OVERVIEW OF ROCKET TESTING AT THE WESTCOTT TEST FACILITY (2016/2017)

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KEYWORDS:

Sea-level testing, nitrous oxide fuel blend, air-breathing, sound suppression, apogee engine testing, resonant acoustic mixing

ABSTRACT:

This paper will give a brief overview of the rocket test programmes undertaken at the Westcott (UK) rocket test facility in the last two years, in particular those undertaken at the Airborne Engineering, Nammo Westcott and The Falcon Project test sites. This encompasses a variety of testing for liquid, gaseous and solid propellant rockets, ranging from fundamental propellant 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. This paper will concentrate upon recent years rocket activities at Westcott; 2016 through 2017 and into 2018. This period has seen a rise in the UK chemical rocket businesses on the site with development hand-in-hand with a significant number of test firings for gaseous, liquid and solid rockets across a range of intended end applications.

The three rocket companies currently involved in rocket development and test activities are as follows:

- Airborne Engineering Ltd. (AEL)
- Nammo Westcott Ltd.
- The Falcon Project Ltd.

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, solid propellants, propulsion subcomponents, manufacturing, qualification, test instrumentation and analysis.

There is a further significant addition to this cluster. Reaction Engines Ltd., the company developing the innovative Synergetic Air-Breathing Rocket Engine (SABRE), are currently investing significantly, both financially and technologically, in building a new test facility at Westcott. This facility will enable further SABRE development through to proving the engine systems and hardware required for the SABRE cycle. This engine has the potential to revolutionise hypersonic transport and space launch vehicles, and represents an important avenue of current UK propulsion research.

This paper will give a brief overview of the rocket test programmes undertaken at the Westcott (UK) rocket test facility in the last two years, in particular those undertaken at the Airborne Engineering, Nammo Westcott and The Falcon Project test sites.

Figure 1: Aerial via of the Westcott J-site facility, with four test bays (bottom), belonging to Airborne Engineering Ltd. (J1 and J2, bottom left), Nammo Westcott Ltd. (J3, bottom middle) and Surrey Satellite Technology Ltd. (J4, bottom right).

2. AIRBORNE ENGINEERING LTD. (AEL)

AEL has two permanent rocket engine test bays (J1 and J2) at the Westcott test facility with various kinds of propellant supply infrastructure and thrust ratings. These facilities have been used for testing gaseous, liquid and hybrid rocket engines, small jet engines and for thermal/pressure testing equipment. The AEL Westcott facility is equipped with data logging equipment and automated software for fast turnaround of post-firing data analysis. This custom automation enables very efficient testing schedules. The test facility is supported by a well-equipped on-site mechanical workshop and instrumentation lab.

Over the last two years AEL's facility has been used for a variety of rocket test programmes. The next few sections summarise several of these.

2.1. Nitrous oxide fuel blends

There is currently a global drive towards less toxic propellants. Nitrous oxide fuel blends consist of a hydrocarbon fuel mixed with nitrous oxide, and have been identified as a potential low-toxicity monopropellant to replace hydrazine. The European Fuel Blend Development programme was initiated as a low TRL investigation to further develop European knowledge and capability in this area. TNO undertook a scoping study to select to a promising fuel blend of nitrous oxide and ethanol, and performed initial miscibility studies [1].

TNO then partnered with Nammo Westcott to organise the test programme, who selected AEL to undertake the hot-fire testing of this propellant in the J1 test bay. The test programme used an existing combustion chamber and a modified test rig to mix a liquid nitrous oxide/ethanol fuel blend in real-time and hot-fire it at several O/F ratios around the target operating condition (O/F 3.18). This required the development of a custom mixing chamber and monopropellant injector. The NOFB was found to have good combustion performance, and no flashback events were seen with the current setup [2].

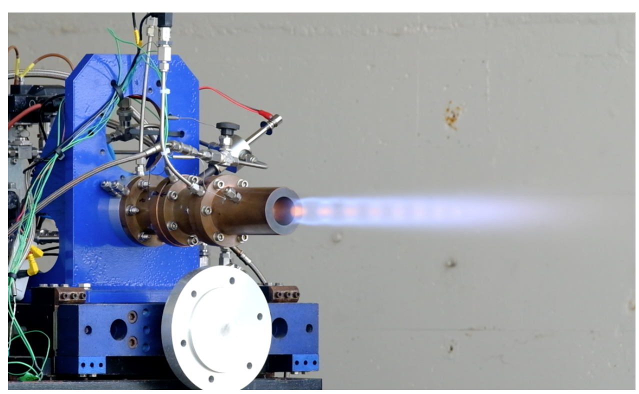


Figure 2: Stable combustion of a liquid nitrous oxide/ethanol fuel blend at mixture ratio 3.85.

