# IM Rocket Motor Design and Assessment

I G. Cullis*, R. J. Cornish, P. J. Gould, P. Ottley, A. D. Wood
QinetiQ, Fort Halstead, Sevenoaks, Kent TN14 7B, United Kingdom
* Email: igcullis@qinetiq.com

## ABSTRACT

Missile systems used in current operational theatres can be vulnerable to bullet and fragment impact. In many cases this is due to shock initiation or detonation of damaged propellant spalled across the central bore of the rocket motor, although the uncertainty leaves it defined as unknown to detonation transition (XDT).This paper describes the research to develop and validate a predictive modelling capability to understand XDT in a double base propellant rocket motor.

## INTRODUCTION

There is a requirement for the UK to be able to both design and manufacture Insensitive Munition (IM) rocket motors and to assess foreign rocket motors for in-service use under a wide range of conditions. Rocket motors can be vulnerable to bullet and fragment impact due to shock initiation or detonation of damaged propellant spalled across the central bore of the rocket motor, although the uncertainty leaves it defined as unknown to detonation transition (XDT) [1, 2].

The primary objective of the work described herein was to demonstrate a validated predictive modelling capability for XDT in rocket motors, including the ability to understand and define the influence of rocket motor design parameters on XDT response. There were two supporting objectives. The first was to demonstrate a material characterisation test process needed to provide the material data for propellant material models, including damage, ignition and burning. The second was to develop and demonstrate of small scale tests to determine a) the propensity of a propellant formulation to exhibit XDT behaviour; b) the importance of rocket motor design parameters and materials to remove/mitigate any XDT response.

The propellant systems studied in the programme were Elastomer Modified Cast Double Base (EMCDB) and composed of various proportions of yellow and black pellets bound with a consistent binding mixture. The propellant systems were provided by Roxel. The black pellets contain a mixture of nitrocellulose (NC) and nitroglycerine (NG) only whereas the yellow pellets contain NC, NG and nitramine. To assess the role of the nitramine in the XDT response 4 propellants, designated A, B, D & E, were manufactured each containing a different ratio of yellow to black pellets. Propellant A had a yellow to black pellet ratio of 2:3. Propellant B was composed entirely of black pellets. Propellant D had a yellow to black pellet ratio of 1:4 and Propellant E had a yellow to black pellet ratio of 3:2.

The paper will describe the work in terms of three technical challenges: Capability to demonstrate XDT, Capability to understand XDT and Capability to predict XDT.

## CAPABILITY TO DEMONSTRATE XDT

A considerable effort has been expended within the programme to develop two small scale tests capable of studying XDT in a rocket motor propellant to characterise fragmentation of the propellant and to observe and characterise the XDT process.

A spherical projectile, a high hard steel ball bearing 14mm in diameter, was selected as the projectile, to eliminate projectile orientation effects at impact with the target. The test is however quite general and cylindrical projectiles could be readily substituted. A total of eight fragmentation experiments and thirty nine XDT experiments were performed under the programme.

Fragmentation: As the XDT process is governed by the ignition and burning of the debris cloud generated by the impact of the projectile the first test was developed to observe the formation and development of the debris and to soft-recover the fragments to enable their size distribution to be determined.

The sample of propellant was a slab 65mm by 65mm by 30mm thick. These dimensions ensured the sample remained intact post impact and a representative volume of material was contained within the debris cloud. To accommodate the vertical alignment of the recovery system a simple explosive launch technique was developed to launch the projectile at velocities up to about 1200m.s$^{-1}$.

The impact and fragmentation process was captured using Phantom 7 high speed video cameras, with refined triggering to provide a robust methodology for the visualisation of the fragmentation process. A frame from one of these visual records is shown in Figure 1 and the fragment size distributions for all propellants is in Figure 2.

