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Development of an IM Compliant, Minimum Smoke, Double Base Propellant Rocket Motor Containing Refractory Materials

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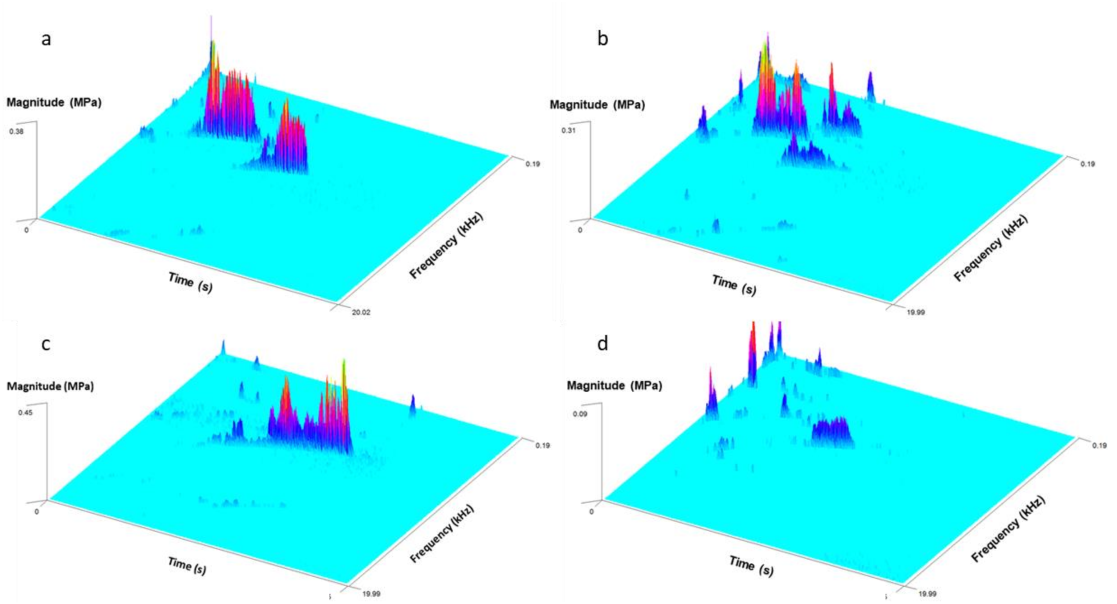
Abstract

Roxel UK undertook the development of a new minimum smoke rocket motor for use in a new missile system. Through static firings it was identified that the propellant charge required the inclusion of refractories in the formulation in order to suppress traditional combustion instabilities. In an effort to maintain a good degree of IM compliance, and sufficiently suppress the combustion instabilities, Roxel characterised the response of propellant containing silicon carbide (SiC) in varying levels, as well as zirconia, across a range of small scale and motor scale tests. These series of tests identified that a reasonable level of IM compliance could be achieved with a minimum smoke, double base propellant rocket motor containing refractory materials. This testing also highlights a requirement for further research into new or soft refractory materials to improve the IM response of motors requiring combustion instability suppression.

1. Introduction

Roxel is the manufacturer of an IM rocket motor for a new missile system, for use on several helicopter platforms. The development testing programme of the rocket motor demonstrated that it was susceptible to combustion instability due to the configuration of the propellant grain.

Acoustic driven combustion instability in rocket motors is a function of the propellant grain cavity geometry, propellant composition, pressure and internal flame field. Combustion instabilities are identified by using Fast Fourier Transformation (FFT) analysis of the pressure data captured throughout a firing to assess the magnitude of any longitudinal, radial or tangential modes.



FFT waterfall plots of: [a] 0% SiC [b] 'Very low' SiC% [c] 'Low' SiC% [d] 'Medium' SiC% showing significant decrease in 1st tangential mode with increasing SiC

There are many techniques to dampen instability which are designed to change or disrupt the oscillating gas flow. One of the most common techniques is to introduce damping by seeding the oscillating gas flow with solid particles. Inert refractory particles can be added to the propellant formulation at a low level (circa 1 to 3%) to perform this function. However, this traditionally results in increasing the shock sensitivity of the propellant leading to a reduction in the IM and, also, the mechanical properties of the propellant. Combustion instability itself is not necessarily a problem to the function of a rocket motor. Indeed it has been proven (reference 1) in Roxel UK's IM Brimstone 2 rocket motor that a minimum smoke propellant with no refractories delivers acceptable performance and an excellent IM signature. It is therefore a key decision of the rocket motor designer on whether to mitigate combustion instability at the potential expense of the IM performance.

