Case Study
ICSS Kepler-3 Rocket Engine: MetalFab Parts Enable Innovative Design

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Additive Industries

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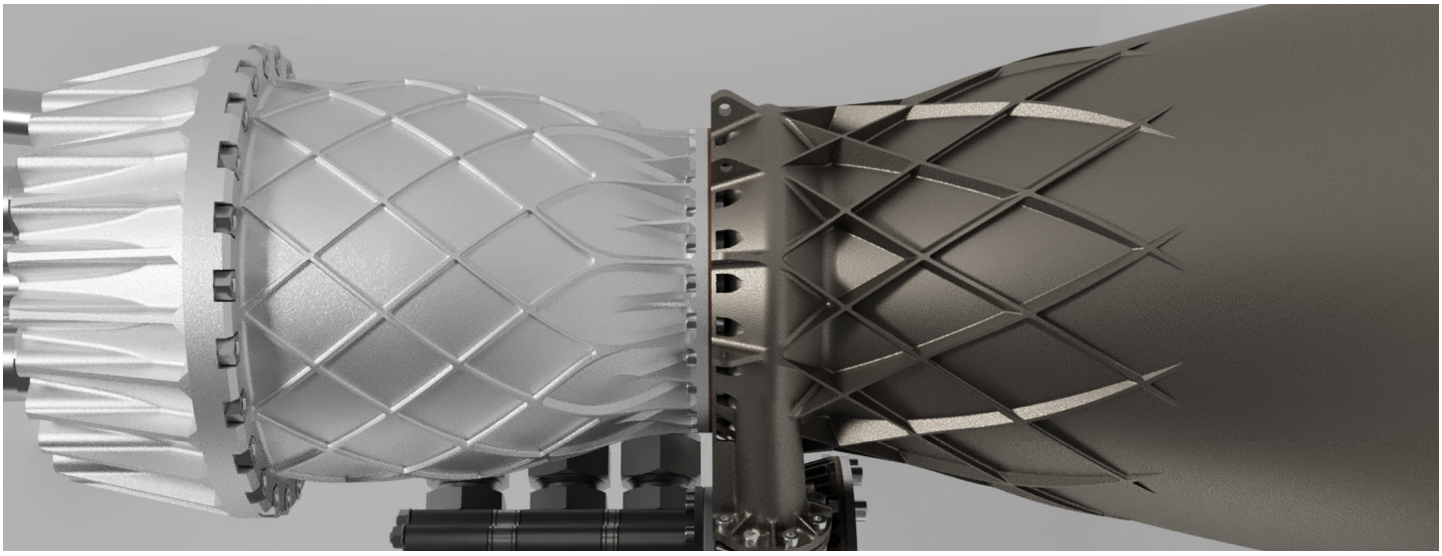
Liquid-fuelled rocket engines are era defining pieces of technology which are powering the space-launch industry, accelerated by the use of metal AM technology. This case study shares the work carried out by Imperial College Space Society (ICSS) aiming to design the world's highest thrust-to-weight ratio bi-propellant liquid engine - its novel design unlocked by Additive Industries MetalFab™ technology.



Introduction

Liquid-fuelled rocket engines are a very visible symbol of the space-launch industry with the rocket engines becoming very emotive pieces of hardware. Metal additive manufacturing technology has played a big role in the pace of development, of which Additive Industries MetalFab hardware is established in the global supply chain.

To give young engineers the exposure and opportunity to work on this technology, Imperial College in London created ICSS and have assembled a 30 person team to work on a rocket engine design project with the primary brief to develop a "large-style engine on a small scale": Kepler-3.

First among the objectives of Kepler-3 is to give passionate students the opportunity to build a rocket engine of the style they might eventually work on, allowing them to engage with and take ownership of complexity early in their careers and the opportunity to demonstrate their ability and passion for propulsion. It was realised early on in development, that Kepler-3 had the potential to achieve a very high thrust-to-weight due to its relatively small size for its thrust. This led to the goal being defined to achieve a world record thrust-to-weight ratio in excess of 200:1 under power from in-house developed pumps before the end of 2025.