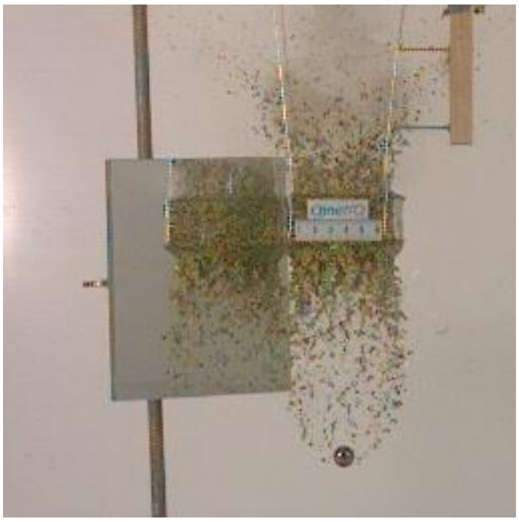

*Figure 1: Debris cloud for Propellant A generated by an impact velocity of 1009m.s$^{-1}$*

During collection and analysis of the fragments, it was noted that some of the smaller fragments adhered to each other. The disparity between the two results for Propellant B at low fragment size may be due to this and it may also have a bearing on the bridge in the data between the high and low size fractions for all propellant variants.

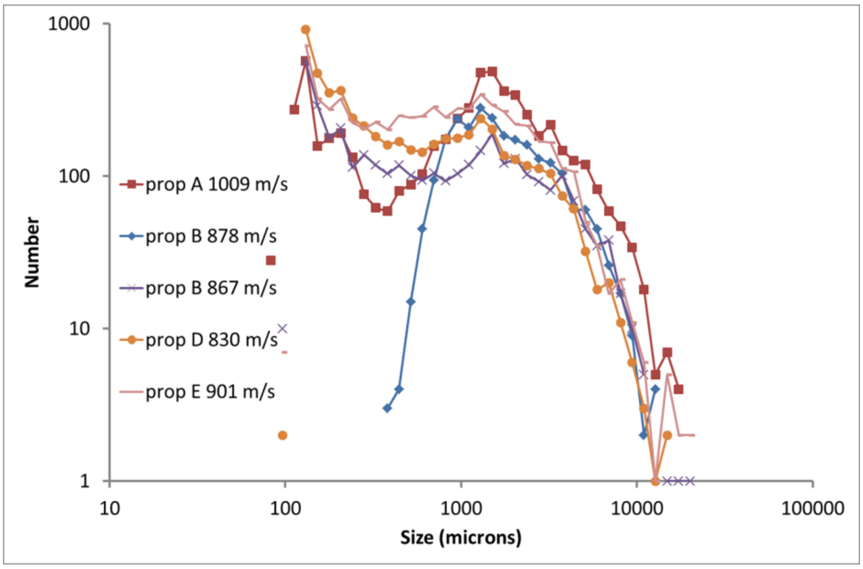

*Figure 2: Particle size distributions for all propellants*

<u>XDT</u>: To study the XDT response, a gun launched system was employed to provide accurate control of projectile velocity. A glass plate was positioned behind the propellant specimen to provide a surface for ignition of the debris cloud when it impacts the plate and is pinched by the projectile. A mirror behind the glass plate and angled at 45° allowed the motion of the rear surface of the propellant and the impact and ignition of the debris cloud to be visualised. The Phantom 7 cameras were demonstrated to be capable of resolving and distinguishing the energetic response as a function of impact velocity, as shown in Figure 3. However the camera interframe time of 2.56μs was unable to resolve the details of the ignition and growth of the reaction and in particular the burn back velocity through the debris cloud, which is a key measurement for validation of the I&G model employed in the numerical simulations.

