previously mentioned, the modular design and the production of spare blanks will allow for quick modification to this design if needed.

3.2 Combustion Chamber Assembly

The Breadboard combustion chamber has been designed such that it is as representative of the Flight Engine combustion chamber as possible, allowing direct translation from this design into the next phase. It utilises two loops of regenerative cooling: one employing MMH from the nozzle exit to the start of the converging section, and the other covering the cylindrical part employing MON-3 as coolant. The upstream throat design was driven by test data from subscale testing, and internal knowledge of the needed parameters based at Nammo. However, one unavoidable difference between the Breadboard and the Flight Engine is the nozzle design, as the former is designed to be fired at sea level and not in vacuum. This creates the need for a lower expansion ratio order to ensure that the flow is not over-expanded and separates during testing any throttle point. Separation can cause localised increased heat fluxes and therefore is unrealistic of what would be present in the Flight Engine. To this end, the nozzle has been designed for the lowest thrust level of 25% of the NOP. Additionally, the Breadboard Engine utilises a conical nozzle instead of a bell shape as it is often utilised during sea level testing due to its ease of manufacturing. Nonetheless, the Breadboard nozzle had to be designed to receive the same heat flux as the Flight Engine’s additivity manufactured nozzle section, hence resulting in the same propellant injector inlet temperatures and cooling jacket performance.

Once the internal geometry had been set, the cooling loop was firstly defined by the printing limitations. These constraints, along with several analysis loops, ultimately defined counter flowing regenerative cooling channels into the two sections, one MON-3 cooled along the cylindrical section of the chamber and one MMH cooled along convergent, throat and divergent sections.

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Once the cooling jackets configuration had been defined, several analysis loops of the regenerative cooling loop were carried out. This iterative approach included CFD analysis to characterise the flow, thermal analysis to predict expected test temperature, and FEA to analyse the thermal-structural response.

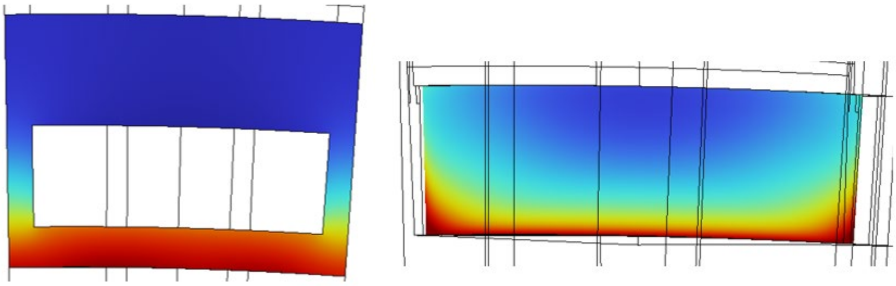

Figure 5: Wall (Left) and Propellant (Right) Temperatures in a Cooling Channel Section after Thermal Analysis

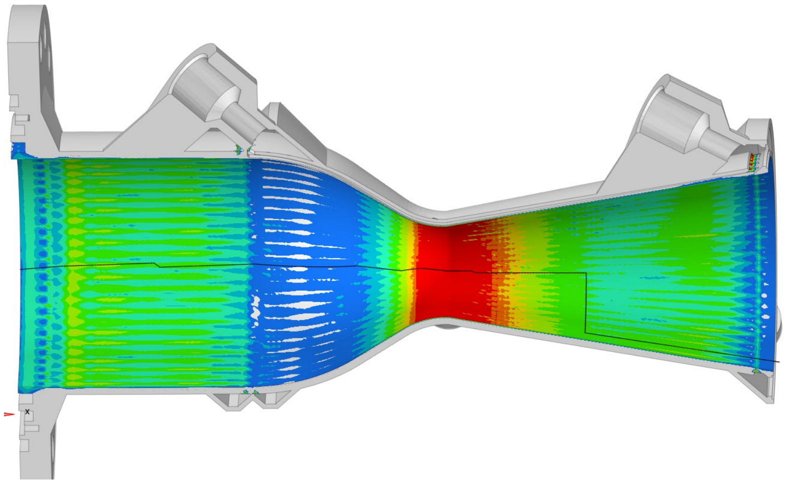

Figure 6: Strain along the Combustion chamber after Structural Analysis

The analysis loop also included the optimization of the manifold design, with the intent of reaching a flow distribution that would be as even as possible within the cooling channels.

