OVERVIEW OF ROCKET TESTING AT THE WESTCOTT TEST FACILITY (2018-2020)

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ABSTRACT:

This paper gives a brief overview of the rocket test programmes undertaken at the Westcott (UK) rocket test facility in the last three years, in particular those undertaken at the Airborne Engineering and Nammo UK test sites.This encompasses a variety of testing for liquid, gaseous and hybrid propellant rockets, ranging from fundamental combustion research to qualification testing.

1. INTRODUCTION

The rocket development and test facilities at the Westcott Venture Park in Buckinghamshire, England (formerly Rocket Propulsion Establishment Westcott) have been at the centre of UK chemical rocket science and technology for over 70 years. The UK chemical rocket industry has, like most industries, seen highs and lows over the period of its history with levels of staffing at Westcott reaching as high as 1,100 people during the 1970's and '80's and as low as 15 people around the millennium. A previous paper concentrated upon rocket activities at Westcott in earlier years [1]; this paper concentrates on the years 2018 through to 2020, with a focus on the activities of Airborne Engineering and Nammo UK.

These rocket companies often work together on new technology trials and agency sponsored research programmes. Each organisation has a set of unique capabilities and expertise that can be pooled together to mutual advantage on such programmes. Together, these capabilities encompass monopropellant and bipropellant thrusters for sea-level and in-space applications, propulsion subcomponents, manufacturing, qualification, test instrumentation and analysis.

The period 2018-2020 has seen a rise in the UK chemical rocket businesses on the site with a significant number of test firings for gaseous, liquid and hybrid rockets across a range of intended end applications.

2. AIRBORNE ENGINEERING

Airborne Engineering (AEL) are specialists in testing for propulsion and challenging environments. Over the period 2018-2020 they have undertaken a variety of internal and customer projects focused on fundamental combustion research, rocket engine manufacturing processes or the testing and control of challenging fluid systems. Some of these projects are detailed in the following sections.

2.1. Additively manufactured combustion chambers

2.1.1. Copper alloy C-18150 (CuCrZr)

In a UKSA Pathfinder-funded programme (PF2-058), AEL and 3T AM collaborated to develop and demonstrate a combustion chamber printed in CuCrZr. This begin with small test-pieces for evaluating as-printed geometries and for flow testing of small holes such as could be used for injectors or film cooling. A small demonstrator combustion chamber and nozzle was then printed and tested at a range of chamber pressures with nitrous oxide and isopropyl alcohol propellants. One such test is shown in Figure 1. More information can be found in Reference [2].

