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Development of IM Brimstone Rocket Motor; An IM, Minimum Smoke, Air-Launched System

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1. Summary

Roxel is the manufacturer of the IM rocket motor for MBDA's advanced IM Brimstone missile, which are supplied to the UK MoD for Tornado GR4. The introduction of the updated rocket motor represents a significant improvement in IM performance (mostly Type V's or IV's). However, being Roxel's first minimum smoke, air-launched system this brought significant development challenges. The paper describes how two particular problems discovered during development were overcome and discusses the lessons learnt that followed.

In order to de-risk the start to qualification, and provide very high confidence that the problems were fixed, a series of motor trials were conducted to demonstrate and measure the design margin. One such trial examined the integrity of the rocket motor charge and its capability to withstand cracking when subjected to thermal shocks. This involves exposing the motor to many successive cycles, where one cycle is defined as 24 hours at +71°C immediately followed by 24 hours at -46°C. The pre-qualification trials demonstrated on a few motors the capability of the improved rocket motor to withstand at least 40 thermal shock cycles. Some of these motors had also previously been exposed to 98 days C2 arctic storage. A few of these rocket motors were then statically fired afterwards at -46°C to further prove the robustness of the charge. This represents a world class achievement never previously demonstrated on motors of a similar class or propellant.

2. Rocket Motor Design

The IM Brimstone Rocket Motor (motor name is "Vulcan") has been developed to meet the requirements of the Brimstone IM Missile for the UK MoDs Tornado GR4. The proposed motor design is a progression of that developed through the UK MoD DOSG funded SLIM Technology Demonstrator Programme, Roxel private venture work and the Guided Weapon Risk Reduction programme (GWRR). Studies and trials spanning

Roxel's IM Brimstone Rocket Motor (Vulcan) more than 10 years have resulted in a mature design with proven Insensitive Munitions capability.

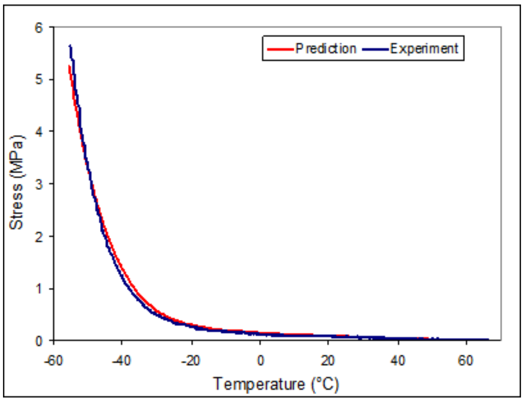
The design concept employs a steel strip laminate (SSL) case structure with lightweight aluminium alloy fixtures containing a case-bonded, minimum smoke, 1.3 hazard class, elastomer modified cast double base (EMCDB) propellant charge. It is capable of operation at temperatures between -46°C and +71°C. Also featured is a minimum smoke propellant pyrogen igniter with an Ignition Safety Device.

3. Issue Encountered

During the development a crack in the conduit of the rocket motor was observed, along with propellant bondline features. An investigation was initiated with the aim of robustly resolving these issues as quick as possible. The programme was managed with a series of independently reviewed milestones to ensure sufficient confidence was obtained to approve start of the qualification process.

4. Improvement Plan

The improvement programme involved four main phases; investigation of failure route causes, evaluation of the improvement options, risk reduction of the revised motor solution and motor qualification.



Model Prediction Compared to Thermo-mechanical Experiment

One of the key areas for improvement was the charge modelling methodology (discussed further in *"Advanced Charge Structural Modelling For IM Brimstone and Future Solid Rocket Motor Systems"*, J. Nota, Roxel (UK Rocket Motors) Ltd., IMEMTS 2015) since failure wasn't originally predicted. Significant improvements have been implemented to create a non-linear viscoelastic model that accurately predicts the response of the motor charge. The methodology now includes consideration of the damage effects from environmental trials and also models the propellant bondline margin. All of this required significant propellant testing to validate the model and led to significant advances in Roxel's propellant damage and propellant bondline test techniques. Using the improved model the optimal design solution was selected to ensure sufficient design margin was present to avoid cracking of the conduit.

Other key areas for improvement included the design and manufacture processes for the propellant bondline. The investigation reinforced known good practices for the bondline that included avoiding liquid rich regions and maximising local powder compaction. The objective of these good practices is to optimise the initial bond strength and ensure it remains robust throughout its life cycle. Examples of these improvements include smoothing the internal lining profile to avoid significant profile changes, process aids to produce a rough adhesive surface finish, staged powder filling and consolidation during the casting process and moisture control. These improvements, as well as other novel improvement techniques that weren't subsequently selected, showed more than a 50% increase in propellant bond

Staged Powder Filling and Consolidation During Casting Process

strength. Failure to adopt these good practices may lead to chemical degradation of the bondline during prolonged exposure to high temperature.

