TNT Hazard Response & Applicability to Counter-Rocket, Artillery and Mortar

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Abstract

A programme of experimental activities and supporting modelling activities have been undertaken to evaluate the minimum performance requirements for a 'one-shot, one-kill' approach to Counter-Rocket, Artillery and Mortar (C-RAM). A number of terminal effect types have been assessed to identify feasible candidate counter-measure technologies. The data produced by the experiments and predictive modelling are presented and illustrate the challenge in achieving a capable counter-measure using conventional lethal mechanisms. The outcomes from the work suggest plausible approaches to C-RAM for both legacy and modern threats.

1 Introduction

Recent UK military operations have highlighted the operational requirement for area protection against attack from Rocket, Artillery and Mortar (RAM). An effective Counter-RAM (C-RAM) strategy requires an understanding around the five NATO defence against mortar attack pillars – prevent (an attack), warn, intercept, respond and protect. The development of a C-RAM capability requires information on the nature of RAM threats, how threats are used and when and where each pillar philosophy can be applied. In the specific case of threat interception, it is essential that threat construction and the effectiveness of counter-measures are established.

Many of the RAM threats of interest are legacy ordnance items typically featuring thick steel casing and high explosive (HE) content. This robust construction along with the fleeting and potentially very small signature makes RAM defeat challenging. The aim of the described work was to identify feasible lethal mechanism options for the defeat of RAM using compact warheads which could be integrated into small to medium calibre ammunition or missiles. The original goal of the programme was to identify lethal mechanisms capable of inducing a prompt hazard reaction in threats to counter-measure insult, implying a requirement for a shock to detonation transition (SDT) response. The threats of interest to the study were TNT-filled RAM, viewed as some of the more challenging of prevalent threats due to the (relative) insensitive nature of this HE. A melt-cast 'creamed' TNT specification was assumed for this work.

An integrated approach using experimental testing and numerical modelling was used to achieve the stated aim; verification of both the design of lethal mechanisms and the ability of the mechanisms to cause the desired hazard response. Four lethal mechanism candidate technologies have been evaluated for C-RAM; single fragment attack, explosively formed projectile (EFP) attack, directed (multiple) fragmentation and shock loading by donor HE in contact with acceptor TNT.

The counter-measure strategies considered for TNT-filled RAM parallel those required for modern Insensitive Munition (IM) compositions. The work described here can therefore inform the requirements for counter-measures to defeat modern RAM threats.

2 TNT Characterisation

The term creamed melt-cast refers to the production method of the TNT. Creamed melt-cast TNT is prepared by melting TNT in a steam heated vessel, stirring in flaked TNT until a slurry is produced. The density achieved by this method was typically 1580kg.m^{-3}.

The first task under the programme was to characterise the hazard response of the creamed melt-cast TNT to shock loading. The main test used to generate characterisation data was gun-launched fragment attack with the output from the tests used to calibrate the Jacobs-Roslund [1] and Cook Haskins Arrhenius Reaction Model (CHARM) [2] hazard response models. These models in turn were used to guide the requirements and design of lethal mechanisms for C-RAM applications.

Under the fragment attack calibration tests, flat-sided projectile (FSP) donors were fired at cylindrical TNT acceptor targets with and without steel cover plates with increasing FSP impact velocity so that the violence of response could be monitored and the transition to a detonating response identified.