Early development testing of the rocket motor confirmed that the level of acoustic combustion instability was unacceptable and resulted in unfavourable ballistic profiles. Therefore, low levels of refractory materials (circa less than 1%) were introduced into the propellant to suppress these instabilities. The paper describes the results from the test programme challenge to develop a rocket motor which contained sufficient refractory material to dampen the combustion instability while also maintaining a favourable IM performance.

Typical response of refractory filled rocket motor [left] and Roxel's IM Rocket Motor [right] to Sympathetic Reaction trial

2. Rocket Motor Design

The rocket motor (motor name is “Vulcan III”) has been developed to meet the technical and environmental requirements of the missile for the various helicopter platforms. The proposed motor design is a progression of the Vulcan Rocket Motor developed for the UK MoD IM Brimstone programme (reference 1) featuring a longer body, larger charge for increased performance, and reduced length nozzle to maintain the space envelope.

Roxel’s Vulcan III Rocket Motor

The design 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 containing ‘low’ levels of silicon carbide. Also featured is a minimum smoke propellant pyrogen igniter with an electronic Ignition Safety Device.

3. Issue Encountered

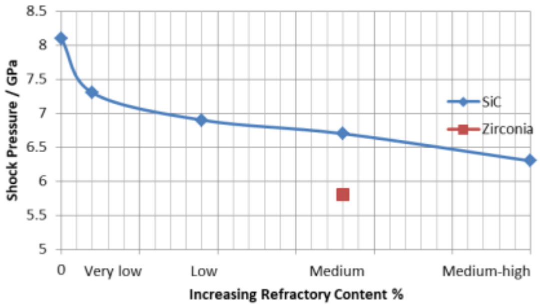
During the early development of the rocket motor scorch marks were observed on the external surface of the case following static firing. Following investigation this was determined to be caused by traditional rocket motor acoustic combustion instabilities due to the removal of instability suppressants to improve the IM properties. During the burn of the rocket motor a high frequency high pressure oscillatory mode was formed which damaged the propellant and caused an abnormal burn profile.

Typical example of case scorch mark following static firing [left] and charge damage observed on Real Time X-ray (RTX) during a static firing [right]

Several novel techniques were investigated experimentally to dampen the pressure oscillations, however; the best reduction to the combustion instability was to add refractory particles into the propellant formulation. This presented Roxel with the challenge of balancing instability suppression with a minimal impact on propellant properties and the IM response of the rocket motor. To meet this challenge both small scale and motor scale test packages were launched.

4. Small Scale Testing – EMTAP Test No. 22

Refractory materials and their particle size are selected to target specific acoustic frequency modes. Two such materials include silicon carbide (SiC) and zirconia. Propellant samples containing a range of SiC content (by mass) and samples containing a comparable amount of zirconia were submitted for EMTAP Test No. 22 Large Scale Gap (LSG) Testing. This was to determine the effect on propellant shock sensitivity and understand whether certain refractory materials affect the propellant sensitivity more than others and also understand whether there is a saturation point in this propellant for these negative effects. The LSG tests showed the traditionally held view that any inclusion of refractories results in a step change to the shock sensitivity. However, further increases in shock sensitivity are not linear and the saturation point was achieved with relatively low levels of refractory content. It was also observed that the zirconia increased the shock sensitivity more than the same mass of SiC.