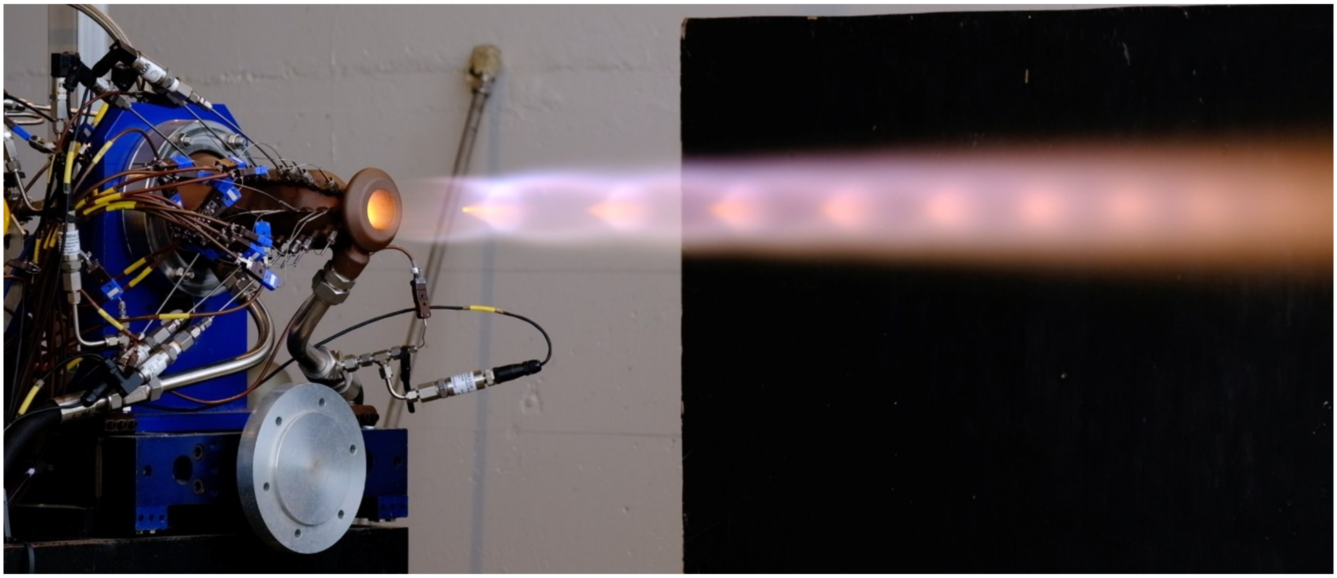


Figure 1: Firing of the additively manufactured CuCrZr combustion chamber using liquid bipropellants in AEL's J1 test facility.

2.1.2. Novel Nickel alloys

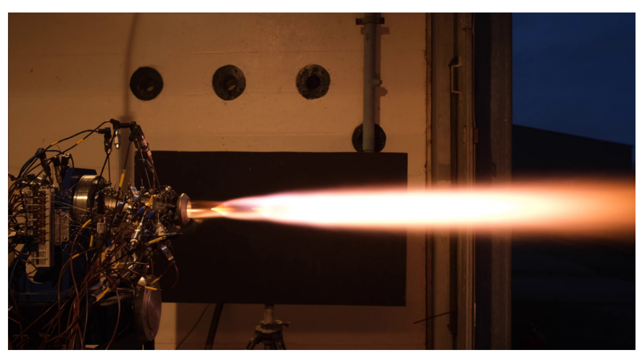
Additive manufacture of rocket engine components has historically been demonstrated using several nickel alloys, most commonly with Inconel 625 and Inconel 718 (IN718). IN718 exhibits good suitability for additive manufacturing, whereas many stronger high-temperature alloys can crack during the process.

Using their proprietary Alloys-by-Design (ABD®) software, Alloyed has developed a series of nickel superalloys designed specifically for additive manufacturing, allowing the crack-free manufacture of higher performance parts. Of these, ABD®-900AM maintains strength up to 900°C, demonstrating an increase in capability over IN718 of ~100°C, whilst being processable with similar parameters. A chamber made from ABD®-900AM therefore allows for potentially higher heat-fluxes than IN718, with only very minor changes to the manufacturing process. AEL, Alloyed and Renishaw collaborated to design and test a combustion chamber made from ABD®-900AM . Figure 2a shows two chambers that were produced for the programme, and Figure 2b shows the ABD®-900AM chamber undergoing testing on AEL's J1 test stand.

The propellants were nitrous oxide and isopropyl alchohol, with a combustion chamber pressure of 20bar and a thermal flux of ~14MW/m^2. Additional work is anticipated including test work on a chamber manufactured with modified laser parameters.

This work is described more fully in Reference [3].

(a) ABD® -900AM (left) and IN718 (right).



(b) Firing of the ABD® -900AM combustion chamber.

Figure 2: Additively manufactured nickel alloy chambers.

2.1.3. Coating for aluminium alloys

AEL's interest in low-cost and lightweight bipropellant engines has lead to the consideration of aluminium alloys for additive manufacture. For high-performance engines, the degradation of mechanical performance at high temperatures necessitates the use of a thermal barrier coating at the combustion chamber firewall. Advances in processes for the application of ceramic coatings to aluminium lead to the design and testing of a small section of regeneratively-cooled combustion chamber from aluminium, with a coating applied. Figure 3 shows the chamber segment being tested on AEL's J2 test stand using gaseous oxygen and hydrogen propellants.