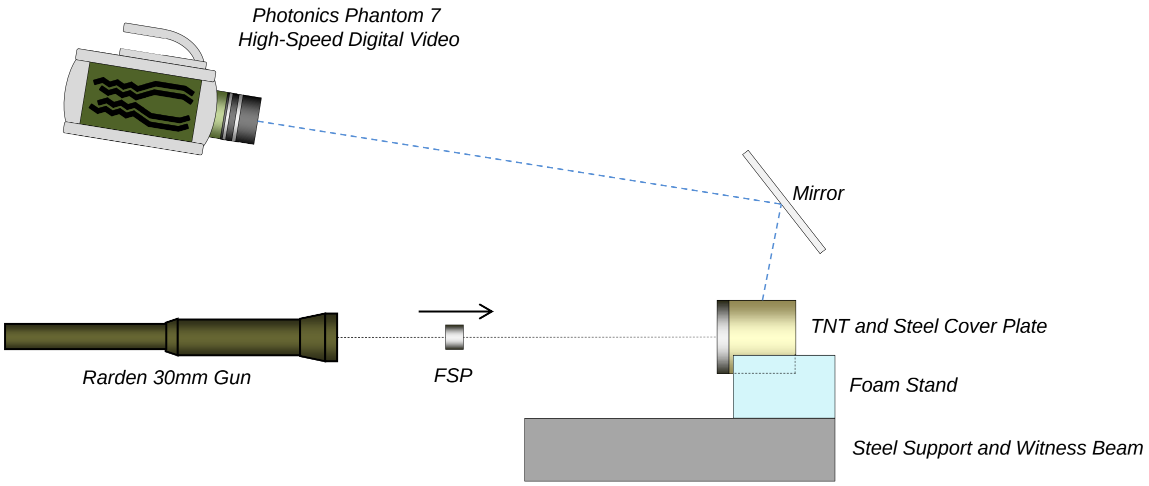


Figure 1: Gun-launched Fragment Attack Test Configuration

The Jacobs-Roslund and CHARM models were originally devised to predict SDT events so the tests to provide calibration data are designed and conducted to ensure that the impact conditions giving rise to a prompt detonation are captured. The FSP impact velocity and the thickness of the steel plate covering the TNT were varied to produce a series of data points to calibrate against. The donor (FSP) and acceptor (HE target) specifications are given in *Table 1* and *Table 2*.

Donor Fragment Parameter		
Material	BS970 Steel	BS970 Steel
Diameter (mm)	20	30
Mass (g)	27	98
Minimum Impact Velocity (m.s^{-1})	1365	1079
Maximum Impact Velocity (m.s^{-1})	2012	1725

Table 1: Flat-Sided Projectile Properties

Acceptor Fragment Parameter	
Cover Plate Material	EN24 Steel
Cover Plate Thickness (mm)	0-14
TNT Length (mm)	65
TNT Diameter (mm)	65
Nominal TNT Density (kg.m^{-3})	1580

Table 2: Target Properties

In total, 38 firings were undertaken with FSPs fired from a rifled bore 30mm Rarden gun. The results generally showed long runs to detonation, with a few examples where detonation was observed to break out near the opposite end of the TNT sample. In many tests it is clear that fragmented charge material was spalled onto a steel supporting beam giving rise to an Unknown to Detonation transition (XDT) like reaction. This obscured the SDT mechanism in many cases and was suppressed in later firings by using a low density foam charge support. It was noted that the TNT charges fragmented easily due to their brittle nature giving rise to some internal burning which was manifest in the bending of the support beam. The hazard response levels and corresponding hazard phenomena are given in *Table 3*.

Hazard Response Level	*Hazard Phenomenon*
0	No Reaction
1	Ignition
2	Burning
3	Deflagration
4	Detonation

Table 3: Hazard Response Levels

It was observed that the 20mm diameter FSP was capable of producing a Level 4 SDT response for covered TNT with cover plate thicknesses up to 5mm. The defeat of the 5mm cover plate acceptor was achieved at the velocity limit for this projectile. The larger 30mm FSP was found to produce a Level 4 SDT for targets featuring cover plates up to 12mm in thickness. The successful or unsuccessful prompt detonation of TNT (‘go’ or ‘no-go’) by the FSPs was then used to calibrate the Jacobs-Roslund and CHARM prediction models which were then used to predict the outcome of attack by other lethal mechanisms. The Jacobs-Roslund parameters used prior to this activity were derived from the work of Johansson and Persson [3] though they tested bare TNT. The CHARM modelling using the recalibrated parameters is compared with the experimental results in *Figure 2*. The velocities shown in *Figure 2* for the go results are the minimum for which detonations were observed while the no-go results are the maximum for which detonations were not observed.