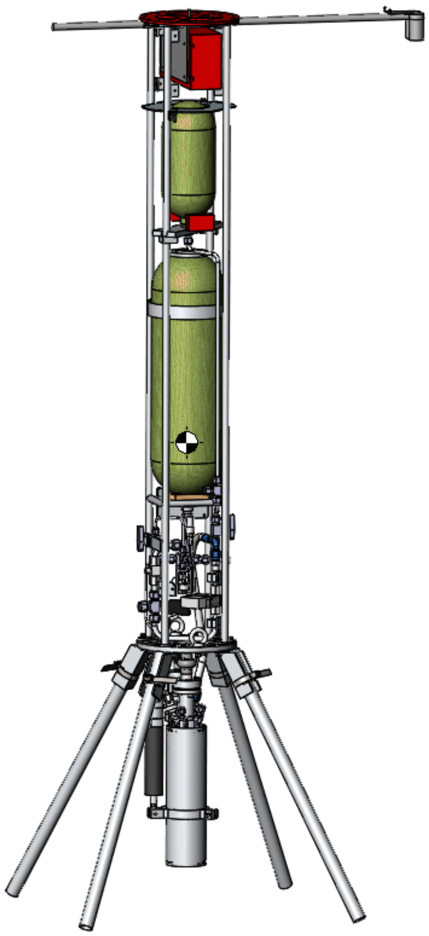


Figure 3: Gyroc 5 vertical take-off vertical landing vehicle, with a gimballed 300N nitrous oxide (N2O) / isopropyl alcohol (IPA) throttlable thruster.

2.2. VTVL lander demonstrator

A project is underway at AEL to develop a VTVL technology demonstrator, in order develop experience in the design and control of VTVL vehicles. A sub-scale vehicle, based on a 300N nitrous oxide (N2O) and isopropyl alcohol (IPA) throttleable bipropellant thruster, has been constructed and was presented at the previous conference [3].

Since then the thruster has been characterised by fitting a model to data from static firings. This allowed feedback control loops to be designed for throttling both the N2O and IPA propellants. The thruster has been successfully shown to quickly and accurately respond to throttle demand. Further work has been done to tune the vehicle flight control loops. The next phase of this programme is to test fly the vehicle.

2.3. Altitude compensating nozzles

Altitude compensating nozzles are required to maintain propulsive efficiency when the same nozzle is used with a range of exit pressures. This is the case for Reaction Engines' Synergetic Air-Breathing Rocket Engine (SABRE) engine, where the same engine is used at all altitudes, up to Mach 5.4 in air-breathing mode, and Mach 25 in rocket mode for space flight.

The 20kN STOIC engine was designed by Reaction Engines as part of their Advanced Nozzle Programme in order to test important technologies for the SABRE engine. The STOIC engine includes an additively manufactured injector block, novel technology for switching between the air-breathing and rocket modes of the SABRE cycle, and an altitude compensating nozzle geometry.

A custom gaseous H2/O2/Air feed system was designed by AEL and installed into their J2 test facility in 2015 [4] to actively control the STOIC engine and transition between engine modes. The STOIC engine hot-firings began in 2015 and continued into 2017, successfully testing features of the SABRE engine at subscale and validating Reaction Engines' simulation and design methodology.

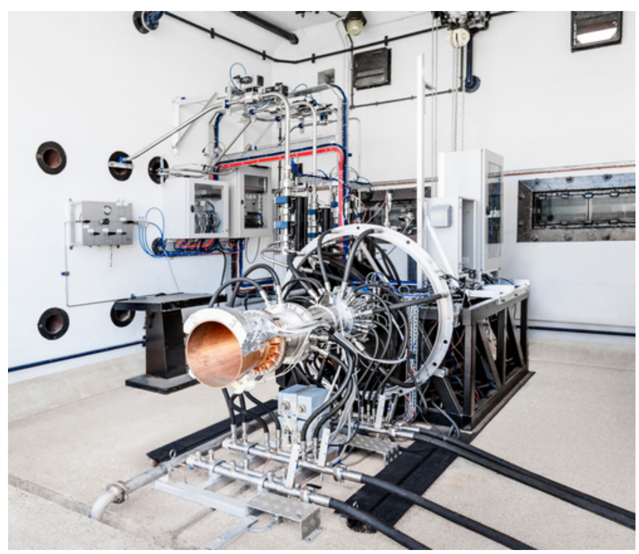


Figure 4: Reaction Engines' 20kN STOIC air-breathing rocket engine, installed in AEL's J2 test facility.