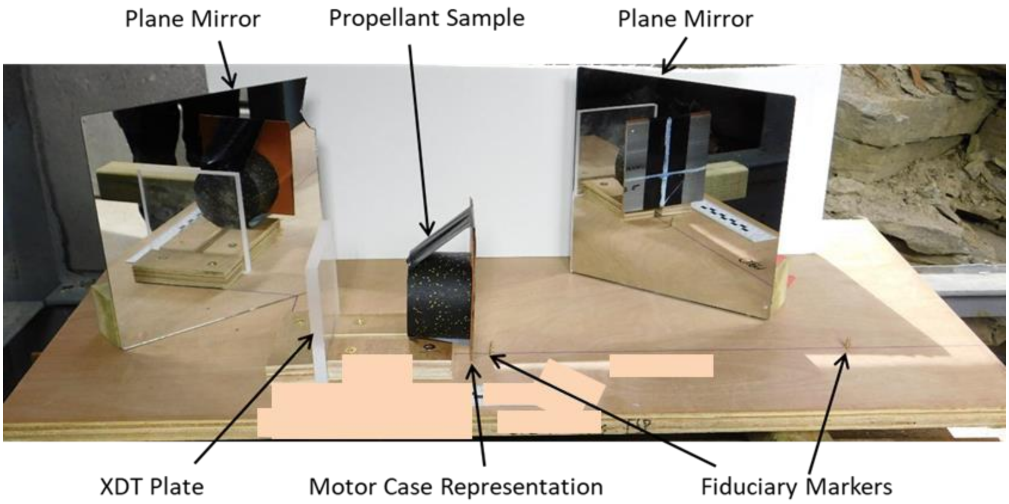


Large Scale Gap Test results for varying levels of propellant refractory content

5. Small Scale Testing – EMTAP Test No. 36A

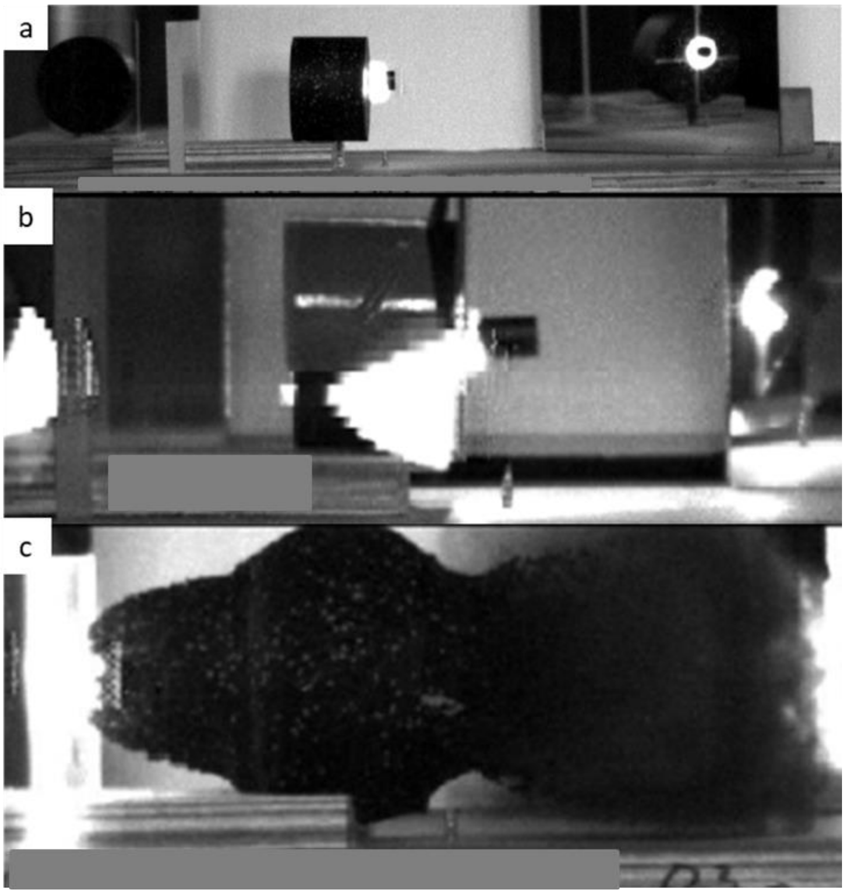
Additional to the LSG tests Roxel undertook the new EMTAP Test No. 36A fragment impact testing, with assistance from UK Defence Ordinance Safety Group (DOSG), on propellant containing low levels of SiC. Roxel were interested in obtaining a better understanding of the motor level response of the propellant so this testing was undertaken primarily with the 14.3mm STANAG projectile instead of the 13.1mm EMTAP projectile. This subscale testing facilitated multiple shots at a significantly reduced cost compared to a motor level trial that provides a better understanding of the Shock Detonation Threshold (SDT) velocity of the material sample rather than a single shot motor result.