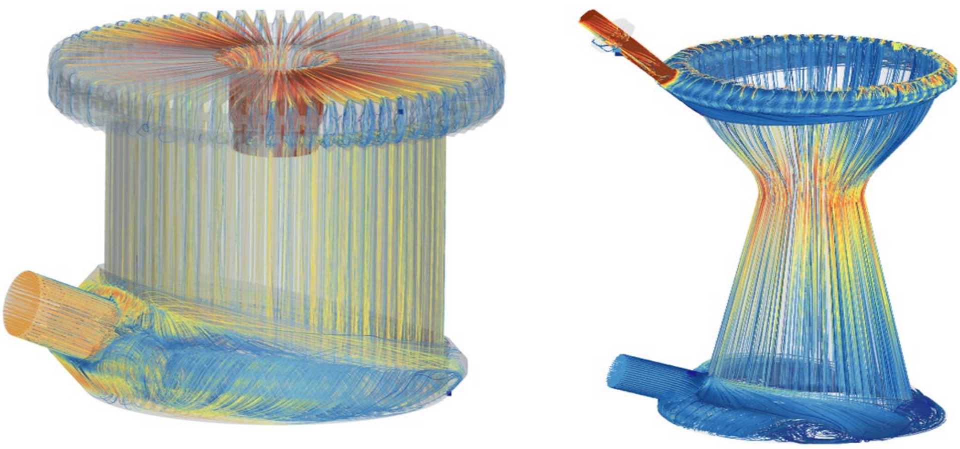

Figure 7: Velocity fields from CFD Analysis in MON-3 (Left) and MMH (Right) Cooling Jackets

Finally, as the chamber is additively manufactured, there are other implications and constraints put on the manifolds design. The most prominent of which is ensuring their design does not remove the ability to depowder each channel individually to ensure there are no powder blockages post printing. This is made harder by the fact that MON-3 and MMH cooling loops must have inlet and outlet manifolds next to each other, as to not have an uncooled section between them. To adapt for this it was decided that the middle manifolds would be printed closed, apart from the one flow port

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in or out, and depowdering take place from the head and exit end of the chamber into each cooling loop. The final design constraint relates again to AM, due to build angles achievable based on overhang limitations that affected for example the manifolds design.

Figure 8: Breadboard Combustion Chamber Final Design

4. Manufacturing

Wherever possible, standard manufacturing techniques will be employed in the build of the RELIANCE engine. However, new technologies, such as **Additive Manufacturing** (AM), will be used for components where there is a clear advantage to use them. This method of manufacturing becomes necessary where geometry is complex or where the use of multiple steps or parts would otherwise be required. AM can be used to keep the piece-part number down and reduce overall complexity of an assembly.

During the RELIANCE subscale phase, significant work was put into designing and validating the AM build process. This included defining and trialing the steps required to take the part from the as-printed build plate all the way though to being ready to test fire. Many of the lessons learnt are transferable to the Breadboard chamber, specifically with depowdering the printed part before removal from the baseplate, followed by machining, and welding. The primary component where this is required is the regeneratively cooled combustion chamber, allowing for the chamber with integral cooling channels to be produced as a single item. This process does still involve several manufacturing and post processing steps in order to ensure the correct geometry and tolerances are achieved in a repeatable way.

Prior to any printing taking place significant work is put into reviewing and generating the “as-built” CAD to ensure a successful build. This focuses on two main points, firstly on ensuring build angles and overhangs in the model are within buildable limits. This has been explored and Nammo have used a conservative approach and ensured all build angles have a good margin of safety from the build failure point. Secondly, the review process checks for thermal choking points during the build, which is where a rapid change of geometry causes excessive heat loads which don’t have sufficient area paths to dissipate through, and hence cause localised build defects.

One critical area that has been investigated is the ability to correctly and reliably print the internal channels’ geometry, ensuring the dimensions are as expected. Deviation between the input CAD and built piece is expected with the majority of AM components, and especially when internal features are present; as heat flows from the solid built structure into the lose powder left inside the channel causing it to sinter and become part of the structure. This is especially relevant in the chamber’s application as the internal channels are so small. For the Breadboard, a local value approach will be used correcting based on the local channel angle. This approach means the print input CAD combined with the print process gives the desired as-printed chamber with correct internal channel dimensions.