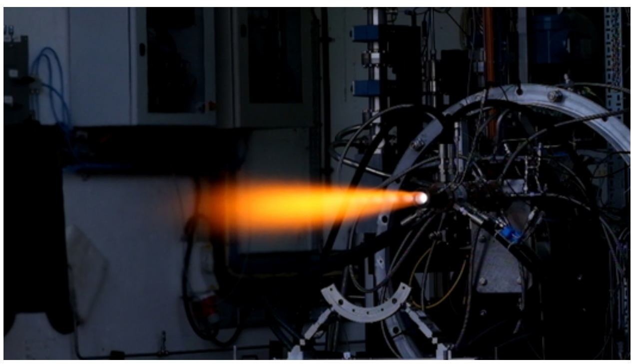


Figure 3: Hot-firing (O2/H2) of an additively manufactured aluminium combustion chamber with a novel barrier coating.

2.2. VTVL Gyroc vehicle

AEL has successfully tested its Vertical-Takeoff-Vertical-Landing (VTVL) demonstration vehicle - named *Gyroc* - for the first time in June 2019. VTVL rockets like Gyroc can be used to test technologies required for landing on places such as the Moon or Mars. Airborne believes that this is the first time such a vehicle has been successfully tested in Europe. Fig. 4 shows the vehicle hovering in tethered flight.

Gyroc uses non-toxic rocket propellants (nitrous oxide and isopropyl alcohol,) weighs about 20kg and can hover for over 30 seconds. It has a gimballed, throttleable engine whose action is controlled by a custom on-board IMU and flight computer, with feedback control loops for attitude, position and propellant throttling. After more testing, Airborne plans to scale-up the vehicle so that it can be used to assist other organisations developing autonomous planetary landing technology and who need a way to perform testing in a realistic way on the Earth.

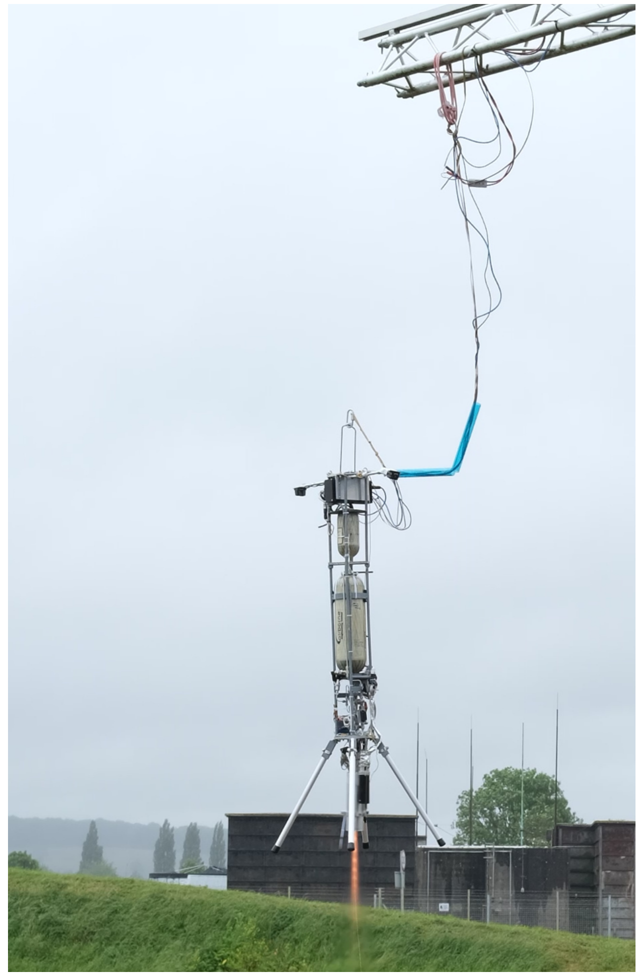


Figure 4: Gryoc VTVL rocket vehicle tethered hover - the first successful European flight of a VTVL vehicle.

Although the development of Gyroc has been entirely self-funded by Airborne Engineering, the company is grateful to the European Space Agency who have kindly provided some additional funding to support the recent test programme. A further test programme of flight envelope expansion and control techniques is being planned with ESA for 2021.

More information about the Gyroc vehicle can be found in [4].

2.3. LOX facility

AEL has begun work on upgrading its J1 test bay with a liquid oxygen feed system, capable of a mass flow of up to 7.5 kg/s and a feed pressure of up to 90 bar. This feed system is scheduled to be completed in 2021.

Figure 5: Testing of the vitiated air hot-gas source for testing a single module of the HX3 subsystem for customer Reaction Engines' SABRE engine. A pitot probe on a traverse is used to check flow uniformity in temperature and velocity.