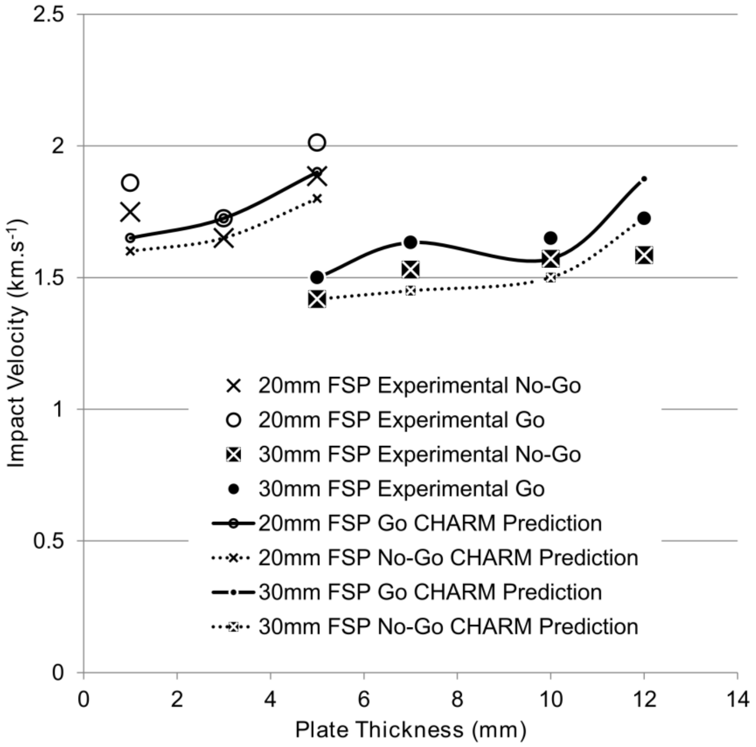


Figure 2: Gun-launched Fragment Attack Response Data and CHARM predictions

As RAM threats typically have casing thicker than 9mm, these data show how challenging threat destruction or ‘hard kill’ would be for gun or explosively launched single projectile based systems. These data are for normal impact and therefore real world oblique engagements by non-cylindrical fragments would require a substantial increase in impact velocity to produce a prompt detonation response.

3 Explosively Formed Projectile Attack

Once the TNT had been characterised for the purposes of hazard prediction model calibration, the next task was to evaluate the potential of other lethal mechanisms to defeat RAM.

To assess the potential of unitary projectiles with higher impact velocities to stimulate a detonation hazard response in the TNT, the study turned to EFP technology. Three iron EFP donor charges with initial explosive diameters of 30, 42 and 60mm were designed using the GRIM Eulerian hydrocode [4] to achieve a velocity of ~2750m.s^{-1}. The EFP research test vehicles and the comparison of projectile shape prediction with experiment are shown in *Figure 3*.

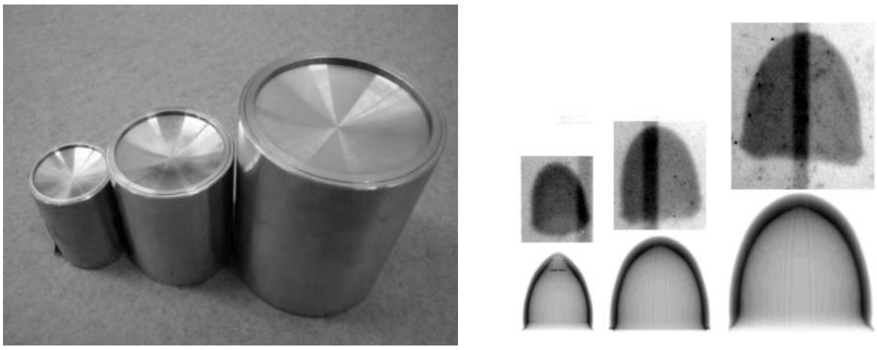


Figure 3: EFP bodies (left), Comparison between predicted EFP profile (bottom right) and observed radiograph profile (top right). 30mm EFP on left, 42mm in middle and 60mm on right.