A significant amount of physical testing was conducted to demonstrate the improvements to ensure that programme decisions were made on quantifiable evidence with a sound technical understanding backing it up. In summary;

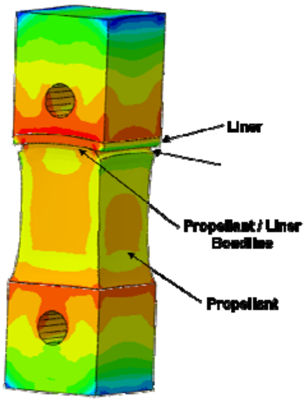
- ➔ Over 1000 x-ray inspections
- ➔ Over 600 thermal shock cycle transfers
- ➔ Over 400 bondline tensile tests
- ➔ Over 200 propellant tensile tests
- ➔ Over 40 bondline assessment (BLA) charges manufactured
- ➔ Over 30 motors manufactured

5. Improved Rocket Motor Performance

In order to provide very high confidence that the problems have been fixed a series of motor trials were conducted to demonstrate and measure the charge design margin. The critical environmental trial that examines the integrity of the charge and its capability to withstand cracking is the thermal shock trial. This involves performing many successive cycles, where one cycle is defined as 24 hours at +71°C immediately followed by 24 hours at -46°C. This trial is particularly testing because the motor is repeatedly fully conditioned cold such that it is repeatedly exposed to high levels of strain. This, therefore, demonstrates its capability to withstand cumulative cyclic damage and rapid changes in temperature. The confidence trials demonstrated on a few motors the capability of the improved rocket motor to withstand at least 40 thermal shock cycles with no signs of cracking. Some of these motors had also previously been exposed to 98 days C2 arctic storage which cycles between -46°C and -37°C. This therefore provides evidence of a significant margin for the charge and bondline. Furthermore, a few of these rocket motors were then statically fired afterwards at -46°C. This proves that the charge (and structure) can withstand the pressurisation loads, at its highest strain condition (at cold), after a

Vulcan Rocket Motor -46°C Static Firing After Exposure To 98 days C2 Diurnal Cycling and 40 Thermal Shock Cycles significant amount of cumulative damage, which further demonstrates a robust margin for the charge.

Various techniques were developed and introduced in order to test the motor propellant bondline fresh and after a series of environmental trials. This is particularly challenging given the motor has a case bonded charge and is therefore not easily removed. Nevertheless, tensile bond test samples were machined from actual motors in order to characterise the bondline across the temperature range. These results were then used within the improved modelling methodology to predict a positive bondline safety margin. The propellant bondline performance was measured after completing the sequence of confidence trials, which replicated the forthcoming qualification trials and explored the design margin with aggravated robustness trials. These included 40 thermal shock cycles and long periods of storage at constant 71°C. An increase in the propellant bond strength (from fresh) was measured across the temperature range at the end of all of these trials. This increase is on top of the increase achieved at fresh (discussed in section 4). Therefore this demonstrated that a robust and consistent solution had been achieved for the propellant bondline.

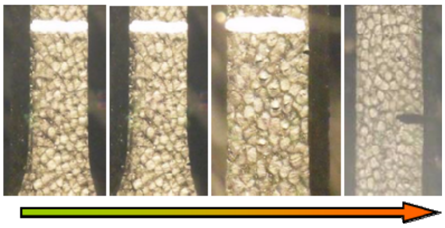


Tensile Bond Test Sample Modelled (Von Mises Stress Presented)

6. Development Lessons Learnt

From this experience there are many lessons that have been learnt that have been implemented for future development programmes. Below is a summary of some of those lessons:

➔ Extensive Propellant Characterisation.
To conduct sub-scale propellant trials that go beyond the typical characterisation trials. Specifically to assess the response of the propellant to damage effects from thermal cycling, low temperature strain endurance and thermo-mechanical cycling damage.