2.4. Customer projects

2.4.1. HX3 Single module flow tests

This test campaign studied the performance of a heat exchanger with a letterbox-shaped cross section for a single module of the HX3 subsystem of Reaction Engines' SABRE engine. This required AEL to design a custom hot gas heat source, which was capable of providing partially combusted air with variable massflow and temperatures controlled from 700K to well in excess of 1200K. Flow uniformity was key for the performance results, so temperature and velocity uniformity for the hot gas source was verified at atmospheric pressure using a pitot probe on a traverse (Fig. 5). The customer's experiment was then bolted onto the hot gas source in a custom housing so that it could be tested at elevated pressure.

The program required two separate air feeds; one for combustion at high equivalence ratio and a second for dilution to the required temperature. A hydrogen gas feed was used for fuel, and a separate nitrogen or helium gas feed was used for the heat exchanger coolant. Each of these required closed loop feedback control of massflow (0.1% accuracy achieved) and the coolant feed additionally required active feedback control of pressure (0.5% accuracy achieved). AEL therefore designed a custom actuated high temperature needle valve system to maintain a fixed backpressure in the heat exchanger as the coolant heats rapidly from ambient temperature. Cooling water was provided to the housing in two separate feeds.

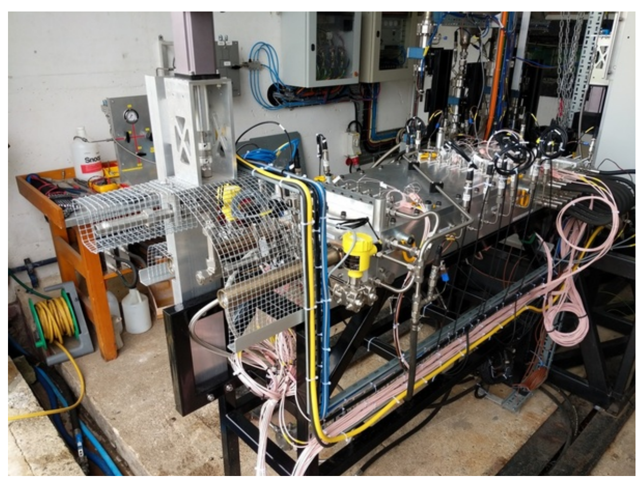


Figure 6: The test-rig assembled with REL's experiment attached to AEL's hot-gas source and feed systems.

2.4.2. Preburner injector testing

This test campaign studied the combustion performance of novel air-hydrogen injectors for the preburner of Reaction Engines SABRE engine. The subscale testing involved providing two air feeds (<1kg/s) and two hydrogen feeds (<5g/s), each of which required closed loop feedback control of massflow. Constant massflow profiles were used to evaluate combustion performance and ramped profiles to evaluate flame blow-off. Instrumentation requirements included standard pressure and temperature measurements, high-speed pressure measurements for combustion oscillations, high speed video and laser imaging for non-intrusive monitoring of the flow field (Fig. 7).

Figure 7: Reaction Engines' Preburner injector test rig for evaluating the combustion performance of the injectors for the SABRE engine preburner.

2.4.3. Protolaunch HILBERT engine

Protolaunch are developing novel chemical engine designs for microlauncher applications. Using an alternative cooling and pressurisation cycle, these engines have improved performance compared to traditional gas blowdown cycles, but without the costs and complexity associated with turbomachinery based cycles. Together with AEL, Protolaunch performed an initial commissioning and hot firing of its HILBERT prototype engine. This engine serves as a testbed to validate the engine design and will be used to further explore the performance envelope of the cycle in future campaigns. Figure 8 shows a picture from the test firing.