Figure 5: Sound suppression testing at AEL's J2 test facility. A custom water spray system and diffuser duct cools and slows the plume to significantly reduce the emitted sound.

2.4. Sound suppression

Sound emission from rocket engine testing must be kept within safe working limits for the safety of staff and local population. To de-risk the design for the new Reaction Engines TF1 test facility, subscale tests were undertaken to analyse the performance of sound suppression methods.

The test programme in 2016 examined the effect of using water to cool a rocket exhaust to reduce the emitted sound level. This used the 20kN H2/O2 STOIC engine at the AEL J2 test facility and a water spray system. The test programme in 2017 added a custom diffuser duct to further slow the exhaust plume. The engine thrust level and water massflow were varied, both with and without the diffuser duct. The frequency and amplitude of the emitted sound was then analysed to study the effect of the sound suppression methods. These subscale tests successfully demonstrated that the diffuser duct design reduced sound efficiently and matched theoretical prediction well.

Figure 6: Water spray injection into the plume of the 20kN STOIC engine for sound suppression testing.

Figure 7: Hydrogen rich gaseous injector testing, to validate the performance of a novel H2/O2 injector for inlet to a turbopump.

2.5. Fuel rich gaseous injector testing

Reaction Engines are currently designing the DEMO-A engine to demonstrate the thermodynamic cycle for the SABRE engine. The DEMO-A engine turbopump may be started using a supply of hot gas, produced by burning gaseous hydrogen and oxygen. The mixture is extremely fuel rich in order to provide a low turbine inlet temperature. The hot gas must be generated in a separate combustor with injectors that can maintain combustion at such a rich mixture ratio, whilst providing enough mixing that the burnt gases are homogeneous and contain no “hot-spots” that could cause undue stress on the turbine blades.

Reaction engines has designed a novel injector for operation in this challenging operating condition, where the volumetric flow rate of the fuel is much larger than that of the oxidiser. Two competing injector geometries were subscale tested at high pressure in the AEL J2 test facility. Thermocouples were placed at the end of the combustion chamber in the exhaust flow in order to measure the temperature distribution. This required accurate attention to mixture ratio at startup and shutdown of each test, because mixture ratios nearer to stoichiometric would result in immediate destruction of the thermocouples. Excellent performance was seen for both injector types with a wide throttle range, with almost complete combustion and temperature distributions that matched simulations well. This project is currently proceeding to larger scale tests.

2.6. Design of a LOX/LCH4 facility

In 2016 a feed system was designed to provide liquid oxygen, liquid methane and liquid nitrogen to the J1 test bay. This included bulk tanks, high pressure run tanks, a flare stack and a water coolant system. This was to support a customers’ test program for thermally cycling combustion chambers to test for fatigue resistance. The feed system therefore required a lot of automation to facilitate up to 100 short firings per day. Notably this included automatic post-test leak checking using a Helium mass spectrometer, automatic data analysis and regeneration of pressurant gases using water bath vaporisers and a separate hot water system.

Unfortunately this test programme was postponed by the customer after the successful detailed design review with ESA, but it is hoped that some of the cryogenic feed system will be built in 2018. This should allow testing of small LOX/hydrocarbon engines or pressure-fed combustion chambers.