The test setup was designed to reflect a motor level trial as much as possible. A propellant sample of 70mm diameter and 50mm thick was mounted on a stand with the representative rubber case insulant and case materials attached to the front face. Fragment velocity was calculated using fiducial markers of a specified separation with location and attitude of fragment impact assessed using the high speed video footage and plane mirrors. Finally, a plate of PMMA was mounted at a distance reflective of the motor conduit to investigate any XDT responses. Every shot was recorded with high speed video cameras at 120,000 FPS.



Example of test setup for EMTAP Test No. 36A

The results of this testing indicated an SDT vulnerability threshold of circa 1790m/s when in a “bare motor” configuration and no propensity for an XDT response. The SDT vulnerability threshold further increased to over 1900m/s when representative packaging was also used as part of the test setup (i.e. reflective of the missile in transit). Barriers and air gaps (constituting the rocket motor case and missile packaging) attenuate the velocity of the fragment and therefore reduce the impact shock into the propellant. This, therefore, further supports the necessity to conduct IM tests in the full, representative configuration according to the Threat Hazard Assessment.



HSV footage from EMTAP Test No. 36A test: [a] attitude and location check [b] sample showing prompt SDT response [c] sample showing lower order response

The EMTAP Test No. 36A testing is an excellent new tool to characterise a propellant material's SDT vulnerability threshold and therefore aid in the design process. However, it should not replace the testing of the response of a full rocket motor configuration under the impact IM threats. Shock attenuation of a fragment cannot fully be represented by a sub-scale test. Roxel UK has experience of a minimum smoke CDB propellant rocket motor system with higher levels of refractory content, multiple case barriers, a relatively large calibre, which consistently produced a Type V response to the 2530m/s fragment impact IM trial (reference 2).

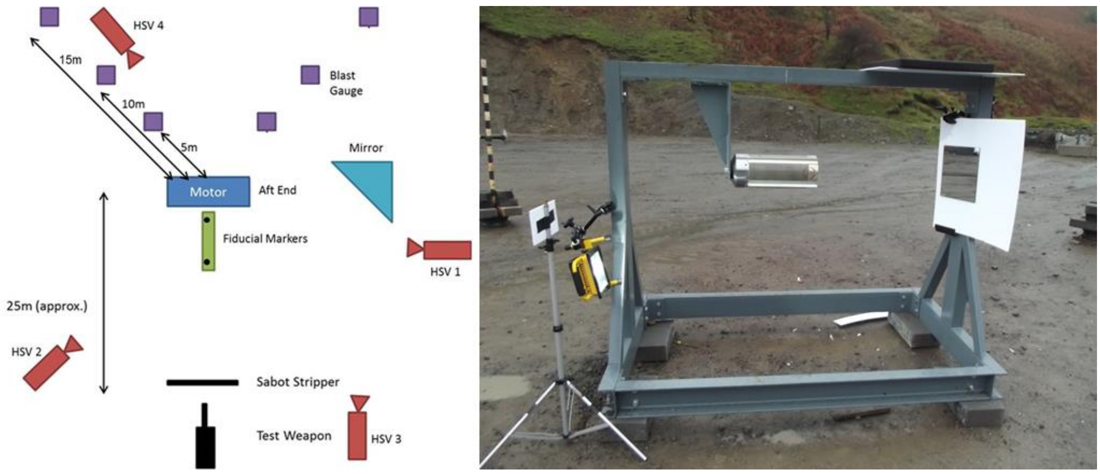
Therefore, given the results of the Vulcan III rocket motor EMTAP Test No. 36A SDT vulnerability threshold were near to the 1830m/s fragment impact IM trial velocity it was considered necessary to proceed to motor level impact trials.