Engine Design

Kepler-3 is a high-pressure, high mass-flow-rate, cryogenic, regeneratively-cooled, bi-propellant rocket engine, running on isopropyl alcohol (IPA) and liquid oxygen (LOx). Unusually for student rocket engines, the ICSS team have designed and manufactured their own, high-speed turbo machinery, running a gas-generator cycle. E qually unusually, the engine has been designed to run oxidiser-rich overall (5:1 overall molar ratio vs the 4.5:1 stoichiometric ratio) in order to demonstrate the potential for cleaner-burning first-stage engines.

The mass flow rates and key pressures for the engine are listed in Table 1. The engine's expected performance, revised based on recent changes for improved cooling, are listed in Table 2.

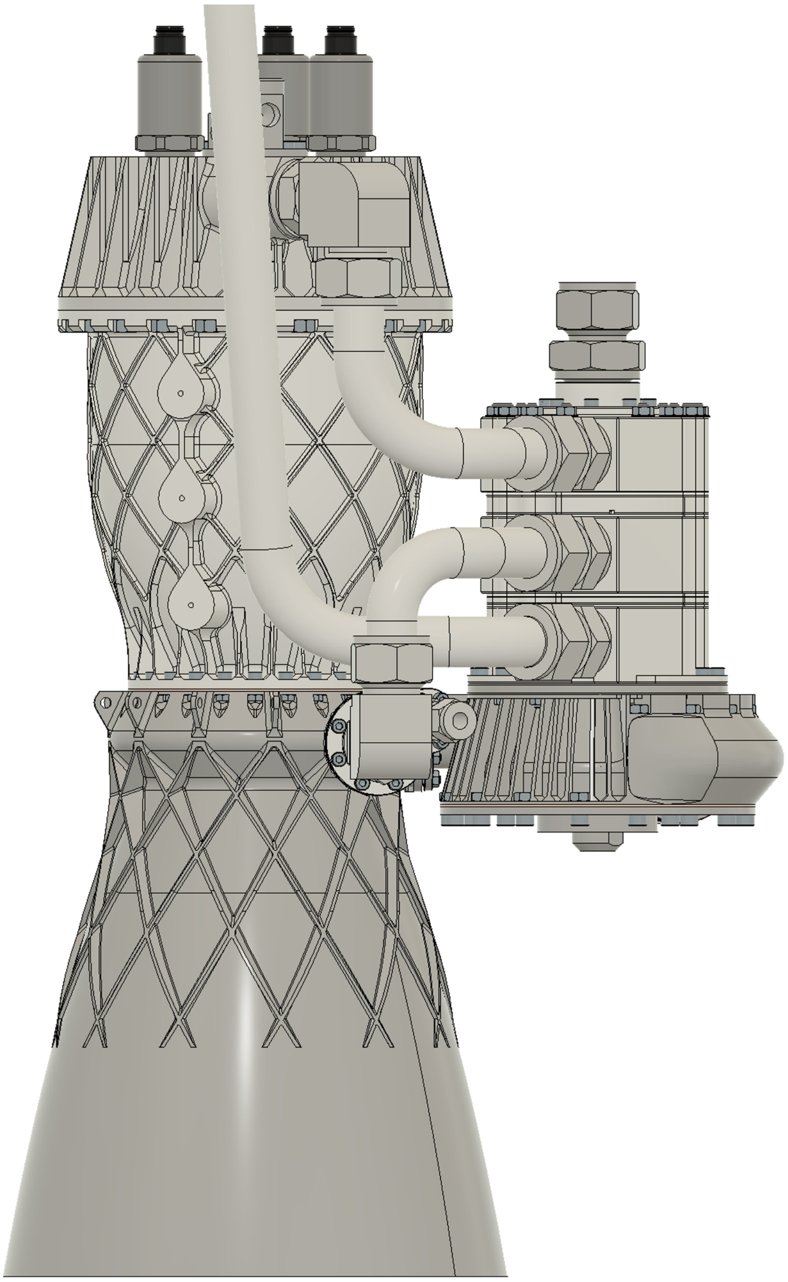


Figure 1. Kepler-3 rocket engine test configuration

Property	Value
Chamber Pressure	68.8 bar
Total mass flow rate	10.2 kg/s
Pre-burner LOx mass flow rate	0.093 kg/s
Pre-burner IPA mass flow rate	0.28 kg/s
Chamber LOx mass flow rate	7.0 kg/s
Chamber IPA mass flow rate	2.5 kg/s
Lip-Coolant LOx mass flow rate	0.2 kg/s

Table 1: Overall designed pressures and mass flow rates.