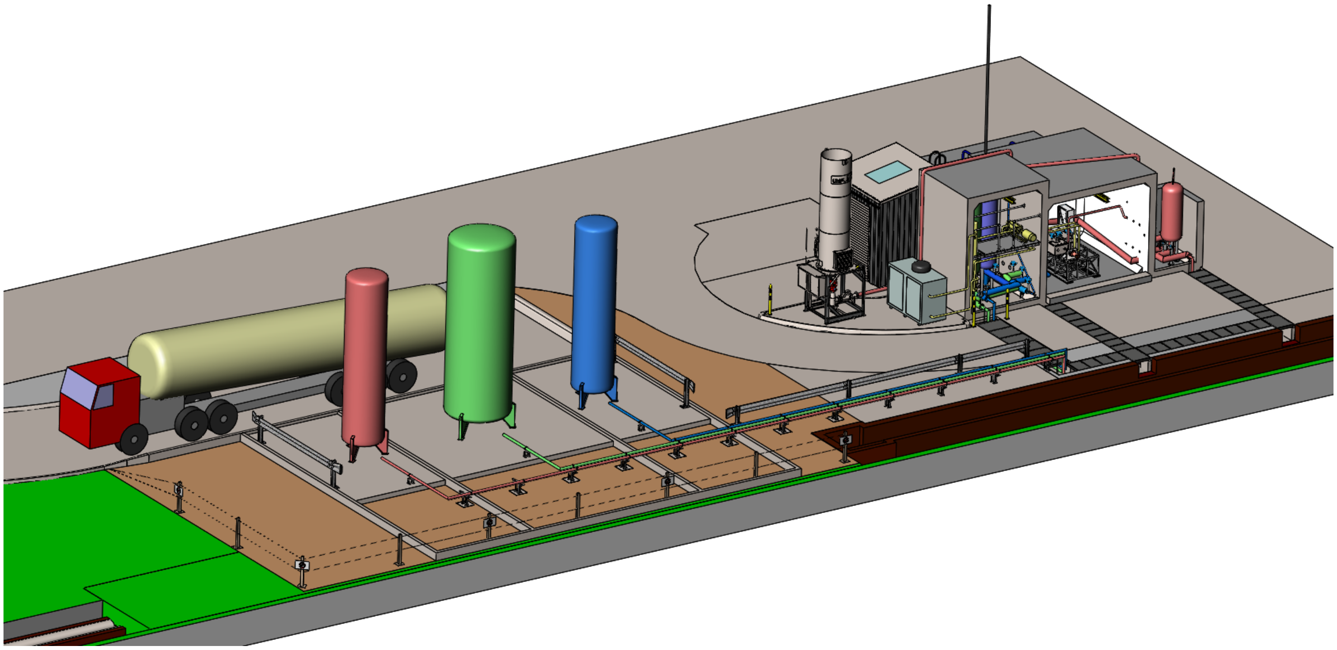


Figure 8: Design of a LOX/LCH4/LN2 feed system for the J1 test bay, including bulk storage tanks, high pressure run tanks, flare stack, water coolant system and boiler house to feed water bath vaporisers.

3. NAMMO WESTCOTT LTD.

Nammo Westcott, which became part of the Nammo group in 2017, is a major supplier of chemical propulsion to the key spacecraft manufacturers. Their rocket engines and thrusters serve commercial, defence and science markets. In 2016 it was a Nammo Westcott engine that provided the insertion burn to allow NASA's JUNO spacecraft to successfully enter into orbit around Jupiter.

Nammo Westcott currently has 22 employees and has development, production and test activities in the following areas:

- Hypergolic bipropellant apogee engines
- Hypergolic bipropellant thrusters for attitude control
- Monopropellant thrusters for attitude control
- Chemical propulsion subsystems and components
- Rocket engine test services
- Manufacturing and non-destructive testing

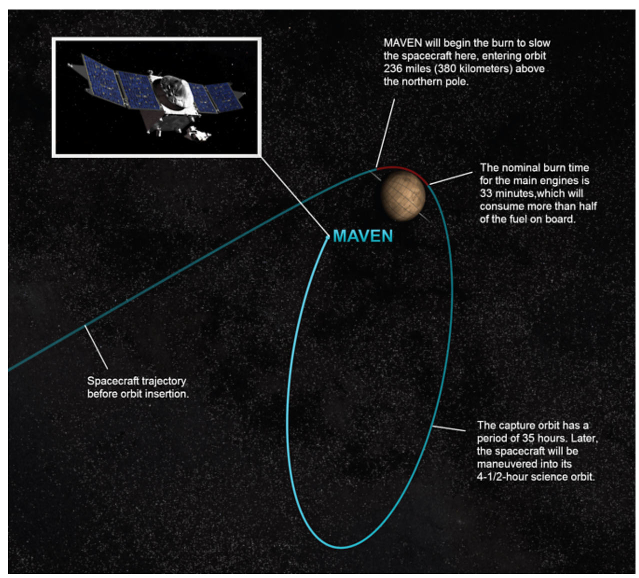


Figure 9: MAVEN Mars orbital insertion (credit NASA [5]).

3.1. LEROS 4 high thrust apogee engine

The requirement to reduce propellant mass at launch from Earth is much more stringent when interplanetary missions aim to land, perform the necessary science and re-launch back to Earth. For Mars orbit insertion the spacecraft main engine typically burns more than 50% of the propellants on board, as described in Fig. 1 for NASA's MAVEN mission.