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The work done by Nammo and Alloyed on this topic has resulted in a strong level of confidence in achieving the correct internal channels dimensions, and will be validated through CT scans and pressure drops seen during water flow testing.

One key step in any AM build is **depowdering** the part after the initial build whilst the part is still on the baseplate and before any the heat treatment. This is important as any lose powder left on the part will sinter fully during the heat treatment process and become fused to the part. The cooling channels in a regeneratively cooled engine make this step even more crucial as any powder left in the channels is impossible to remove at a later date and could cause coolant blockages during testing. This could subsequently cause localised or global heating of the chamber depending on the severity, and ultimately lead to the chamber not being cooled sufficiently and melting during testing. In order to correctly remove the powder, the middle manifolds cannot simply be all pressurised because this doesn't guarantee every channel is de-powdered, as once a couple of channels are clear the flow will take the path of least resistance and risk not clearing the others. Having individual feeds into each channel allows for discrete checking of the powder coming out.

The channels will be inspected for remaining powder with a **CT scan**, hence showing if the purging process needs to be repeated or if it is ready to move onto heat treatment. CT scanning is the only feasible way to inspect the internals of the part. In addition to checking for channel blockages, it also allows for checking the internal geometry has printed correctly, focusing on wall integrity and wall thicknesses.

Figure 9: Remaining Powder after a Chamber Print

Every combustion chamber and nozzle Nammo produces undergo a **polishing** process to reach a required surface roughness in order to reduce heat transfer and improve flow conditions. The polishing process mainly concerns the inside of the combustion chamber, with the aim of achieving a very smooth and highly reflective surface, which will reduce conductive and radiative heat transfer respectively. To assess the amount of material removed and achievable surface finish a chamber trial piece has undergone the process, which mirrored the internal chamber profile. This allowed the process to attain to the best achievable finish without limits due to breaking through all the material.

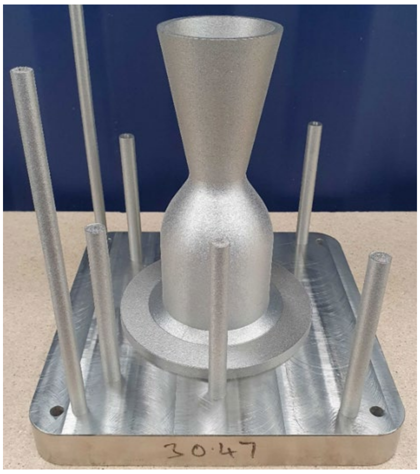

Figure 10: Breadboard Polishing Trial Test Piece

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Once the polishing and channel flow tests are complete, the chamber enters the **machining** step, which focuses on a few specific surfaces. Firstly, the chamber is machined at both ends to allow for sealing interfaces to be constructed between the injector body and the manifold close out plates. Secondly, there are also communication ports, which pass into the active cooling/regenerative cooling channels to allow for the measurement of coolant properties. These, along with the inlet and outlet manifolds ports, are machined flat and tapped to enable connections to be made with good sealing faces.

Once the chamber has been machined, the final process is **welding** the close out plates onto the MMH inlet manifold. The manifold is kept open during the AM step to allow access to individual channels during the depowdering process, as discussed previously. The close out plate is disk shaped and welds via electron beam (EB) welding. The required EB weld parameters vary depending on weld depth penetration and material type. Nammo have experience welding from subscale testing.

The final steps in the chamber development ensure all the processes have been performed as expected and the part is ready for final integration and hot fire testing. Firstly, the CT scanning process is repeated to check internal dimensions and features, the impact of polishing, that there are no defects in the walls, the communication ports are clear and the EB weld depth and quality. Post CT, the chamber undergoes multiple acceptance tests to both check the design is working as expected and ensure the safety of the final part. The former of these is done through water flow tests, first looking at the manifold distribution before characterising the pressure drop down each channel. With the latter taking place using water to perform proof tests, and helium for sealing checks.

The first of the water flow tests will be used to determine if the manifolds are distributing the flow evenly. It will involve flowing water into the MON-3 inlet, and MMH exit manifold, through the channels and out of the open end of each loop. The second test is designed to characterise the pressure drop through the channels and manifolds. This allows for comparison to the predicted pressure drop and any required correction factors to be applied, allowing the set-up to be correctly configured before hot fire testing.