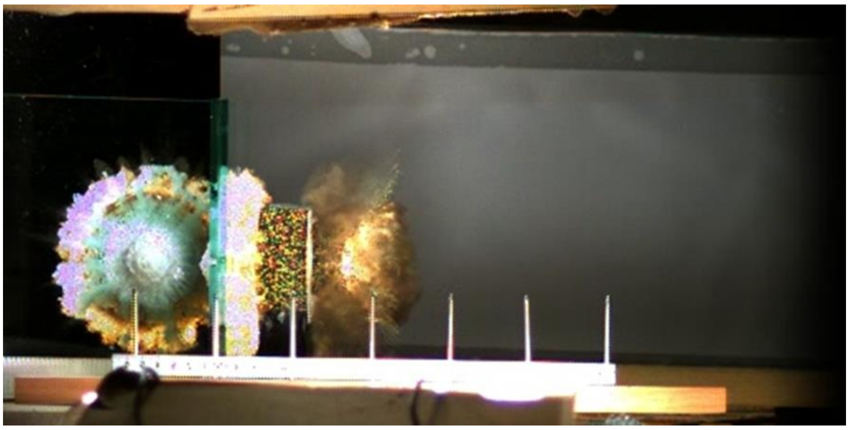

*Figure 3: Phantom 7 image of the propellant burning response*

To overcome this limitation the capability of the new Kirana high speed video camera to resolve the ignition and growth (I&G) process was investigated. The Kirana camera has an inter-frame time of 1.0ns, some 100 times faster. A new triggering system was successfully developed to accommodate the reduced number of frames in an exposure.

The Kirana exceeded all expectations in providing extraordinarily detailed images of the I&G process. An example of these images is shown in Figure 4 for Propellant A.

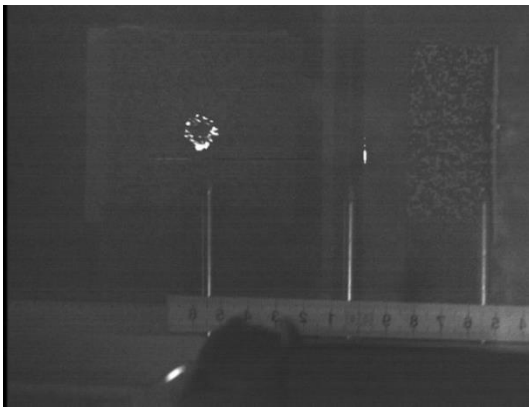

*Figure 4: Ignition process in Propellant A captured by the Karana camera*

The impact velocities and the observed burning, XDT or shock to detonation transition (SDT) response were measured and are presented in Figure 5. It can be observed that within the capability of the gun, a projectile velocity of 2050m.s$^{-1}$ is unable to generate a response more severe than burning in Propellant B, which was to be expected, e.g. due to the lack of nitramine in this composition.

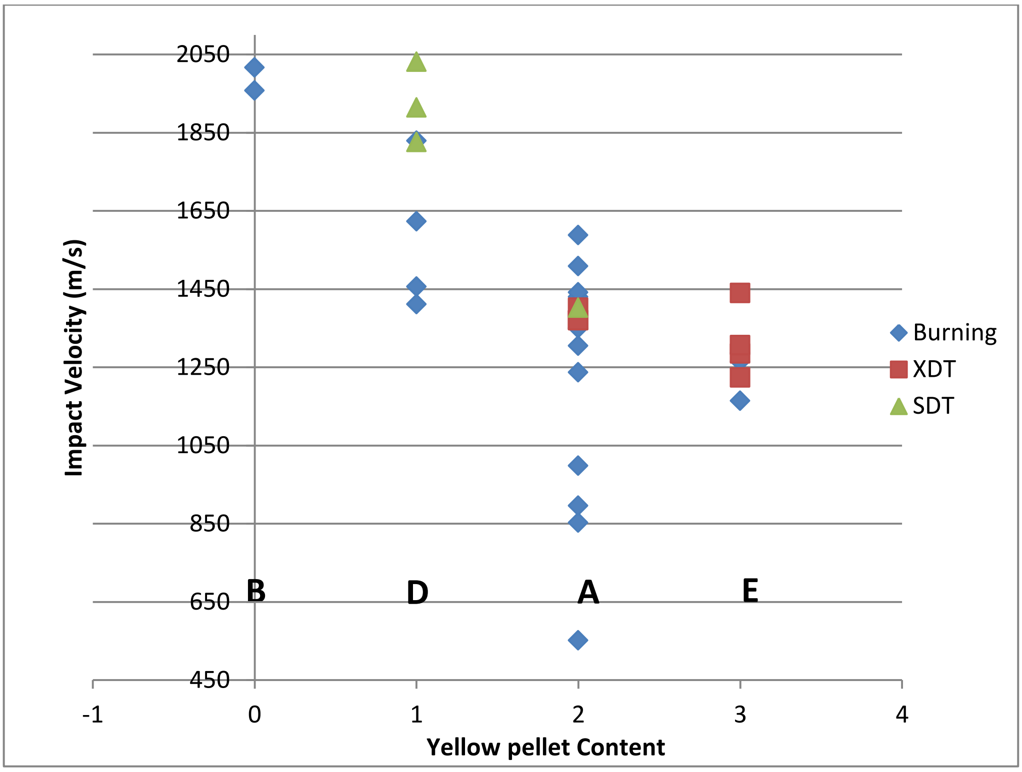

*Figure 5: Observed energetic response as a function of impact velocity and yellow pellet content*