Whereas for the gun-launched fragment attack experiments a range of cover plate thicknesses were examined to gradually establish the threshold barrier thickness for mitigating prompt detonation, the EFP tests only used 5 and 9mm thick cover plates. The 9mm cover plate is representative of relatively thinly cased RAM threats. The same geometry of TNT billet used for the gun-launched fragment attack study was used as the basis for the acceptor charge in the EFP firings.

The three EFP designs were fired at the acceptor targets and the results of the EFP firings are given in *Table 4*.

Cover plate Thickness (mm)	*EFP Charge Diameter (mm)*		
	30	42	60
5	1	3	4
9	1	1	3

Table 4: Creamed TNT Hazard Response to EFP Attack

The results show that detonation of thickly covered melt-cast creamed TNT was only achieved for the largest 60mm EFP tested against the thinnest 5mm cover plate utilised. The results have implications for warhead design using this lethal effect – the hard kill objective drives the solution and implies large calibre guns and interceptors would be required.

Prior to the EFP testing, hazard response modelling was undertaken to predict the hazard responses. CHARM did not predict the Level 4 detonation event, while the Jacobs-Roslund model predicted that the 60mm EFP would be able to produce a Level 4 detonation against the thicker 9mm cover plate acceptor target, which was not observed. These predictions highlight the issues in utilising the hazard assessment toolset to effectively guide the design process. There is a requirement to calibrate the models against a range of data points to ensure a good fit across velocity or energy regimes. The final Jacobs-Roslund curves for fragment/projectile impact as derived during this work are given in *Figure 4*, also highlighting the experimentally accessed regions used to generate the model parameters.