6. STANAG 4496 Fragment Impact Trials

Roxel proceeded to undertake motor level fragment impact trials at 1830m/s with varying levels of SiC in the propellant, selecting 'very low', 'low' and 'medium'. The aim of these trials was to investigate whether scaling up to a fully representative asset changes the response from that determined based on small scale data. Propellant charges were cast into motor cases to create a rocket motor fully representative of the intended production standard with only the propellant blend (SiC refractory content) varying between each motor.

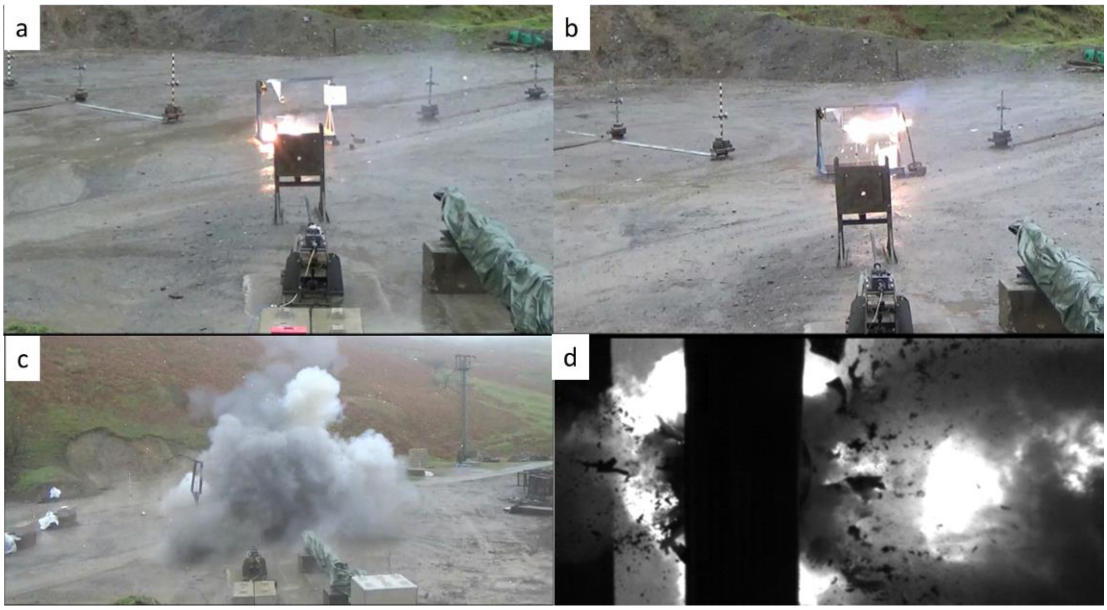
The principle of this design achieving a good fragment impact result is related to the properties of the SSL case and the EMCDB propellant (reference 3). It relies on the propellant being sufficiently insensitive and the case and insulation to provide a sufficient level of fragment velocity attenuation to below the SDT vulnerability threshold. Further to this, the nature of the SSL construction means that very large venting areas are created to ensure a benign low pressure burning response.

Each motor was mounted to the test fixture using the forward end only as this is reflective of how the motor would be held in the missile configuration. Blast gauges and high speed video cameras were used to capture the response of each motor to the fragment, with the velocity being calculated from pre-set fiducial markers.



Motor Fragment Impact trial arena layout [left] and motor mounting [right]

As expected the rocket motor containing 'medium' SiC levels gave a high order, detonation response while the motor with 'very low' SiC levels gave a lower order burning response similar to the 0% SiC (legacy) response (reference 1). Note that as a result of the impact the motor was removed from its mounting and burned benignly on the trial arena floor. Interestingly the motor containing ‘low’ levels of SiC also produced a low order burning response. The blast gauge data and high speed video footage was presented to the UK SME’s and has been given an unofficial rating of Type I for the ‘medium’ SiC content motor and Type IV/V for both the 0% and ‘low’ SiC content motors.