In addition to water flow checks, the chamber and its welds will undergo a proof test carried out with water. This happens when the chamber has been fully machined and involves taking the chamber and channels to 1.5 times Maximum Expected Operating Pressure (MEOP). By recording the pressure inside the engine sections, it can be affirmed that the wall integrity has remained if the water pressure is not decreasing.

After the pressurisation tests, helium gas will be used to perform sealing verification tests by pressurising different sections and monitoring for detection of Helium in sections that should be sealed off from the gas.

5. Testing

For the Breadboard Engine, the critical functions to be validated under testing are:

- The performance of the engine at the nominal point.
- The throttleability capabilities of the engine.
- The off-nominal performance of the engine.
- The stability at different throttle points.
- The ignition in vacuum.

The flow chart in Figure 12 provides an overview of the testing to be performed on the Breadboard Engine.

Both the injector and the combustion chamber assemblies will first go individually through a series of tests including proof, leak and water flow tests. Then, the engine will be fully assembled and proof and leak tests at assembly level will be performed before the hot fire test.

The Breadboard hot fire testing is divided into three main sections: Ramp-up, Screening and Comprehensive testing.

Ramp-up tests provide insight as to how well the component assembly can reach steady state, and withstands the hot fire conditions for short periods without any unexpected outcome. This further assures it is safe to proceed to longer durations of firing. Screening tests will verify the engine against the technical specification criteria to observe if it meets the basic operational requirements for a stated duration. These requirements include but are not limited to, start-up, shutdown, and minimum burn duration. Comprehensive testing will be performed once the previous tests have been performed successfully and all the necessary requirements are met. This testing includes operational box exploration, nominal performance check and extended fire duration.

The preliminary Breadboard Engine test plan includes a total of 25 separate hot fire tests for an accumulated burn duration of over 20 minutes.

DOI: 10.13009/EUCASS2023-470

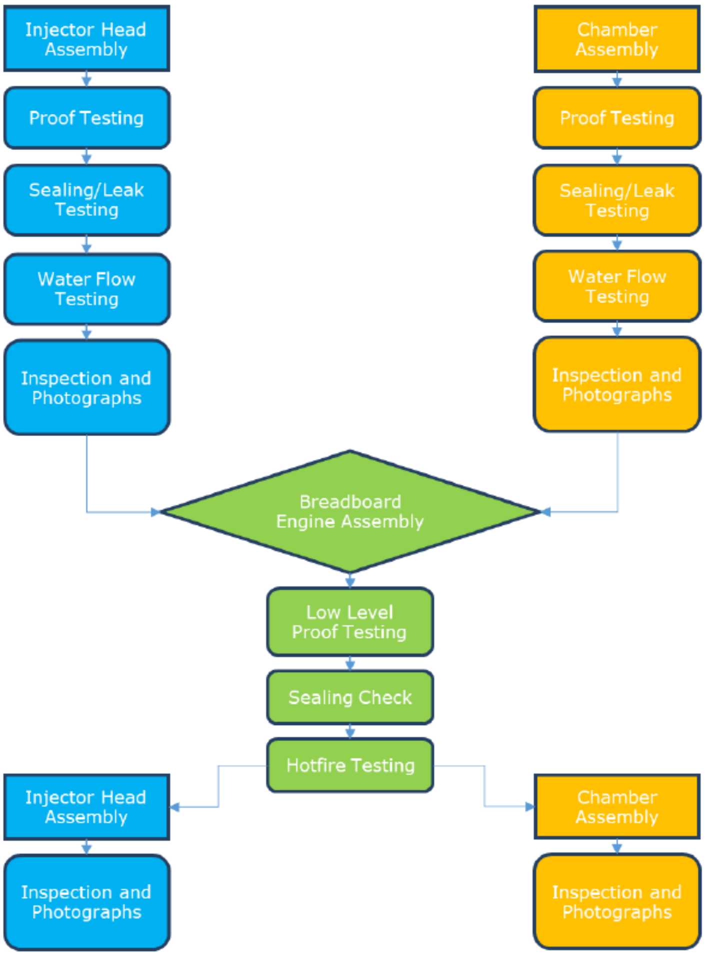

Figure 11: RELIANCE Breadboard Engine Test Flow

The Breadboard Engine will have extensive instrumentation to gather accurate data and validate the models utilized by Nammo. This includes, but is not limited to, measuring line pressure drops, assessing jacket cooling performance, and evaluating pintle injector design. Additionally, it will be equipped with accelerometers in order to assess stability and vibrations in all directions. A low temperature IR camera will also be used on one side of the engine that will be devoid of sensors in order to capture as well further surface temperature data form the chamber.