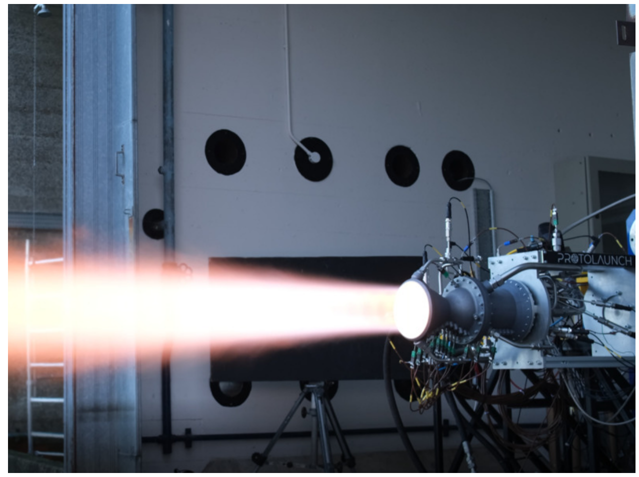


Figure 8: Initial commissioning testing of Protolaunch's HILBERT engine at AEL's J1 facility.

3. NAMMO UK

In 2019 and 2020 major progress has been made on the National Space Propulsion Test Facility, currently in the final stages of construction at the Westcott facility. The facility will ultimately consists of a series of test stands for rocket engines of various thrust classes, all joined to a common vacuum system to maintain a vacuum level of approximately 1.5 mBarA. The first phase of this work, which has now been completed, was to implement a hypergolic test stand in the J3 facility as a Medium Altitude Facility (MATFa) [5]. The term medium altitude is used because the facility operates at approximately 50mBarA whilst running and uses only the rocket engine under test to provide the pumping capability. Other than a small vacuum pump, used to create the correct conditions before ignition, the facility is pump-free and hence is easy to maintain and low cost to run.

A supersonic diffuser connected to the exhaust of the engine provides the necessary pressure recovery from the exit plane pressure of the engine all the way up to ambient pressure. The start sequence for the system necessitates a fast acting and high flow vacuum valve to seal the system. This is to provide the switch between the initial vacuum conditions and the steady state firing conditions where, downstream of the diffuser, the hot gases are exhausted to atmosphere. This valve was implemented using an in house designed lightweight aluminum "blow-off cap" which is ejected once atmospheric pressure is achieved downstream of the diffuser.

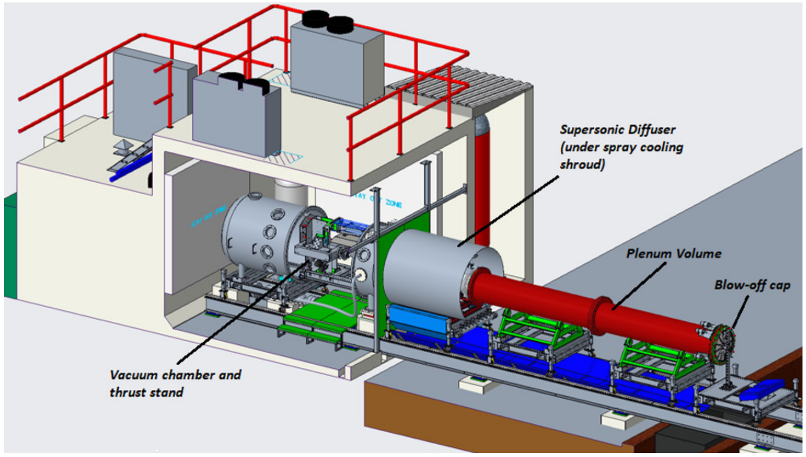


Figure 9: CAD model of the J3 facility configured for MATFa operations.

A plenum volume is also implemented between the diffuser and the blow-off cap to smooth the initial transient and to prevent the diffuser unstarting. A novel cooling approach was taken to the diffuser which would traditionally use a spiral water jacket. The CFD analyses, performed on the diffuser to optimise the geometry, suggested significant uncertainty on the thermal power and location. Accordingly an external spray cooling approach was taken such that the water could, if necessary, be focused to cool areas of high heat flux. This approach also created a low cost diffuser which has only a single skin.

The MATFa facility was primarily aimed at testing the LEROS 4 (HTAE – High thrust apogee engine) with a nominal thrust of 1kN and accordingly a single axis thrust stand capable of measuring up to 2kN thrust was implemented. The HTAE has so far undergone a successful firing campaign achieving specific impulse values of 321 seconds (when compensating from a MATFa expansion cone to a full HATFa cone) at combustion chamber temperatures compatible with the use of C103/R512E materials.