Motor Fragment Impact trial results:
[a] ‘Very low’ SiC% [b] ‘Low’ SiC% [c] ‘Medium’ SiC% [d] Close up of ‘Low’ SiC response

This test result demonstrated that there are effects at motor level which aren’t accounted for at the sub-scale testing, even with the improved EMTAP Test No. 36A. It is possible to achieve a design containing sufficient refractory materials to dampen combustion instability, which is also compliant to the STANAG 4496 Fragment Impact requirement.

6. STANAG 4396 Sympathetic Reaction Trials

Sympathetic Reaction Trial Setup

To build on the positive Fragment Impact results obtained Roxel also completed Sympathetic Reaction trials with motors containing ‘medium’ and ‘low’ SiC levels. Two motors (per trial) were configured side-by-side on the trial range to be held by the forward end only at a separation distance representing missiles in their storage containers and included a metallic structure between them to represent the missile containers. In both trials the donor motor was painted orange and the acceptor grey to aid fragment mapping and the rear face of each of the witness plates were painted similarly. In-bore detonation using plastic explosive was used to initiate the donor motor.

The event was captured by four high speed video cameras and three banks of Blast Over Pressure (BOP) gauges with 120° separation at 5m, 10m, and 15m.

The trial with ‘medium’ SiC content motor demonstrated a Type I detonation response of the acceptor motor, which was confirmed by the BOP gauge data and review of the high speed video footage that showed asymmetric growth of the blast indicative of a secondary detonation.

‘Medium’ SiC% Response [left] and asymmetric blast growth [right]

The ‘low’ SiC content acceptor rocket motor demonstrated a Type III explosive response when subjected to the same stimuli. Review of the BOP gauge data showed no secondary detonation peak and the high speed video footage clearly showed the acceptor motor being entirely engulfed in the blast with no secondary blast growth.

‘Low’ SiC% Response [left] and acceptor motor engulfed by donor blast [right]

Review of the arena camera footage and the fragment maps highlighted another significant difference between these trials which was that the ‘low’ SiC content motor ejected significant fragments including pieces of propellant which were still burning, whereas everything was consumed in the detonation of the ‘medium’ SiC content motor.

7. Conclusion

Roxel UK has successfully proven that a compliant fragment impact and sympathetic reaction IM performance can be achieved with their Vulcan III rocket motor with inclusion of sufficient SiC refractories to dampen combustion instability.

The EMTAP Test No. 22 Large Scale Gap tests demonstrated the traditionally held view that any amount of refractory results in a step increase in sensitivity but also showed that the sensitivity further increases with increasing levels of SiC.

The selected propellant blend with ‘low’ SiC content was subsequently taken through the new EMTAP Test No. 36A to better understand the SDT vulnerability threshold. Small scale samples representing propellant in the motor configuration, and propellant in a packaged missile configuration achieved an SDT vulnerability threshold of 1790m/s and over 1900m/s, respectively.
This data was then supported by motor level (1830m/s ± 60m/s) Fragment Impact tests where an unofficial Type IV/V reaction was obtained for motors with propellant of 0%, ‘very low’ and ‘low’ SiC levels which then degraded to a Type I reaction at ‘medium’ SiC content. This effect was then further investigated with motor-to-motor Sympathetic Reaction trials with the motors set up to represent their storage conditions while on deployment; a Type III reaction was achieved with the ‘low’ SiC content motors whereas the ‘medium’ SiC content motor gave a Type I reaction.

These trials further demonstrated that a level of IM compliance could be achieved for propellant containing refractories if other design considerations are taken. Additionally it showed that, in this motor configuration, the inclusion of inert refractory materials did not increase the propensity for an XDT reaction.

The testing undertaken highlights that in certain design configurations it is possible to retain refractory materials within the propellant, which may affect small scale sensitiveness, without negatively impacting the motor scale IM performance. Follow on work might explore this conclusion further considering the role of alternative or soft refractory materials and their ability to balance combustion instability dampening and achieve a good IM performance.

8. References

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[2] “Roxel IM technology, analysis of trial results, future IM programmes in France and UK”, A Strickland and J-C Nugeyre, IMEMTS 2009 (Tucson).

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9. Acknowledgements

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