The results for Propellants A & E show the impact velocities required for XDT and SDT overlap with those for a burning response. This has been interpreted as being due to a homogeneity issue in the distribution of the yellow pellets and the diameter of the projectile.

## CAPABILITY TO UNDERSTAND XDT

The second element of the programme was the development of material science based material models capable of describing and predicting the thermo-mechanical response of double base propellants under a wide range of strain, strain-rate and temperature.

The extensive material characterisation tests were developed and executed by Cambridge University, with the majority of the research performed by Rachael Boddy as part of her studies for a doctorate [3].

Equation of State: Group Interaction Modelling (GIM) [4, 5] was used to predict the Equation of State (EoS) of the different propellants is able to predict the measured Hugoniot very well, Figure 6.

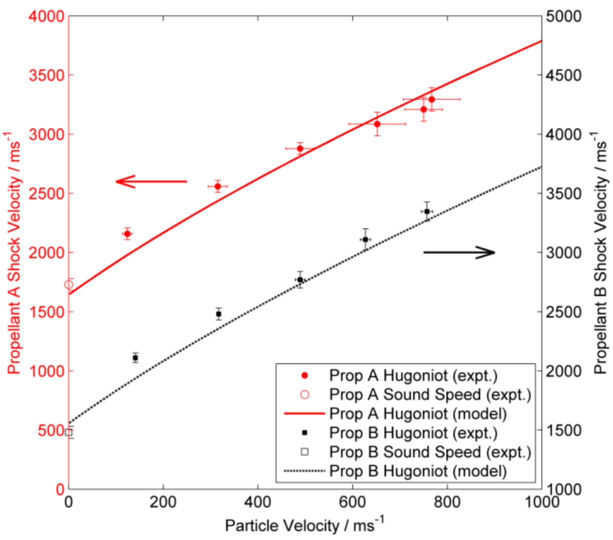

*Figure 6: Comparison between experimentally measured Hugoniot points, elastic sound speeds and GIM*

Constitutive Response: The major result from the constitutive response tests was the finding that the modulus of the propellants is not affected by nitramine content meaning that particulate composite theory is not relevant. Damage to the materials depends upon the temperature of deformation with that at -30°C being more gradual than at room temperature. Whilst the development of the underlying theory and the construction of a model to predict the constitutive response have made good progress, the material model requires a better description of the propellant thermal properties as a function of temperature which can be derived from heat capacity measurements and thermal expansion. This has highlighted the general lack of thermomechanical behaviour data of the properties of the components that constitute the propellants. The completion of a materials science based predictive constitutive model awaits fundamental data on the behaviour of NG over a wide temperature range. Until this can be accomplished a lower fidelity interim semi-analytic constitutive model, fitted to the material deformation data has been developed and employed successfully in the modelling programme.

A key requirement of the material model is the ability to describe the damage and fragmentation of the propellant to generate the debris cloud. The current model has been constructed using basic ideas from percolation theory to provide a description of the evolution of damage into cracks within the material. Percolation theory was developed to address the following representative question: “Assume we have some porous material and we pour some liquid on top. Will the liquid be able to make its way from hole to hole and reach the bottom?" The analogy is with the progress of a crack through the material.

The damage model presumes that sites for debonding within a yellow pellet or pellet separation are distributed uniformly through the propellant and can be identified with pores in percolation theory: we suppose the spaces between particles form a lattice of damage sites of which more or fewer are damaged (occupied). A major challenge has been to discover whether this allows description of a transition from distributed damage to fracture. Fracture is considered to be the formation of cracks with a length scale larger than the particle size. The ability to describe the formation of cracks is important for the damage model, since the increase in the surface area associated with these cracks is responsible for the increased burning rate that can transition into a violent burn or detonation.