Property	Value
Firing Duration >40.0 s	>40.0 s
Predicted Thrust	25.0 kN
I_{sp}	259 s
Average Chamber Temperature	3 550 K

Table 2: Overall designed performance metrics.

The turbo machinery unit has been designed to be separable from the engine, allowing for modular operation. Basic details about its performance are shown in Table 3.

Property	Value
Design RPM	70 000 RPM
Design Power 155 kW	155 kW
	207 HP
Pumped Pressure	90 bar
Average Pre-burner Temperature	1180 K
Average Turbine Exit Temperature	1 080 K

Table 3: Pre-burner and turbo machinery performance metrics.

Injector Design

The Kepler engine investigated the performance of two different types of injector design. The first injector, cold-flow tested in 2024, was a 121-element coaxial shear injector, with the oxidiser flowing through the outer annulus and fuel flowing through the core. This style of injector was chosen for its excellent performance in supercritical conditions, with a dark core length of only 5 mm which ensures the maximum time for combustion in the main combustion chamber. For 2025, this injector was upgraded to a fully additively manufactured 97-element coaxial swirl design. This design utilised the design freedom enabled by additive manufacturing to introduce a swirl to the fuel inside the core of each injector element, leading to better mixing performance throughout the operating range of the engine. This feature would be be practically impossible to achieve without additive manufacturing.

Cooling Strategies

Multiple cooling strategies are in-place across the main-combustion chamber and nozzle:

1. **Regenerative:** being found to have the higher cooling capacity and being convenient for the plumbing, the supercritical oxygen flow to the injector is passed through helical cooling channels (only achievable through additive manufacturing), providing adequate cooling for the combustion chamber walls, as opposed to the IPA. The heating of the oxygen dramatically reduces its density, significantly contributing to the mixing performance of the injectors.
2. **Film:** 20% of the oxygen flow into the injector is routed through slots around the edge, creating a region of high-density oxygen flow along the walls of the chamber. Simulations have shown that this region has significantly reduced temperatures compared to the central region, but not adequate in isolation.
3. **Dilution:** marked as “lip-coolant” in Table 4, an especially fed volute injects a significant amount of high-pressure, cryogenic oxygen into a narrow space left between the chamber liner and the nozzle. The $\dot{m}$ has been calculated to dilute the flow striking the lip where the nozzle supports the chamber liner down to 820 K. This diluted flow is expected to provide protection to the wall section immediately down-stream and up until the injection of the turbine exhaust.
4. **Hot film:** the exhaust from the turbine is injected from a volute around the wall of the nozzle. As noted in Table 3, the turbine exhaust is expected to be at 1080 K. Expanding this flow through the ring of nozzles will lead to a sonic temperature of 980 K, falling to 580 K at the end of the nozzle. This should provide excellent protection to the nozzle. This is a similar principle to what was done on the H1 engine for the Saturn I rocket but in the supersonic regime.
5. **Auto-ablative:** the use of IPA permits the dissolution of <1% tetraethyl orthosilicate (TEOS) into the fuel. Deposition of refractory silicone dioxide on impacted surfaces is expected to reduce wall heat flux by 30% for this engine.

Property	Value
Chamber Pressure	37.75 bar
Total mass flow rate	5 kg/s
Chamber LOx mass flow rate	3.7 kg/s
Chamber IPA mass flow rate	1.3 kg/s
Lip-Coolant LOx mass flow rate	0.2 kg/s
Buffer Gas mass flow rate	0.417 kg/s
Buffer Gas Pressure	7.8 bar

Table 4: Reduced mass flow and pressure conditions for testing

In-house modelling indicates that the use of TEOS will not be necessary and, being expensive, we will try to avoid its use if possible.