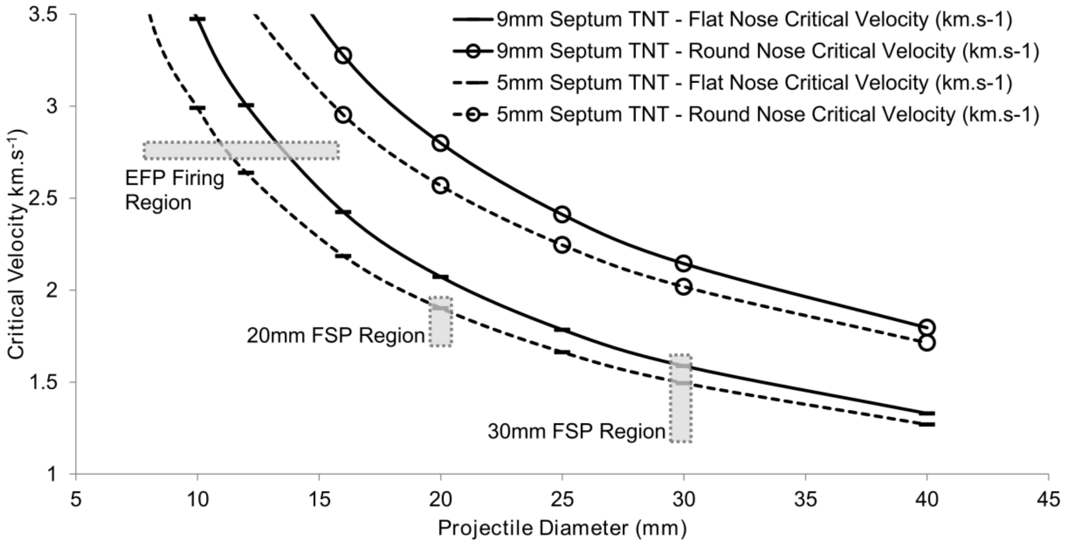


Figure 4: Jacobs-Roslund Curves for Covered Creamed Melt-cast TNT

In addition to CHARM and Jacobs-Roslund hazard response models, Held's v^2d model [5][6] can be applied to the residual projectile (i.e. projectile after perforation of cover plate) and a threshold criterion can be derived. The charateristics of the residual projectile can be difficult to determine experimentally so these can be estimated using hydrocode prediction. Using the GRIM hydrocode [4], the predicted residual projectile diameter and velocity after cover plate perforation were used to generate v^2d curves for the 30, 42 and 60mm EFPs and compared with the experimental observations of go or no-go. Detonation was only observed experimentally for the 60mm EFP against the 5mm cover plate, for which a v^2d value circa $50mm^3\mu s^{-2}$ was derived from simulation. This is above the $40mm^3\mu s^{-2}$ threshold reported by Arnold [7] for a TNT-filled 120mm mortar, which used shaped charges as the donor. The observed cases of deflagration gave a v^2d value circa $29mm^3\mu s^{-2}$. The v^2d curves and threshold criteria are shown in *Figure 5*.

The v^2d criteria could conceivably rise with increasing cover plate thickness, not remain constant as shown in *Figure 5*. This again illustrates the need to conduct a broad range of tests to establish a good empirical fit for the hazard model.

Whilst the defeat of melt-cast creamed TNT-based RAM threats by stimulating detonation appears to be impossible for low-calibre EFPs, the technology may still provide an effective counter-measure. It was observed after the EFP firings that no significant unreacted TNT was recovered - a small amount of powdering was observed for the 30mm EFP tests but generally the TNT was completely consumed. This suggests that the requirement for threat defeat by stimulating a detonation response may restrict the potential C-RAM options to larger and more costly counter-measures. If stimulating detonation in the threat is relaxed, there still remain the challenges of how to achieve threat kill assessment and how to mitigate potential collateral damage.

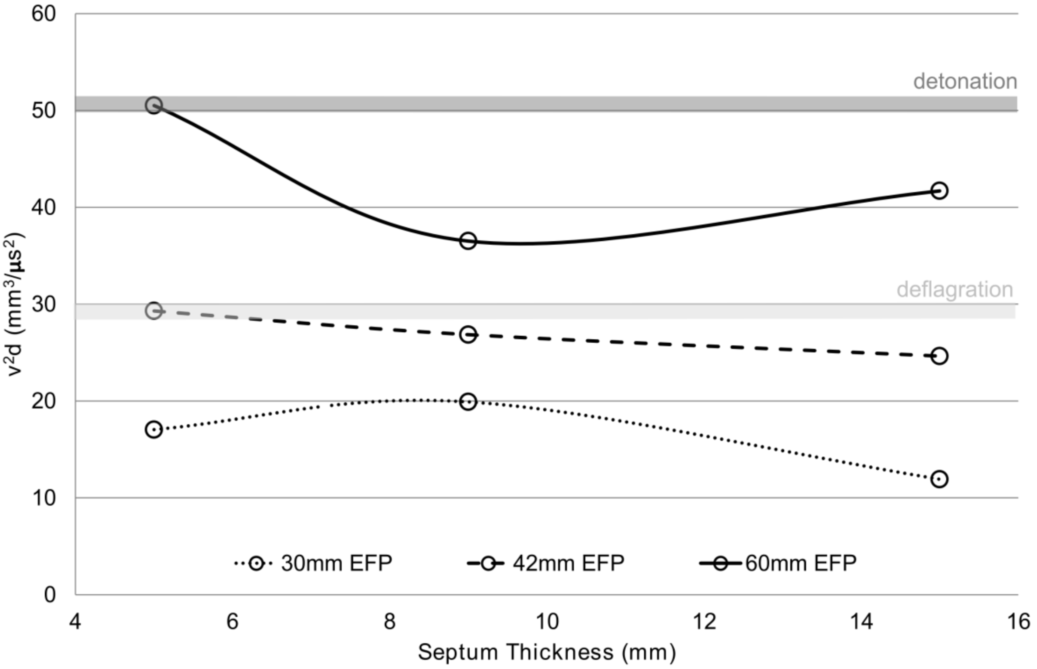
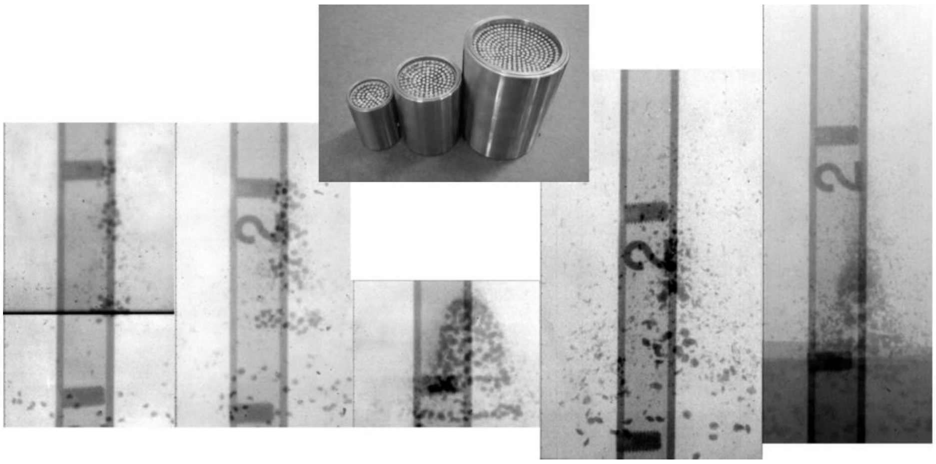