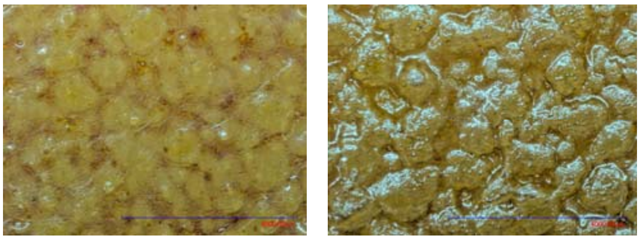
Increase In Damage Cycles

➔ Advanced Non-Linear Viscoelastic Model.
Use of the advanced model to closely predict the non-linear viscoelastic response of the rocket motor charge (discussed further in *"Advanced Charge Structural Modelling For IM Brimstone and Future Solid Rocket Motor Systems"*, J. Nota, Roxel (UK Rocket Motors) Ltd., IMEMTS 2015). Also, to calculate both fresh safety factors and safety factors for cumulative environmental trials. This is achieved through the use of a damage methodology that is established from the extensive propellant characterisation trials.

➔ Charge Design Robustness.
Consideration of techniques to reduce the stress and strains in critical areas of the rocket motor charge design, for example, conduit diameter size, peripheral stress relief liner, improved propellant properties. All of which are to be quantified through motor level design margin trials.

➔ Bondline Process Improvements.
To achieve a robust propellant bondline then the following manufacturing process principles should be followed:

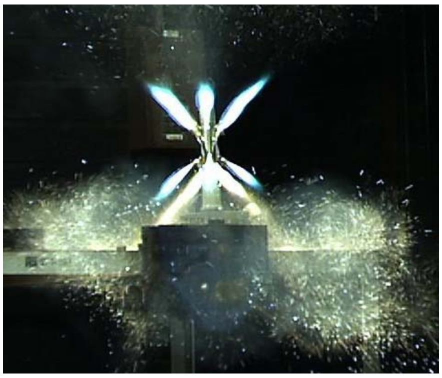
- Smooth case lining for better propellant consolidation.
- Use of a process aid to physically create a rougher and increased bond surface area (see images below), as well as, produce a chemically cleaner surface to promote diffusion bonding of the propellant to the liner.



Bonding Surface Finish: (Left) Original, (Right) Improved

- Balance the lining cure temperature to optimise both the propellant bond and the case liner bond strength.
- Control moisture throughout the process and during storage.
- Staged powder compaction during the powder filling operation and increase the propellant casting consolidation force in order to reduce liquid rich regions at the bondline.

➔ Motor Bondline Testing.
It is imperative to quantitatively characterise the motor propellant bond strength. Furthermore, this can only be achieved by testing it at the motor level. This ensures that the manufacturing process parameters and appropriate load levels are considered. For cartridge loaded systems this is simply achieved through removal of the charge from the motor to create test samples. For case bonded systems this is slightly more challenging and requires metal-propellant machining capability. Tensile test samples of the propellant-liner-case bond can then be extracted and the residual strength measured at various temperatures and rates.



Igniter Firing

- Early Igniter Integration Trials.
  Although not related to the original problem it is highly recommended to conduct igniter testing at the beginning of a development programme. The interaction between the initiator, the gaine charge and the pyrogen is complex and requires careful design. The aim is to find the balance that ensures fast motor ignition at the cold end and limits the peak pressure hot. A difficulty to overcome is to achieve an effective ignition of the pyrogen without risking it cracking under cold firing conditions due to close proximity to the initiator and its associated shock wave.

- Design Margin Trials.
  Development trials which explore failure modes and demonstrate a design margin are extremely important. Some of the aggravated trials that have been found to be fruitful are as follows:

  - **Cooldown to failure.** This involves incrementally cooling the rocket motor down from its hot condition until it reaches its cracking temperature. The charge dimensions are measured at each temperature increment. This can be used to validate the charge structural model to ensure it is predicting the correct response and subsequent failure point of the motor.

  - **Thermal shock cycling to failure.** This involves performing a continual sequence of thermal shock cycles until either a failure is observed by x-ray or the trial reaches a safety point. A thermal shock cycle is typically cycling between the hot and cold operational extremes with minimal transition time and 24 hours conditioning time at each temperature. This trial demonstrates the charge and bondline robustness to a highly aggravated thermo-mechanical environment.

  - **High temperature trial.** This involves storage of the motor at constant high temperature until either failure at the propellant or bondline is observed or the trial reaches a safety point. Whilst this trial is highly aggravated when compared to typical in-service environments it can be used to quickly demonstrate the robustness of a motor bonding system to withstand chemical ageing.

  - **Cumulative damage pressurisation firing**. After successfully completing a design margin trial or extensive environmental trials then the motor asset can either be dissected and the propellant and bondline residual strength established or it can be fired. By firing the motor at the cold operational extreme temperature, after having experienced environmental cumulative damage trials beyond that required, then a pressurisation margin can be established.

    Either firing the motor at a colder temperature or with a smaller nozzle throat area are alternatives to consider having regard to changes to the viscoelastic response of the propellant.