The LEROS 4 1100N High Thrust Apogee Engine is being developed to reduce the propellant consumption during planetary orbit insertion by providing much higher thrust than is currently available; this slows the spacecraft more rapidly and therefore reduces the total burn time required. This saves a considerable amount of propellant when working against the Martian gravitational field, therefore reducing total mass of the spacecraft at launch [6].

The LEROS 4 is a MMH/MON3 bipropellant mission enabler for ESA inter-planetary satellites and has been the subject of a five year development programme by the Nammo Westcott rocket development and test teams [6]. Heritage LEROS design knowledge from the 1980's and 90's has been the subject of intensive update to state-of-the art thermal, structural and performance modelling technology that was not available to the original design teams. Using this new suite of computerised rocket design tools the LEROS 4 has been through a number of design iterations at less cost and faster than was possible before. Even with improved analysis methods, substantial hotfire testing was still required to validate the design.

The LEROS 4 was fired over 1400 times during development testing in 2017. Injector and chamber combinations were fired extensively in order to identify the best possible configuration for the final high performance solution that showed stability of combustion and thermal equilibrium throughout the extremes of input pressures, propellant temperatures and bubble ingestion testing.

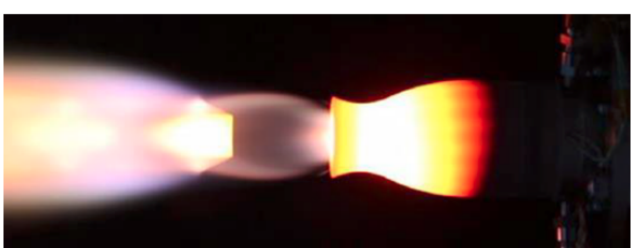


Figure 10: LEROS 4 engine steady state injector and chamber testing at the Westcott J3 sea-level facility.