Figure 5: Held v^2d Criteria for EFP impacts

4 Directed Fragmentation Attack

Whilst it is clear that single fragment attack (such as fragments typical of a traditional anti-aircraft warhead) would not be effective in stimulating a detonation response in many TNT-filled RAM threats based on the presented data, it was not known whether directed, simultaneous fragmentation could be an effective mechanism. The specific mechanism of interest from this effect is the so-called ‘cumulative mechanical damage’ [8] effect, which can produce a region of enhanced damage due to fragment impact shock interaction in the target. To examine this lethal mechanism, 30, 42 and 60mm diameter directed fragmentation charges were designed using 3mm and 5mm steel spherical fragments. The directed fragmentation charges and the radiographic images of the observed fragment swathes are shown in *Figure 6*.



30mm 3mm Fragments	**42mm** 3mm Fragments left 5mm Fragments right	**60mm** 3mm Fragments on left 5mm Fragments on right

Figure 6: Directed Fragmentation bodies (centre, top) and radiographs of fragment swathes

The directed fragmentation charges were fired at the acceptor targets and the results of the firings are given in *Table 5*.

Cover plate Thickness (mm)	*Fragmenting Charge Explosive Diameter (mm)*				
	30	42		60	
	Fragment Diameter (mm)				
	3	3	5	3	5
	Hazard Response				
5	0	1	0/1	3	3
9	0	0	0	3	1

Table 5: Creamed TNT Hazard Response To Directed Fragmentation Attack

No reaction or low order reaction results were observed for the smaller 30mm and 42mm fragmenting charges. The largest 60mm charges were able to produce a deflagration response except in the specific case of the charge with 5mm fragments against the thicker 9mm cover plate. The results show that stimulating detonation of thickly covered creamed TNT is beyond the capability of the charge sizes considered by this study. Unlike the EFP firings, unreacted TNT was recovered after many of the firings. The recovered TNT ranged from largely intact to limited small pieces of TNT, as shown in *Figure 7*.

Figure 7: Structural responses of TNT. Clockwise from top left; Translation and relatively intact, large pieces and smaller debris, limited TNT debris (larger pieces identified)

The state of the recovered damaged TNT can be classified according to *Table 6*.