7. IM Performance

The IM Brimstone rocket motor insensitive munition response represents a world class performance for air to ground launched systems. The IM signature has been established by the UK national authority to be as follows.

	Fast Cook Off	**Slow Cook Off**	**Bullet Impact**	**Fragment Impact 1830ms^{-1}**	**Fragment Impact 2530ms^{-1}**	**Sympathetic Reaction**
IM Brimstone Rocket Motor	V	IV*	V	IV	I	V*

* Demonstrated at missile level.

- ➔ Bullet Impact.
  The rocket motor incorporates a Steel Strip Laminate (SSL) case, which has excellent bullet impact IM mitigation properties. The premise for achieving bullet impact mitigation relies upon the material properties of the SSL case and the EMCDB propellant (no refractories or nitramines). The impact of the bullet is below the vulnerability threshold for a detonation response and the propellant will, therefore, react with a burning response and the SSL case will delaminate upon impact to reduce the level of confinement. A Type V response was achieved.

Vulcan Rocket Motor Type V IM Response to Bullet Impact;
(Left) During Reaction, (Right) After Trial Condition

- ➔ Fragment Impact.
  The premise for achieving fragment impact mitigation relies upon a system level approach combining the material properties of the SSL case, EMCDB propellant and velocity attenuation barriers in the rocket motor design. Barrier layers between the outside of the rocket motor and the propellant will facilitate a level of velocity attenuation of the fragment. Therefore, the case and case insulation will reduce the impact velocity into the propellant. At 1830ms^{-1} the impact of the fragment is below the vulnerability threshold for SDT of the propellant and also an XDT (unexplained detonation transition) response as the fragment passes through the charge conduit. The propellant will, therefore, react with a burning response and the level of confinement will then dictate the motor response. The velocity of the impact and exit of the fragment will cause the SSL case to delaminate and create a large vent area for pressure.

Vulcan Rocket Motor Type IV IM Response to Fragment Impact;
(Left) Initial Impact, (Right) Subsequent Burning Response

The 1830ms^{-1} trial conducted was assessed to be a Type IV IM response. The fragment was stopped by the igniter and therefore did not create an exit vent area. This, coupled with the method of retaining the motor, led to a few large fragments being expelled for a relatively low pressure event. With a different test setup or impact point then a Type V response might be expected.

A 2530ms^{-1} fragment impact trial was also conducted which gave a Type I response. It was considered that an XDT response was initiated.

➔ Fast Cook Off.
Mitigation of the fast heating threat relies upon the material properties of the SSL case. The threat scenario involves high temperatures that will cause the SSL adhesive to degrade such that the case will lose its structural integrity and create a large vent area. Under fast heating conditions the EMCDB propellant will auto-ignite at temperatures above circa 150°C. Upon reaching this temperature the propellant will ignite and burn. At this point then almost all of the structural strength of the SSL case adhesive is lost and the case will unravel and release the gas pressure. A Type V response was achieved.

Vulcan Rocket Motor Type V IM Response to Fast Cook Off;
(Left) During The Fire, (Right) After Trial Condition

➔ Slow Cook Off.
A slow cook off trial was conducted at the missile level within its missile packaging by MBDA. This represents the configuration in which this threat scenario would typically occur. Under slow cook off conditions the EMCDB propellant reaches its auto-ignition temperature and generates pressure. The lightweight rocket motor structure will then fragment and disperse several components. The aft closure is designed to eject under a rapid and high pressurisation rate (see image below). Within the missile configuration the fragment release is largely contained and as such results in a well mitigated response. A Type IV reaction was achieved.

Type IV Response in Slow Cook Off Trial – Ejected Aft Closure
(Images Courtesy of MBDA UK)

- Sympathetic Reaction.
  A sympathetic reaction trial was conducted at the missile level, within its packaging, and was arranged in a 2x2 formation by MBDA. The reaction of the acceptor rocket motors is similar to that of a fragment impact response. This is then followed by a fast cook off response for any secondary reactions to other acceptor motors. A Type V reaction was achieved.

8. Conclusion

In 2013 high confidence had been obtained that the improved rocket motor design was robust. This included the motor successfully completing 40 thermal shock cycles. The subsequent qualification programme was completed without incident in 2014 and the rocket motor certification followed soon thereafter. During qualification the production phase was readied and detailed productionisation activities were conducted. The first production deliverables were received by MBDA mid-2014 and hundreds of motors have been delivered since then. This, therefore, provides the UK MoD with a robust, minimum smoke rocket motor with a very good IM signature for use on the IM Brimstone missile on Tornado GR4. There are also many future opportunities for this rocket motor that are now made possible on the back of this success for new fast jet and helicopter platforms and the export market.