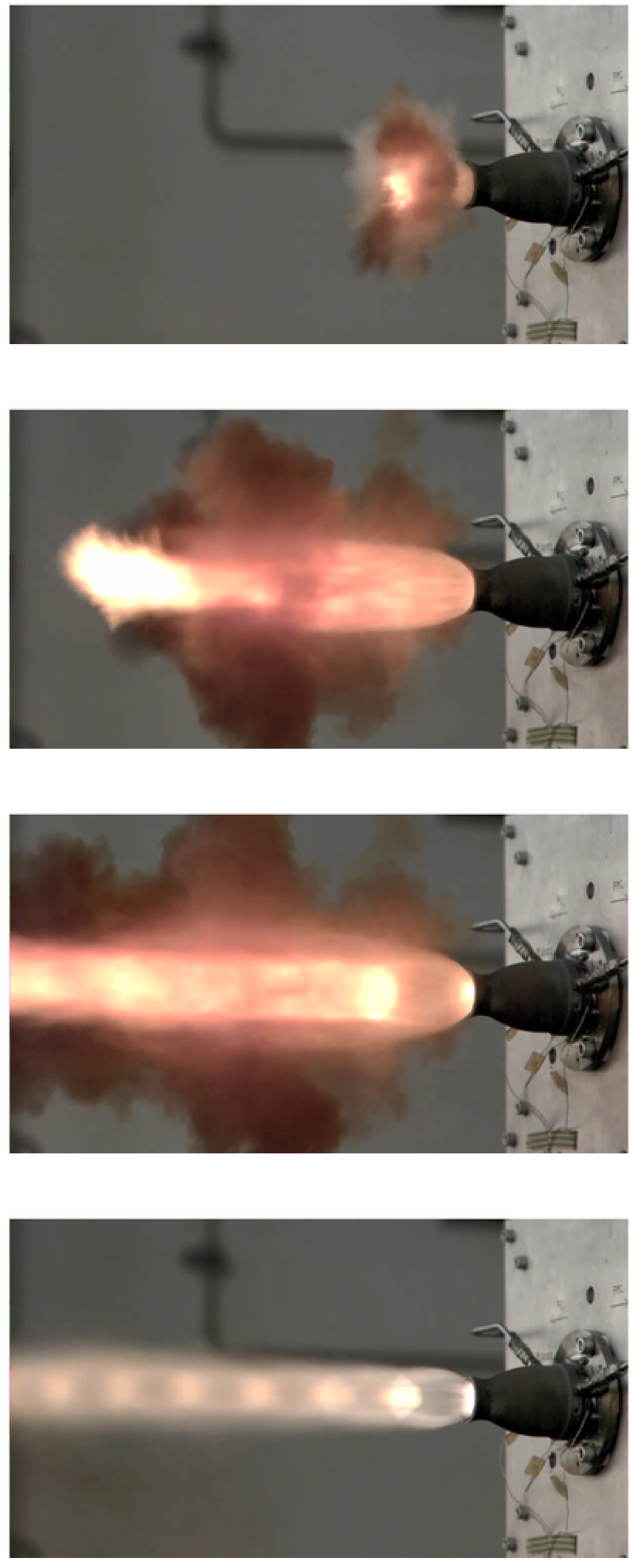


Figure 11: Ignition sequence for LEROS 4 undergoing early development testing at the Westcott J3 sea-level facility.

3.2. LEROS 2c apogee engine

The requirement for lower cost satellites has become a primary focus of the spacecraft primes. There is increasing competition in the global space industry which is driving more competitive technology for geostationary communications and data platforms. This inevitably needs the propulsion component and subsystem suppliers to respond with new products that require innovation and often challenge traditional 'heritage' space approaches to materials, manufacturing and testing.

The LEROS 2c is Nammo Westcott's answer to this requirement. Targeted by customers to produce a new high performance 430N 321s Isp MMH/MON3 apogee engine at a cost that is 30% lower than those currently incumbent upon European geo-satellites, the Nammo propulsion team set to work on this joint ESA/Nammo development.

Using the heritage LEROS 2b (407N, 319.5s Isp) as a known and proven design point, the first point of focus was on materials. The current apogee engine solutions used by the European primes feature expensive platinum alloys for their combustion chambers. It would therefore be extremely difficult to meet the cost target using noble metals so early on the decision was made to utilise a C103 Niobium chamber with the proven R512E disilicide oxidisation resistant coating. The capabilities of additive layer manufacturing were used to reduce the number of parts for the new head-end design and hence also the number of seals required. The expansion cone material choice was a titanium alloy which offers mass saving over the heritage LEROS niobium expansion cone route. Finding a supplier who could spin-form the complex gradient curve to the required challenging tolerances proved difficult, but persistence and collaborative working produced success. The Nammo manufacturing team worked closely with the mechanical design team to develop a strong, high integrity titanium/niobium jointing process to enable the new expansion cone to be electron-beam welded to the chamber.

Significant effort was put into structural and thermal modelling of the new engine which resulted in reduced development timescales and provided a higher level of confidence than previously possible in the new design solutions. Development model injectors, head ends and chambers were manufactured to the new designs and an extensive programme of hotfire testing commenced.

(a) LEROS 2b

(b) LEROS 2c

Figure 12: The LEROS 2b (a) alongside the innovative LEROS 2c (b) engine.

The LEROS 2c was taken through all Development Model test firings at Westcott J3 during 2016 and throughout 2017 undergoing hours of hotfire testing and producing valuable performance data. This took the engine through to the Engineering Model phase that included significant high altitude hotfire testing at Moog Niagara Falls. High performance and capability was proven and the LEROS 2c is due to go through a full ESA NeoSat Qualification programme when the UK National Propulsion Test Facility high altitude main engine facility is commissioned at Westcott in 2019.

3.3. National propulsion test facility

Westcott has been chosen as the site for the new UK National Propulsion Test Facility. This state-of-the-art facility has been awarded significant funding by the UK Space Agency as it is seen as a strategically essential capability for the UK to have in order to build its fundamental space growth aims.

Currently all chemical rockets with thrust exceeding 20N produced in the UK have to be taken overseas for high altitude testing. This is a tremendous draw upon the UK's ability to be cost and schedule competitive. The UK National Propulsion Test Facility will provision two new capabilities to UK rocketry: high altitude testing for qualification and production testing of in-space thrusters and engines up to 1500N, and low-cost medium altitude testing for new product and alternative propellant testing.

The Nammo Westcott J3 sea-level facility is forming the basis of the new altitude capability as it offers already proven system control, data capture, propellant feed, pressurisation, and conditioning systems together with the necessary health and safety provision. The development from sea-level to altitude testing includes: vacuum cell, heat exchangers, cooling for rocket exhaust gases, a steam-ejector vacuum generation and control system, steam boiler, cooling water re-use systems, etc. The design, build and commissioning phases are being managed by the European Space Agency Chemical Propulsion team based at ESA ESTEC. Commissioning of the new system is planned to take place in 2019.