Innovations

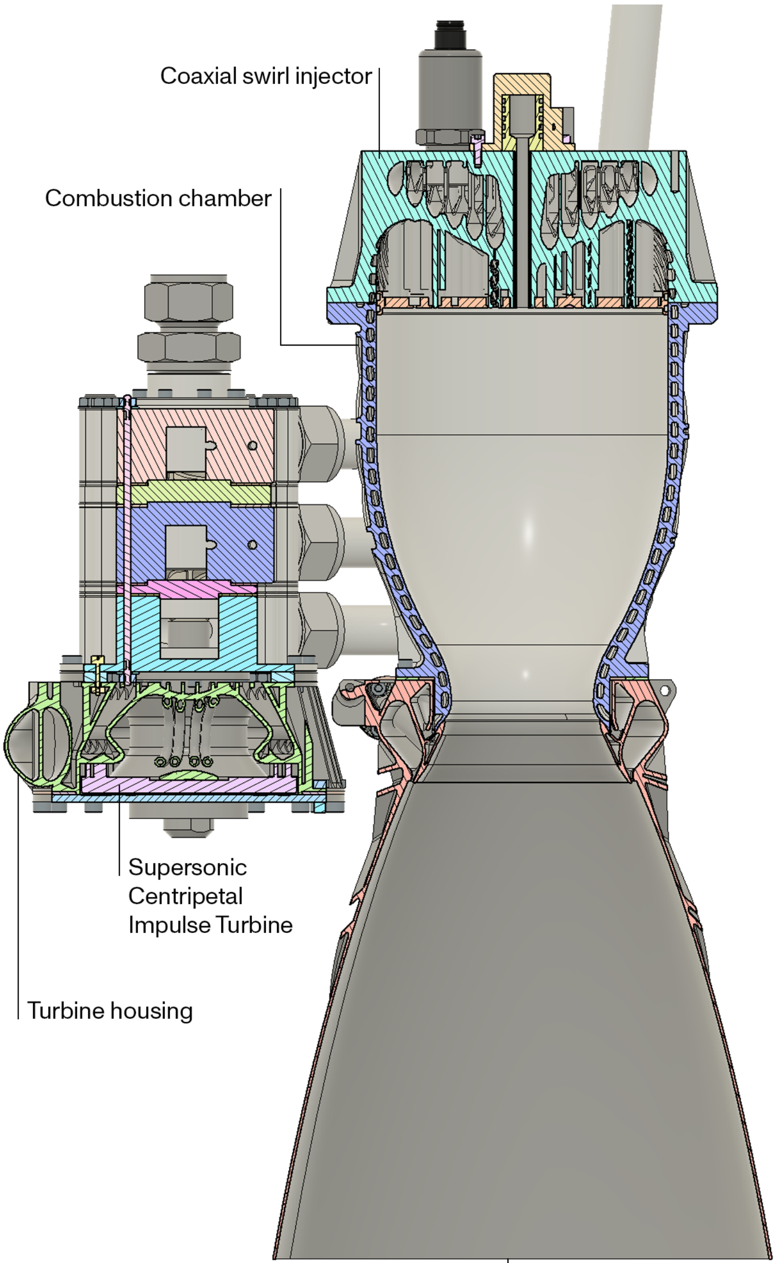
There are several innovations within this engine:

1. **Injector manufacture:** the AM enabled injector has been manufactured with a novel combination of only two parts. The specific configuration has not been seen elsewhere in literature and effectively utilises additive manufacturing to minimise sealing required to separate propellants.
2. **Regenerative-cooling with oxygen:** offers greater heat capacity than using IPA.
3. **High-speed turbo machinery:** running at 70 000 RPM, applying the speeds used for hydrogen pumps to a single-shaft design with denser fuels. This has allowed a smaller and lighter turbo machinery unit for its power.
4. **Supersonic hot film:** unlike on the H1, the injection of gas-generator exhaust will be choked and with adequate pressure to engage supersonic flow. This is expected to provide better cooling and recovered thrust performance.
5. **Autogeneous re-pressurisation:** The Kepler engine is designed to evaporate a small amount of each propellant through cooling channels in the turbomachinery housing. This evaporated gas is then used to pressurise the tanks, removing the need for a separate pressurant to be carried.

Additive Manufacturing

To support the design, manufacture and testing of the Kepler 3 engine, Additive Industries will be producing a range of parts on the MetalFab system. The system has a great pedigree for producing such parts in the Space industry with a large global installation base in place and many pieces of serial production flight hardware successfully produced on the systems.

The key benefits of the MetalFab hardware for production Space applications include the 420 × 420 × 400mm build envelope with 4 × 500W lasers in full field configuration - meaning all 4 lasers can reach all areas of the base plate allowing high quality parts to be produced with high laser efficiency. Further, the MetalFab has a range of automated calibration operations ensuring consistency and quality across multiple build jobs and multiple systems, giving confidence for serial production manufacturers where quality is non-negotiable.



Finally, due to the modular system architecture, production can continue automatically with build changeovers and powder extraction proceeding without operator input, and operate as a multi-material system.