Cover plate Thickness (mm)	*Fragmenting Charge Explosive Diameter (mm)*				
	30	42		60	
	Fragment Diameter (mm)				
	3mm	3mm	5mm	3mm	5mm
	TNT Damage Level				
5	1	2	2	3	3
9	1	2	2	2	3

1 – TNT relatively intact; wholly unreacted
2 - Small TNT pieces recovered; some reaction possible
3 - No TNT recovered; pulverisation

Table 6: TNT Structural Response To Directed Fragmentation Attack (Top) And Key (Bottom)

These findings show that low calibre, low fragment number directed fragmentation would not be suitable for either hard or soft-kill countermeasures and that large calibre or large fragment projecting arrays may at least offer a soft-kill capability.

5 High Explosive Shock Initiation

The final counter-measure mechanism considered was shock initiation using a donor explosive charge. To characterise this mechanism, the Energetic Materials Testing Assessment Policy (EMTAP) Large Scale Gap Test (LSGT) was used. The standard configuration of the test is shown in *Figure 8*.

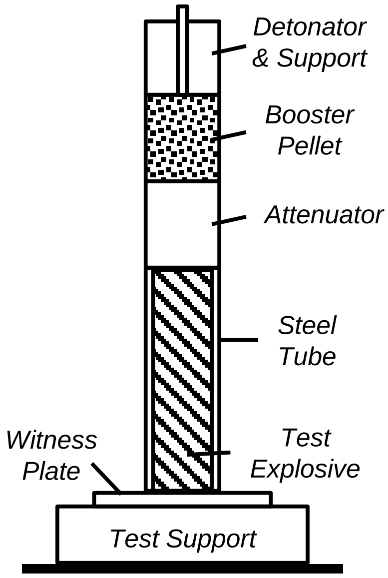


Figure 8: Schematic configuration of EMTAP Test 22, LSGT. Note, the trial set-up can be inverted such that the witness plate is at the top, if required.

This test is actually a medium scale test covering a pressure range from about 0.8 to 10GPa. The input pressure pulse is generated by the initiation of a tetryl explosive (donor) pellet. The acceptor charge diameter is circa 36mm by 141mm long and cased in a steel tube with 5.5mm wall thickness. The acceptor charge is situated on a 10mm thick steel witness plate which is used to confirm a detonation event, which will punch a clean hole through the plate. The thickness of the attenuator is varied so that detonation is inhibited. The thickness of the attenuator can be correlated with shock pressure transmitted to the acceptor explosive.

Fifteen LSGT firings are undertaken in order to establish the attenuator thickness at which detonation of the acceptor charge occurs. The standard attenuator material is polymethyl methacrylate (PMMA) with a density of 1186±1kg.m^{-3}. A wider (attenuator) gap in the LSGT indicates a lower level of stimulus (i.e., lower equivalent pressure) to achieve detonation when compared to a narrow gap. A material which requires a lower stimulus (i.e., lower equivalent pressure) to achieve initiation is more sensitive to shock initiation. Equivalent pressure is so called because it is the pressure equivalent to a certain thickness of attenuator. The pressure is that measured just inside the attenuator at the attenuator-acceptor interface. The tests are monitored with high speed video (HSV).

The first set of fifteen trials was completed using just the standard PMMA attenuators. The second set of trials utilised an additional steel attenuator of fixed thickness (15 mm) in addition to the PMMA. This additional steel attenuator was included to represent thick RAM casing.

The HSV of the tests provide evidence of the violence of the non-detonative reactions. The videos provide information on the break-up of the casing and in most cases show that the detonation leads to the production of small fragments.

The modified large scale gap test performed using the PMMA attenuator yielded a median gap of 39.1mm corresponding to an equivalent median pressure of 3.2GPa. (Note. The EMTAP Manual quotes 2.9GPa for creamed TNT of density 1563kg.m^{-3}.) The test that used a PMMA attenuator combined with a 15mm steel attenuator yielded a median gap of 12.2mm and an equivalent median pressure of 7.9GPa. Note that the latter result corresponds to a pressure just inside the PMMA attenuator at the PMMA / steel interface rather than the PMMA / acceptor interface.