The percolation model developed under this programme is now able to describe the observed fragment distribution, as shown in Figure 7 and should be compared with Figure 2.

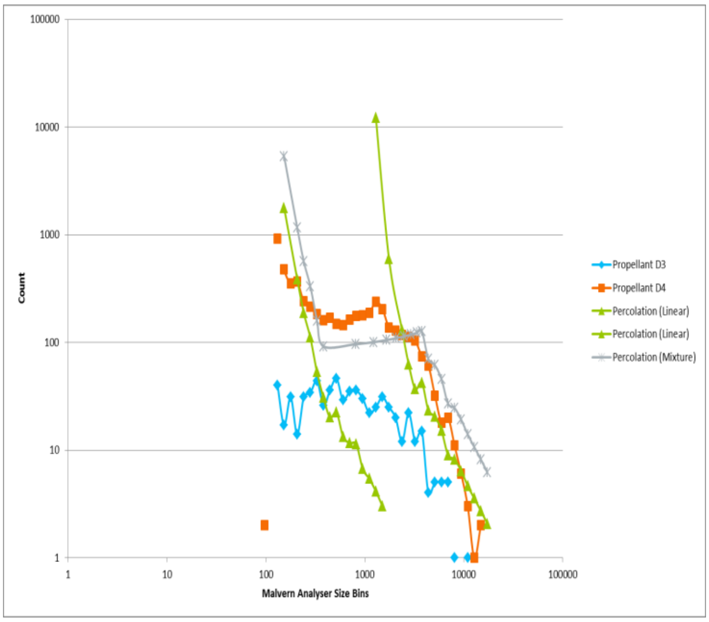

*Figure 7: Percolation model prediction of Propellant D fragment size distribution*

Further work is underway to provide a link between the tensile damage and the fragmentation percolation model using additional tensile data and a better understanding of damage in these propellants such as may be acquired from detailed analysis of tensile tests and Taylor-type friability tests.

The percolation-theory-based models of the distribution of fragments have shown that if appropriate parameters are carefully selected then they can capture the distribution of small and large fragments reasonably well.

## CAPABILITY TO PREDICT XDT

The final element of the technical strategy is the development of a validated numerical simulation methodology capable of predicting the response of a rocket motor to fragment attack.

The development of this capability has centred on the QinetiQ in-house developed multi-material Eulerian hydrocode GRIM.

Fragmentation: Using the material models, described above, and the improved description of damage GRIM3D can predict the experimentally observed fragmentation behaviour of the double base propellants in this study. Figure 8 compares the profiles of the predicted and experimental debris clouds for Propellant A. This includes the ability to predict the shape and velocity of the fragment cloud and position of the projectile at the front of the debris cloud. The validation of GRIM3D and the material models to predict fragmentation in different energetic materials will require additional tests.

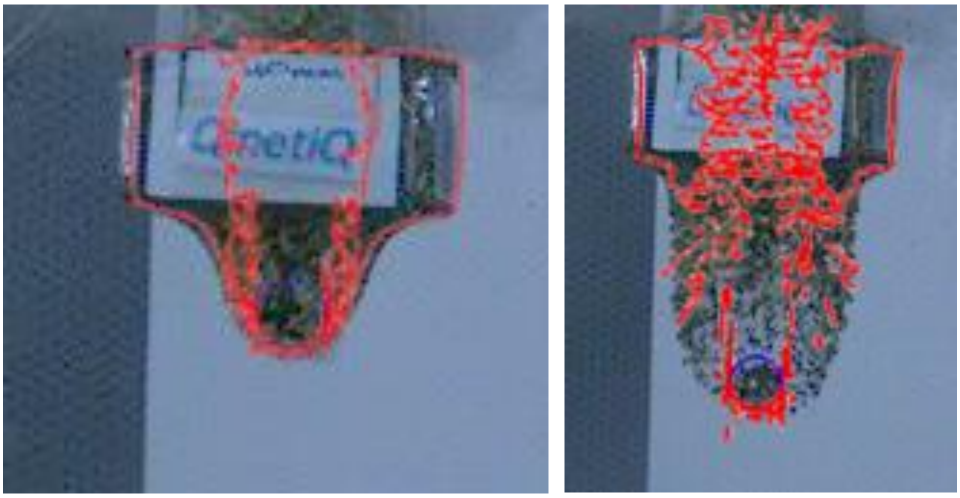

*Figure 8: Comparison of GRIM3D material interface with experiment for Propellant A at 76.1µs and 125.9µs*