The MATFa facility has also been used to test other developments and also established engines. Hence it has so far demonstrated a test capability between ~90N all the way to 1100N thrust. The next phase is to convert the facility into a High Altitude Test Facility (HATFa) through the implementation of an alternative diffuser, followed by very high performance heat exchanger called the plume inter-cooler. The cooled plume gases are then directed through the common vacuum manifold to a large bank of conventional electric vacuum pumps which take the cooled gases from approximately 35 mBarA to ambient pressure.

The system build is progressing well at the start of 2021 with the pump house fully constructed and the pumps already delivered and awaiting installation. The cooling system required to deal with multi-MW of power is also currently being installed. The facility will still be able to able to switch between MATFa and HATFa operations as required to allow the appropriate test to be performed. The MATFa operations are lower cost than the HATFa operations, but the choice of the electric vacuum pumps translates to an economical approach to high altitude rocket testing and, perhaps more importantly, a fast start up and shutdown time. Inherent in the design is a level of redundancy automatically built into the banked pump arrangement. Thrusts as high as 1500N will be achievable in the HATFa and hence this endeavor represents a huge leap forward in the rocket test capabilities at Westcott.

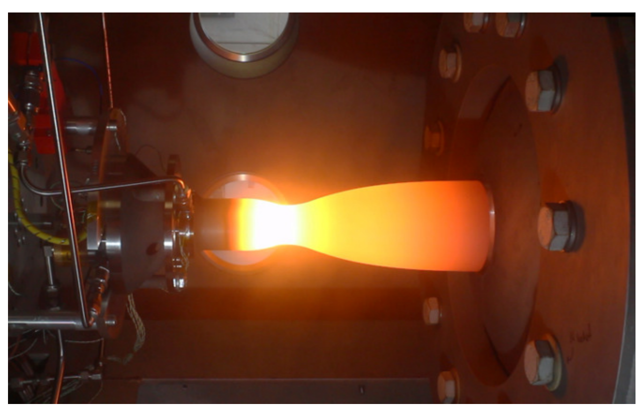


Figure 10: The HTAE at 50mBarA ambient pressure.

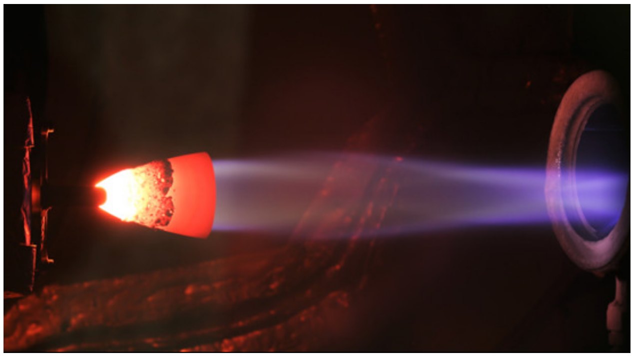


Figure 11: LEROS 10 undergoing a steady-state firing test at the Nammo F-Site High Altitude Facility.

3.1. Leros 10 Qualification

The LEROS 10 thruster (nominally a 10N attitude control and apogee backup thruster) has recently undergone an extensive qualification campaign for a major Spacecraft Prime which was notable for the length and complexity of the campaign. In total, the firing activity lasted for 13 months in the Nammo F-Site High Altitude Test Facility (capable of firing up to 20N thrust and approximately 1 to 1.5 mBarA ambient pressure).

During the qualification of the LEROS 10, it demonstrated some significant highlights including:

- Total throughput: 900kg MON3/MMH
- Thrust range: 6 to 14N
- Specific impulse: 285s minimum
- Operation firing life: 67 hours
- Total number of pulses: 79,179
- Minimum Ibit: 50mNsec
- Inlet pressure range: 7 to 24 barA
- Max qualification single firing duration: 3.75 hours
- Propellant temperature range: -5 to +60°C
- Qualified number of deep thermal cycles: 775

The LEROS 10, achieving qualification status, represents a major milestone for this engine which started life at the end of the 1990's. Despite the apparent age of the design, the engine is very relevant to modern applications and the choice of the relatively low cost chamber materials (C103/R512E) provides a significant cost advantage over similar thrust class competitive offerings.