These results suggest that shock initiation of creamed melt-cast TNT filled RAM should be possible, however the counter-measure has to be carefully designed to ensure that the median pressure of 7.9GPa or higher is successfully transmitted to the threat HE filling.

6 Summary and Conclusions

The hazard response of RAM representative targets to four lethal mechanism types have been studied, namely single fragment impact, directed fragmentation, explosively formed projectiles and high explosive shock initiation. Small-scale charges exploiting the directed fragmentation and EFP mechanisms were developed with 30, 42 and 60mm (explosive) diameters, designed to fit within various implementations of C-RAM lethal packages.

The experimental tests have shown that it is extremely difficult to produce a prompt shock detonation response in the material using small-scale projectile attack; with no detonation observed at all in the RAM case thickness regime of interest to this study. Shock initiation of the threat using a HE donor was shown to be the most feasible means of stimulating a detonation response. As this particular creamed TNT preparation is relatively insensitive, the study is able to inform strategies for the defeat of a broad range of RAM threat HE content, ranging from more sensitive (containing e.g. RDX/TNT compositions) through to modern IM compliant compositions.

Less violent hazard response modes were also observed which although not meeting the objective prompt hard-kill requirement, do seem to defeat the TNT either through deflagration, burning or pulverisation. Whilst there is a potential collateral damage issue from a residual threat (where the casing remains intact), the consumption of the explosive means that the blast and fragmentation (or indeed other explosively formed lethal effects) threat is removed.

Three main hazard response tools have been assessed and developed under this programme, namely Held's v^2d empirical model, the Jacobs-Roslund empirical model for fragment attack analysis and the CHARM ignition and growth model embedded within a hydrocode environment.

The main limitation of all the tools is that they were only ever intended to determine a shock to detonation outcome. More complicated detonation responses e.g. XDT or burn to violent reaction cannot be predicted by the toolset and neither can lesser violent hazard responses such as deflagration or burning. Practically, this means that as design tools, they will only be able to guide the design of effects which lead to SDT. The consequence being that this approach could produce designs which are larger than necessary. The objective of current CHARM development is to add XDT predictive capability by modifying the 'hot spot' model. This broader model will allow the prediction of both detonation transitions and will offer enhanced capability as a design tool.

Each of the empirical models was developed for use in a certain regime, with v^2d designed for shaped charge assessment and Jacobs-Roslund for fragment attack. The v^2d model threshold criterion has been estimated based on experimental results and supporting hydrocode modelling. For EFP (i.e. high velocity) attack, the threshold criterion for detonation of TNT was found to be higher than that reported in the literature ([7] reports $40\text{mm}^3.\mu\text{s}^{-2}$ compared with circa $50\text{mm}^3.\mu\text{s}^{-2}$).

The Jacobs-Roslund model can be fitted to experimental data to provide a good prediction of whether SDT would take place. Currently the melt-cast TNT fit captures all the fragment attack experiments and the single EFP attack which were observed to produce detonation. It is not known that if further SDT data could be obtained in higher velocity regimes whether the form of the model would allow recalibration to reflect the fragment attack and shaped charge/EFP data.

CHARM has been calibrated to fit the fragment attack data, but not the high velocity EFP events. Like the Jacobs-Roslund model, this model requires a recalibration each time data is obtained for a different regime. A broad range of experimental data is initially required to seed the model, but once calibrated against such a data set this model can be exercised to assess a variety of different lethal mechanism for SDT.

7 Acknowledgements

The authors would like to thank the Defence Science and Technology Laboratory (Dstl) who provided funding for the work. The authors also wish to thank Steve Ashlin, Tony Cannon, Phil Ottley and Mark Rhodes of QinetiQ for their contribution to the study. The authors also wish to acknowledge the Weapons Science & Technology Centre, Dstl and MOD stakeholders for their support and advice. The authors would finally like to thank the QinetiQ staff based at Fort Halstead and Pendine who contributed to and supported the work.

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