The bulk behaviour of the block of Propellant A, depicted in Figure 8, is shown in Figure 9 and shows the ability of the simulation to predict the concave curvature of the sides of the propellant slab, due to the propagation of damage. The experimentally observed late time ejection of a plume of material from the impact surface of the block is also predicted by the simulation.

I&G Model Development: The final element in the modelling methodology is the development of an I&G model capable of describing and predicting the XDT process.

In its original formulation the Cook Haskins Arrhenius Reaction Model (CHARM) [6] contained the necessary algorithms to describe the chemistry of ignition and growth of a reaction in a homogeneous material and a pore collapse hotspot mechanism to model the response in a heterogeneous material. Uniquely the CHARM chemistry is described by a series of linked Arrhenius equations that are temperature based. The models were fitted to reproduce SDT events based upon an assumption of an initial pore number density and size. The chemistry was fitted to One-Dimensional-Time-to-Explosion (ODTX) data and fragment attack data. In this form the model has been shown to be highly successful in being able to predict the SDT response of a range of weapons subjected to fragment attack.

The model, however, lacked the necessary interface with the material constitutive response algorithms to account for damage sensitisation of energetic materials, believed to be a significant contributor to the XDT response of a rocket motor. A link between CHARM and the QinetiQ constitutive model algorithms was therefore developed to make predictions of the damage induced sensitisation of an energetic material [7].

A considerable amount of development work has been required to describe the evolution of the hotspot distribution within the energetic material under conditions of expansion and recompression. Another challenge has been has required changes to the mixed material cell algorithm, inherent in Eulerian methodologies, to avoid non-physical states, characterised by overheating of the material.

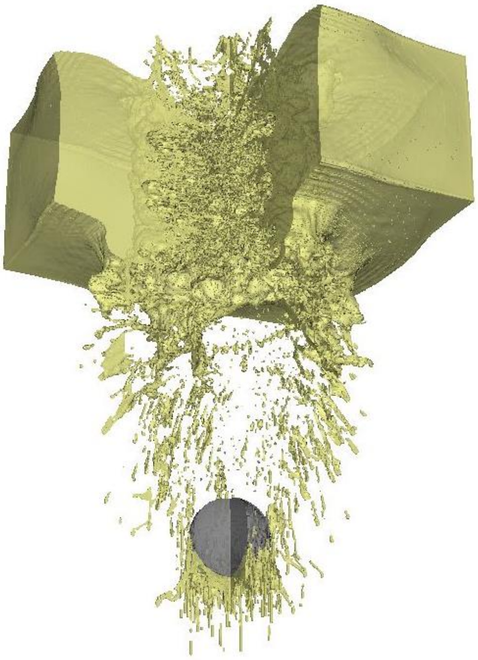

*Figure 91: GRIM3D predicted debris cloud for Propellant A cut-away view at 119µs*

<u>Small Scale Tests</u>: The initial validation process was to demonstrate the ability of GRIM to reproduce the experimentally observed SDT and XDT responses of the different propellants in the small scale XDT test using CHARM.

To allow the ability to change the composition as part of a rocket motor design study a different strategy was developed, which used published reaction data for the components of the propellant (NC, NG, and Nitramine) to fit the CHARM chemistry. This has proved to be successful to date, but further detailed research is required to determine the robustness of this approach. The resulting CHARM reaction sets for each propellant in the study have been shown to be capable of reproducing the observed response trends in the small scale XDT experiments, Table 1.