Finally, the test facility will include multiple sensors to support the operation of the test facility itself. These will also be used to assess engine performance and as input to engine post-test analysis. These will include load cells to measure thrust, Coriolis mass flow meters for both propellant lines, and valve position sensors for the throttle valve and the main engine valves, which will be directed from the test facility control system.

Once the Breadboard engine testing is completed, the Breadboard E-pump systems, which would have been validated by water testing prior, will be then fitted onto the Nammo J4 test site. Propellant functional system testing of Breadboard E-pump systems with MON and MMH will then follow.

After that, the Breadboard engine will be installed back into the test cell in order to perform another test campaign, this time E-pump-fed. The E-pump-fed Breadboard engine testing would reproduce and extend on the testing performed with the engine alone, with a similar level of accumulated firing time.

The Breadboard Engine test campaign is currently planned for Q4 2023.

DOI: 10.13009/EUCASS2023-470

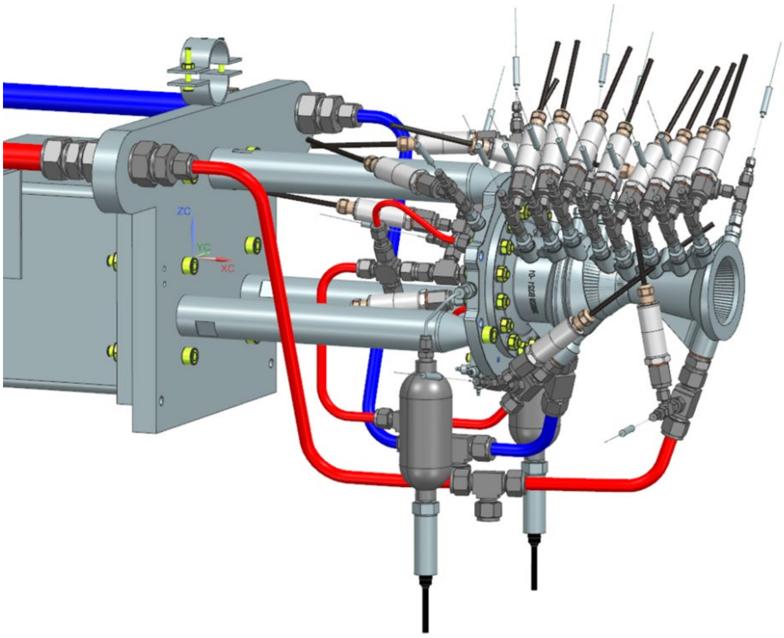

Figure 12: View of the Breadboard Engine CAD Model Attached to the Test Stand

6. Conclusion

RELIANCE is a new and sensational engine development, making use of breakthrough technologies such as electric pumps and additive manufacturing, together with heritage solutions like the pintle injector not yet developed in Europe, in order to deliver an engine with completely new capabilities to the European space programme.

The Breadboard Engine is the first full-scale model of the RELIANCE engine to be designed, manufactured and hot fire tested as part of the RELIANCE development.

Presented in this article were, firstly, the main characteristics of the RELIANCE Breadboard Engine, with particular focus on the engine cycle, technology used and performance achieved. Secondly, a more detailed description of the design of the pintle injector and regeneratively cooled combustion chamber. Later, the manufacturing and processing steps that will lead to the production of the Breadboard hardware are described. Finally, an overview of the test plan is given, with particular focus on the hot fire testing.

The Breadboard Engine successfully completed the Critical Design Review in May 2023 and is currently being manufactured, moving towards full engine testing in Q4 2023. The goal of the Breadboard Engine is to reach TRL5 in and provide adequate results and data to successfully perform the Preliminary Design Review of RELIANCE (PDR-F) at the end of the pre-development Phase of this activity.

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