The use of AM offers many benefits for the Kepler engine with freedom of design driving performance improvements, part integration and size reduction.

The key parts to be produced are:

Nozzle:

- Nickel alloy IN718
- AM enables integration of multiple fluid manifolds into the nozzle for cooling
- Mass-saving single wall nozzle extension using turbo machinery exhaust for cooling (first time this has been tried since early developments in the 1960s)
- Controlled Liquid oxygen cooling for the main chamber and the engine throat

Turbine Housing:

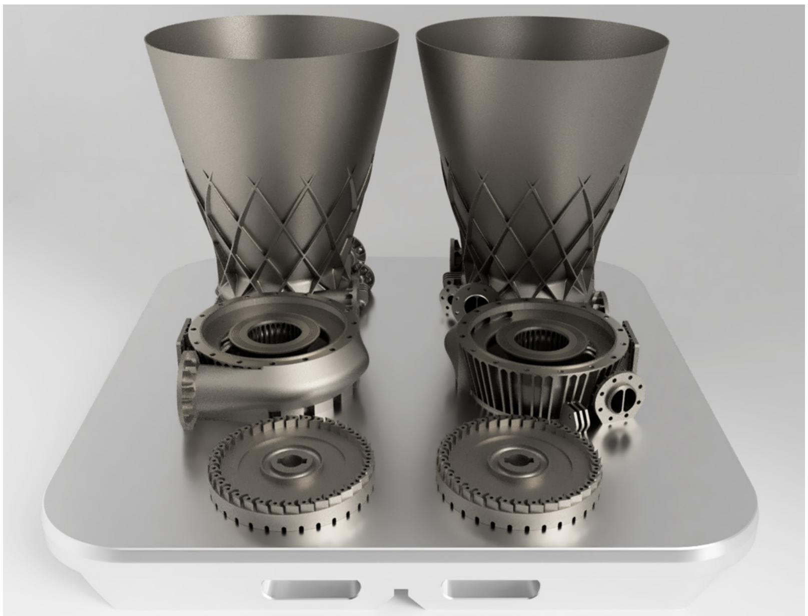
- Nickel alloy IN718
- Autogenous re-pressurisation (AGRP)
- AM enables channels to be integrated into the two turbine housing components for AGRP
- Removes the need for a high pressure nitrogen tank in a rocket

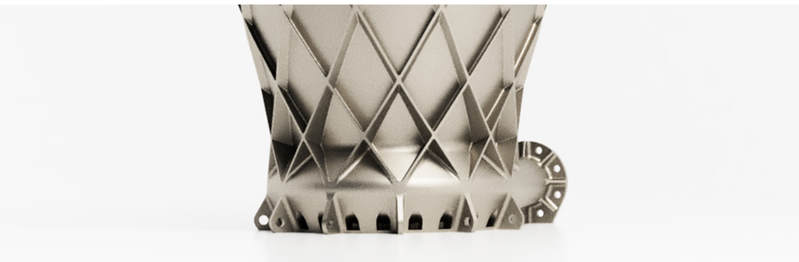
Supersonic Centripetal Impulse Turbine:

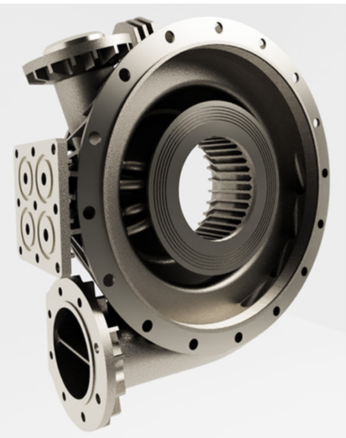
- Nickel alloy IN718
- Compact single-stage supersonic centripetal impulse turbine
- Specifically designed turbine blades,
- Impulse turbine is easy to design and control, and shouldn't suffer from cavitation or wear to the same extent as a reaction turbine would.
- To increase turbine efficiency, a small amount of reaction was included in the turbine through small adjustments to the blade geometry
- AM allows design team to achieve complex curves without the challenges of machining IN718.
- As turbine will be operating at high RPM, it enables the validation of performance of AM components under high mechanical and thermal loads
- The tight tolerances for the turbine and minimal gaps between rotor and housing for improved performance can be tuned and achieved with Additive Industries MetalFab machines