The facility will be managed and engine testing scheduled by the Science and Technology Facilities Council who are responsible for running many of the UK's key test sites. Chemical rocket manufacturers and academic institutions from all over the world will be able to book test time in the National Propulsion Test Facility which has the mandate of bringing new business and innovation to the UK space industry.

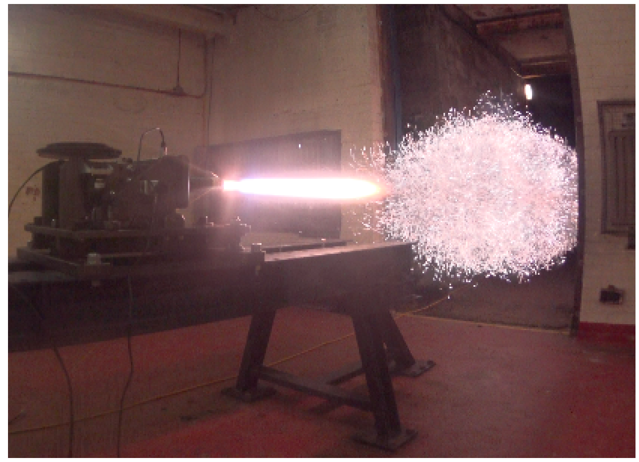
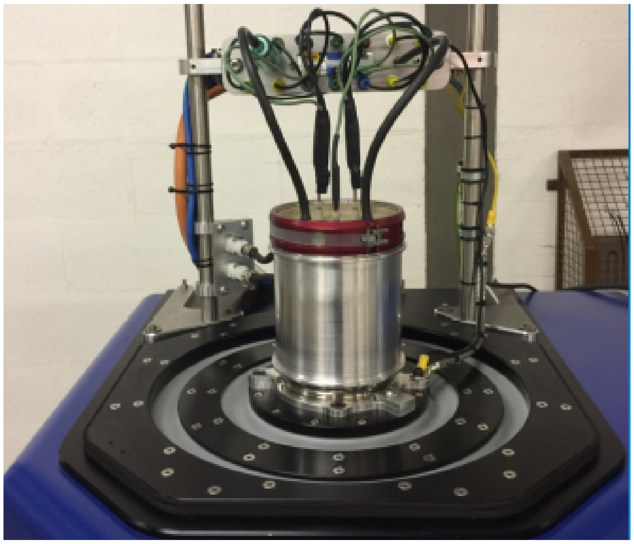


Figure 13: Falcon low thrust test stand for characterising new propellants and testing small motors.

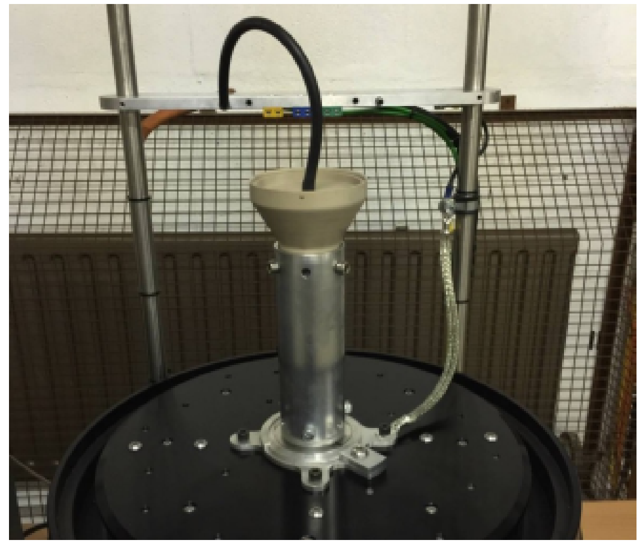
4. THE FALCON PROJECT

Falcon specialises in fast-track, bespoke research and development, design, manufacture and testing of rocket motors and rocket engines. Falcon's 34-acre Westcott facility is licenced by the UK Health and Safety Executive (HSE) for production of rocket propellants and static testing of rocket motors. Falcon's Westcott facility has solid propellant production facilities using traditional mixing equipment or one of five resonant acoustic mixers. There are three test stands, one for low thrust propellant characterisation and small motors, one higher thrust test stand (90kN) for testing fast burning propellants, and one bespoke test stand for their Linear Rocket Motor technology.

Figure 14: Falcon UK's Westcott production and testing facility, in the original Westcott solid propellant storage area.



(a) Batch production setup using Resodyn LabRAM II mixer



(b) 'Mixed in case' setup using Resodyn LabRAM mixer

Figure 15: Resodyn equipment with custom Falcon designed vessels for mixing solid propellant.