3.2. Electronic Pressure Regulator (EPR)

The Electronic Pressure Regulator, currently being developed by Nammo UK, represents an exciting and novel approach to pressure regulation for a range of spacecraft propulsion systems [6]. It is primarily aimed at the fine control of Electric Propulsion systems but due to the high dynamic range of the proportional valve, it can also be used in chemical systems at flow rates up to 600mg/s of Helium. Specifically the EPR system consists of the high pressure proportional valve (HPPV), the associated propellant heater to offset Joule-Thompson effects and the remaining instrumentation and pipework system.

The EPR has the following performance parameters achieved through the use of the precision piezo actuated valve assembly:

- In-flight pressure variation and control
- Scalable design
- Suitable for control of liquids and gases (all titanium wetted design)
- No need for multiple regulators (e.g. High pressure and low pressure in series regulators)
- Low leak rate (<2 x10-5 scc He /sec)
- High flow capacity ($\leq$1.2 g/s Xe or $\leq$600mg/s He)
- Programmable by telecommand
- Regulation accuracy <0.1 Bar
- Response time to 90% of the new level <1second
- Proportional flow control compatible with 16bit drive electronics
- High inlet pressure range up to 310 BarA (4496 psia)
- Pressure set point range from 0.5 to 22 BarA (7.25 to 319 psia)

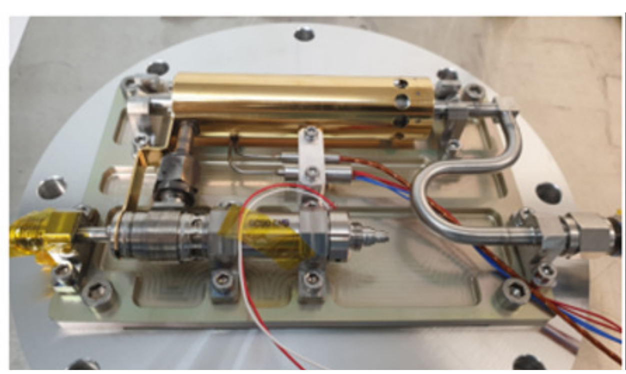


Figure 12: HPPV and Heater Assembly on integrated plate.

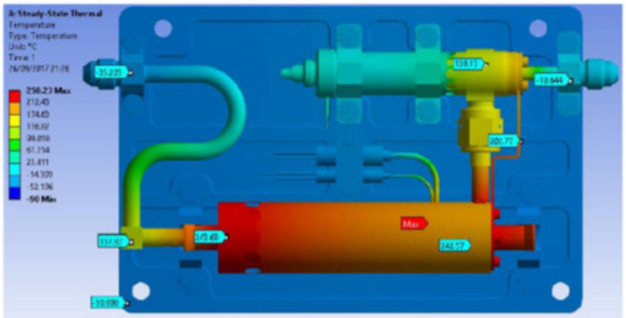


Figure 13: HPPV and Heater Assembly thermal analysis.

In the recent extensive engineering model campaign performed at the Nammo UK Cheltenham facility, the electronic pressure regulator completed the following notable tests:

- Proof Pressure at 465 barA
- Internal and External leakage between 1BarA an 310BarA
- Open and closed loop operating modes
- Extensive thermal vacuum testing with Xe, N2 and He propellants over -40°C to +70°C temperature range
- Life cycle of 15,000 fully open/closed cycles.

The EPR has been under test for customer specific programmes for some time and Nammo will be taking two configurations through qualification during 2021 together with delivery of flight models. The performance and capability of the device is gaining a lot of interest from other potential customers. The ability to actively control the set point without resorting to bang-bang control (with the associated limitation of the number of the cycles) represents a major performance improvement as well as potentially simplifying the architecture of the propulsion system.

4. CONCLUSIONS

The site at Westcott has a long history of UK propulsion testing, initially for predominantly military applications. The site is now home to several commercial companies with a range of rocket testing facilities and skills. These capabilities encompass monopropellant and bipropellant thrusters for sea-level and in-space applications, solid propellants, propulsion subcomponents, manufacturing, qualification, test instrumentation and analysis.

This paper describes some of the varied test programmes undertaken at Westcott in the last three years (2018-2020). There is increasing investment at Westcott with several new test facilities and feed systems planned for the next few years, which should further increase UK rocket testing capability.

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