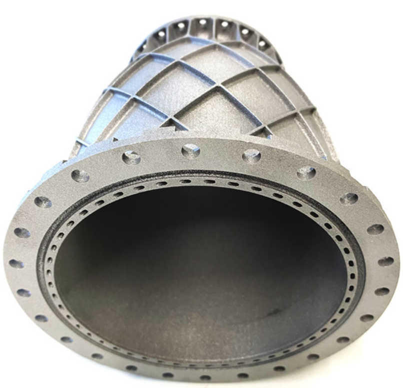
Coaxial Swirl Injector:

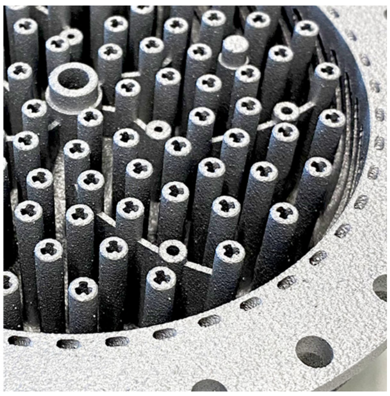
- Aluminium AlSi7Mg0.6
- Varying oxidiser manifold height to maintain more constant pressure distribution and more even injection of oxidiser into the chamber for more efficient combustion
- Swirling geometry inside the injector pins for better mixing than straight shear pins











- Side injection of IPA fuel to free up space on top of the injector
- Incorporation of a hydrogen torch igniter port central
- Reduced number of components = less seals and improved assembly and safety
- Internal geometry designed to be support free
- Optimised to reduce the weight

Combustion Chamber:

- Aluminium AlSi7Mg0.6
- Designed for structural performance under combined pressure and thermal loads and increase safety factor against yield and buckling failure modes.
- AM design combines the original copper liner, outer aluminium casing, and flow guide rings (to interface with the nozzle and control flow area throughout cooling channels) into a single component
- Integrated cooling channels in the walls
- Incorporation of measurement ports along the cooling channels (important for validating our cooling models, which has significant impact on engine performance and reliability).
- Reduced thickness of outer casing as we can use a web structure to maintain strength and rigidity, helping to lower weight.
- Aluminium AlSi7Mg0.6

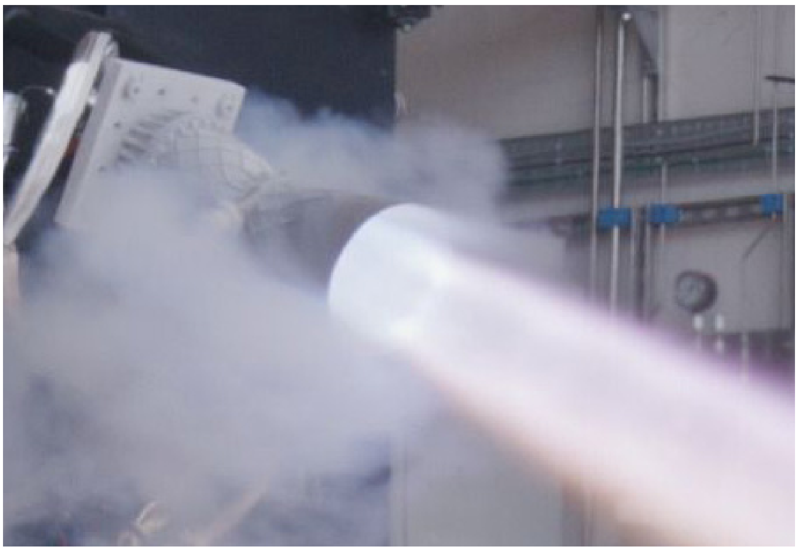
AM Production on MetalFab™

Two of each of the IN718 parts are produced on a single build run utilising 4 lasers and Additive Industries approved process parameter set which provides an optimal balance between material properties, surface finish, accuracy and productivity . The Additive Industries Dynamic Laser Assignment (DLA) tool allows all 4 lasers to act simultaneously as one whilst ensuring the maximum part quality is achieved by avoiding lasers scanning in the emission path of neighbouring lasers. This results in a build time of just over 20 hours for 6 parts.

The same approach is employed for the AlSi7Mg0.6 parts with two combustion chambers and two coaxial swirl injectors placed on the build plate, with 4 laser assignment using DLA. In a genuine series production environment it should be noted that It is possible to fit up 6 parts on the MetalFab, with laser efficiency still optimised and balanced. Resultant build time for the AlSi7Mg0.6 parts is 23 hours.