<u>Full Scale Rocket Motor</u>: The ultimate test of the capability has been to show that the models can reproduce the observed response of a full scale rocket motor to fragment attack. A fragment impact experiment performed in 1995 against a full scale rocket motor was therefore selected as a test of the modelling methodology. The fragment was the standard STANAG fragment (14.3mm diameter, 14.3mm long, 160° pointed nose). At an impact velocity of 1897m.s$^{-1}$ an XDT event was observed, whilst at an impact velocity of 1452m.s$^{-1}$ no XDT response was observed.

The model was shown to be capable of reproducing these experiments. However, further mesh resolution studies are required, over a wide range of motor designs to determine the robustness of the methodology as well as studies to identify any numerical artefacts that may initiate non-physical reactions.

| Propellant | Event Classification | Impact Velocity (m.s$^{-1}$) | |
|---|---|---|---|
| | | Experiment | Simulation |
| Type A | SDT | 1525 (lowest) | 1500 |
| | XDT | 1441 (highest) | |
| | | | 1400 |
| | | 1370 (lowest) | |
| | Ignition – no propagation | 1588 (highest) | |
| | Non-detonation | | 1100 |
| | | | |
| Type D | SDT | 1826 (lowest) | 1700 |
| | Non-detonation | | 1600 |
| | Ignition without propagation | 1829 (highest) | |
| | | | |
| Type E | SDT | 1434 (lowest) | 1450 |
| | XDT | 1377 (highest) | |
| | | 1306 (lowest) | |
| | | | 1250 |
| | Ignition without propagation | 1373 (highest) | |
| | Non-detonation | | 900 |

*Table 1: Comparison of Experiment and GRIM for small scale XDT test*

## CONCLUSIONS

Further research is required to improve the physical basis of the heat transfer model in CHARM and the link between heat transfer and ignition.

The work has, however, identified a methodology for the future study of the response of rocket motors to fragment attack. The CHARM chemistry is defined in terms of the energetic components within the composition and validated using ODTX tests. The shell thickness is then determined in the small scale XDT tests. The model is then used in full scale motor design studies. This methodology needs to be rigorously tested and demonstrated in other propellants and rocket motor designs.

The conclusion of the work in this paper is that the research has succeeded in developing a modelling capability able to predict XDT in the propellant characterised in this paper in small scale samples and a single rocket motor subjected to fragment attack.

## REFERENCES

1. Cook M. D., Haskins P. J., Briggs R. I., Flower H., Ottley P., Wood A. D., Cheese P. J., ‘An Investigation into the Mechanisms Responsible for Delayed Detonations in Projectile Impact Experiments’, Proceedings of Thirteenth Detonation Symposium, 2006, pp.814.

2. Cook M. D., Haskins P. J., Briggs R. I., Ottley P., Sharp M., ‘Fragment Impact Studies of Complete and sectioned Rocket Motors’, Proceedings of the 2009 Insensitive Munitions and Energetic Materials Technology, Tucson, Arizona, May 11-14, 2009.

3. Boddy, R. L., “'Damage in Energetic Materials' , Thesis to be presented to the University of Cambridge for the Degree of Doctor of Philosophy.

4. D. Porter, “Group Interaction Modelling of Polymer Properties”, Marcel Dekker, New York1995.

5. Foreman, J. P., Porter, D., Behzadi, S., Jones, F. R., “A model for the prediction of structure–property relations in cross-linked polymers”, Polymer, 49(25), 2008, Pages 5588–5595.

6. Cook M. D., Haskins P. J., and Stennett C., ‘Development and Implementation of an Ignition and Growth Model for Homogeneous and Heterogeneous Explosives’, Proceedings of the Eleventh Symposium (International) on Detonation, Snowmass, Colorado, 30 August – 4 September 1998, p587.

7. Gould, P. J., Cullis I. G., “An integrated model for mechanical damage and burning response in PBX”, Research Bulletin of the Australian Institute of High Energetic Materials, (2010) p112-121.

## ACKNOWLEDGEMENTS

The authors wish to acknowledge the significant contributions made to the research programme by Richard Johnson, Roxel, and Rachael Boddy, Nicholas Taylor and Andrew Jardine, Cambridge University. The authors also wish to acknowledge the financial support of Dstl, UK MOD, under a Weapons Science and Technology Centre contract.