4.1. Resonant acoustic mixing

Mixing of solid propellants requires extreme care in the handling and cleaning of mixing equipment. Many traditional techniques rely on mechanical mixing of propellants, which therefore requires high blade tolerances, robust shaft seals and consideration for equipment cleaning. These cleaning processes can be time consuming and generate hazardous waste.

Resonant acoustic® mixing (RAM) is an innovative mixing technology developed by Resodyn Acoustic Mixers. It comprises of an electromagnetically driven platform which automatically finds the resonant frequency of the platform and load. This results in both macro and micro scale mixing. Because the mixing process is non-intrusive, vessels can have a simpler shape and are easier to clean.

Falcon has adapted RAM equipment to be optimised for solid propellant production, including modifications to mixing vessels for static charge dissipation, vacuum degassing, thermal conditioning and process control. Near infrared, ultrasound, high speed video and x-ray tomography have all been used to investigate the process and finished product, and the resulting propellant has been shown to be mixed extremely well in a shorter time than conventional mixers. The technology has been used to create a variety of motor sizes and the World's first 'mixed in case' motor.

(a) 'Mixed in case' firing

(b) 6-inch motor

Figure 16: World leading tests of propellant made by resonant acoustic mixing: (a) the World's first firing of a 'mixed in case' propellant, and (b), the World's largest RAM motor made using 6 batches.

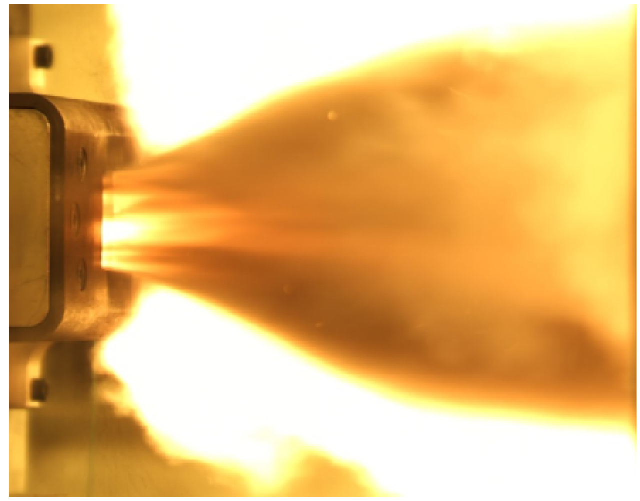


Figure 17: Fast burning propellant testing for Falcon's Linear Rocket Motor on the Falcon 1MN test stand at Westcott.

4.2. Fast burning propellants

Fast burning propellants are sometimes required for high thrust applications such as stage separation or retro rockets for landing. Their design is very sensitive to changes in propellant chemistry and regressive geometry of the grain. Falcon has experience in design and production of fast burning propellants with a range of grain geometries and thrust classes.

One spin-out application of this technology is the Linear Rocket Motor (LRM) designed and tested by Falcon over the last few years for a life-saving military application. When an improvised explosive device detonates under an armoured vehicle, the armour is often sufficient to withstand the blast but the resulting acceleration of the vehicle kills or severely injures the passengers.

ABBS (Advanced Blast and Ballistic Systems Ltd) and Falcon's solution to this problem is to mount an extremely fast burning rocket motor on the roof of the vehicle. When the explosive devices detonates, the explosion is detected and the motor fires with a thrust of over 1MN but for a few milliseconds, counteracting the upwards acceleration from the explosive device and keeping the vehicle on the ground. The net acceleration felt by the passengers is therefore small. To obtain such a high thrust the LRM must have a large throat area and large propellant surface area, but a conventional cylindrical motor would be prohibitively large for the geometric constraints of the vehicle. The LRM is therefore long, thin and rectangular, with nozzles on one face. This provides the necessary throat and propellant area within a compact form factor.

The LRM has been static tested extensively at Falcon's Westcott facility and has been successfully tested on a representative vehicle in a mock attack scenario. The LRM is now entering another production phase with further research planned.

Figure 18: Testing of Falcon's Linear Rocket Motor on a mock-up of an armoured Land Rover driving over an improvised explosive device. The top plume is from the Linear Rocket motor and the bottom plume is from the improvised explosive device.

5. CONCLUSIONS

Westcott has a long history of UK propulsion testing, initially for military applications. The site is now home to several commercial companies with a range of rocket testing skills, which 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 two years. 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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