Once the builds are complete and powder is extracted the parts are heat treated to relieve stress and for IN718 tailor the optimal mechanical properties with a solution treatment followed by a 2-stage age.

The final step is to remove the parts from the base plate using wire EDM and machine the critical mating faces to achieve final finish.



Engine Testing

The Kepler engine was tested successfully across two separate test campaigns throughout May and June 2025. The first test campaign focused on verification of the performance of the additively manufactured turbine.

Supersonic centripetal impulse turbines promise a compact, lightweight and performant design for turbomachinery applications, particularly in the field of rocket propulsion. A representative gas blow-down feed system was designed, capable of matching all key non-dimensional flow parameters for testing. This apparatus incorporated all essential measurement apparatus to determine the four key performance parameters of power, efficiency, total pressure ratio and utilisation factor. Experimental results verified supersonic centripetal impulse turbine performance against ideal analytical models, suggesting these turbines perform within 30% of the ideal blade efficiency, and within 16% of the ideal utilisation factor across a wide range of RPM and flow conditions. Furthermore, the turbine was tested at speeds up to 15000 RPM, validating structural performance under high rotational loads.

The second and most exciting test campaign was the pressure-fed hot-fire of the main combustion chamber. This test substituted the operation of the turbo machinery unit with an industrial test site's pressure-driven feed-system, allowing a reduced complexity test to gather performance data on the combustion chamber with fewer possible issues.

As the test site could only supply a maximum of 1.5 kg/s of IPA fuel, compared to a target of 2.5 kg/s, it was required to operate at throttled conditions with a reduced chamber pressure and overall mass flow rate. The mass and stoichiometric flow ratios into the main injector plate were maintained at their design point, to evaluate combustion performance. The turbomachinery buffer gas was also replaced with excess liquid oxygen for this test.

Two separate hot fire tests were conducted, achieving a sustained thrust of 4.0 kN and 4.4 kN respectively. Ignition was achieved using a hydrogen torch igniter through a central port on the injector plate, and was supported by a gradual ramp up of propellant flow rates over the first 0.5 seconds of each test to enable a pilot flame to form. The achieved thrust values were approximately 30% of the predicted performance, but subsequent analysis was able to attribute this reduced performance to a modification made to the injector to facilitate a throttled test. One ring of the liquid oxygen injector had been blanked off to ensure a safe pressure drop could be achieved during throttled operation and this resulted in a curtain of IPA surrounding the ignited core flow, which prevented ignition of approximately 66 % of the injector elements.

Conclusion

The Kepler rocket engine project achieved several major milestones with the use of metal AM technology, validating its performance across a range of applications within rocket propulsion. In particular, the project demonstrated the applicability of additive manufacture in the production of high-speed turbomachinery components, with turbine performance demonstrated to be within 30 % of the ideal blade efficiency, and within 16 % of the ideal utilisation factor across a wide range of RPM and flow conditions when compared to ideal analytical models. This shows that the surface roughness of components produced on the MetalFab system is accpetable for turbo machinery performance, and allows for rapid development and manufacture of new turbine components. Testing also demonstrated that the structural performance of additively manufactured components on the MetalFab system is appropriate for high-speed applications, especially when appropriate quality control is used to verify mechanical properties of the finished parts.

Furthermore, the Kepler engine hot fire achieved excellent performance, once the minor issue with ignition is accounted for in analysis. In real terms, the C* efficiency on the first run was 32% and 36% on the second. Working back from the recorded data the assumed combustion mode, the part of the flow which did ignite achieved a C* efficiency of between 83% on the first run and greater than 93% on the second, with the coaxial swirl injectors manufactured using metal AM proving to be very effective. The engine test on the whole proved to be a great success in validating the Kepler engine architecture.

Through this project it is clearly demonstrated the value that metal AM with the MetalFab system can bring to the design and manufacture of efficient propulsion systems. With the advanced materials available, high degree of complexity achievable and short lead time it is possible to create highly efficient systems, iterate design rapidly and produce end use parts comparatively cost effectively.

Additive Industries

At Additive Industries, our objective is the success of our customers in achieving the lowest cost per part at market leading part quality.

We pride ourselves on our flexibility to work with our MetalFab™ users in achieving their industrial goals.

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