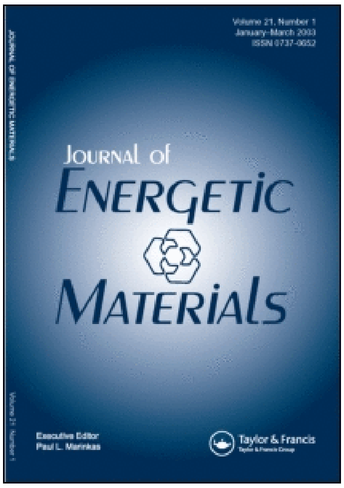

Journal of Energetic Materials
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713770432

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To cite this Article Cartwright, Michael and Simpson, Peter J.(2009) 'Non-Solid Explosives for Shaped Charges. Part III. Metal Liner Devices Used in Explosive Ordnance Disposal Operations', Journal of Energetic Materials, 27: 3, 166 — 185
To link to this Article: DOI: 10.1080/07370650802640325
URL: http://dx.doi.org/10.1080/07370650802640325

Journal of Energetic Materials, 27: 166–185, 2009

ISSN: 0737-0652 print/1545-8822 online
DOI: 10.1080/07370650802640325

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Non-Solid Explosives for Shaped Charges. Part III. Metal Liner Devices Used in Explosive Ordnance Disposal Operations

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Disposal of time-expired and unexploded ordnance has proved problematical in the past because of the procedures adopted; i.e., attach an explosive charge and cause the munition to function or long-range projectile attack. Improvements used explosively driven metallic liners to impact on the munition but detonation occurred with the standard plastic explosive fillings. If the munition can be persuaded to burn or at worst deflagrate, then the region of collateral damage could be reduced, even though the extended detonation safety zone would still be required. This article describes some work performed on the initiation of munitions ranging from simulated mortar shells, filled with plastic explosive PE4, via NATO standard 81-mm mortar shells to 1000-lb (450-kg) bombs by either copper cone or dish liners devices filled with various sensitized nitromethane formulations. Most of these formulations initiated deflagrations in the attacked

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munitions. Detonations resulted in some cases when plastic explosive, PE 4, or chemically (DETA) sensitized NM was used as the device filling. The results were analyzed in terms of the critical rate of energy delivery. Both heat dose and blast overpressure produced by the deflagrations were measured and indicated that the region of collateral damage would be extensively reduced even though the safety exclusion zone, based on full detonation, would have to be maintained. Use of these fillings would reduce the hazard to the operator during EOD work.

Keywords: explosive ordnance disposal, liquid explosives, shaped charges

Introduction

Lifetime expired munitions and unexploded ordnance containing high explosives (HE) have the potential to detonate during explosive ordnance disposal (EOD) procedures. Recent U.K. in-service disposal procedures either attach a plastic explosive charge, causing the munition to function, or use a system that attempts to induce deflagration in the munition. Though simple functioning is effective, it is unacceptable from the collateral damage point of view and the current environmental regulations [1]. Dumping at sea and open burning and detonation have been banned except under special circumstances [2]. Munition incineration must be in carefully controlled furnaces with extensive flue gas control [3]. If the munition cannot be moved on the grounds of safety, then disposal in situ must occur. Even when mitigation procedures are used the extended collateral damage zones produced may be unacceptable. A number of render safe procedures and systems have been developed to reduce the probability of detonation occurring during disposal operations. These systems focus on initiating burning or deflagration but try to ensure that it does not transition to detonation (detonation to detonation transition; DDT). The key is to impact the UXO with sufficient energy to perforate the case and initiate deflagration but not enough to cause detonation. Current methods of achieving this aim are based on two strategies: long- and short-range attack.

Long-range deflagrator attack [4,5] involves firing a projectile at the munition from a 12.7-mm (0.5″) machine gun mounted in a hardened shelter. Either conventional ball ammunition or ammunition fitted with a pyrotechnic composition is used. Research [6] has shown that a 12.7-mm projectile can be effective in attacks against GP bombs and submunitions with thin skins only if the impact is normal to the surface; otherwise, there is no penetration of the case and ricochets occur. Armor-piercing hard core incendiary (APHCI) rounds, shown in Fig. 1, have an armor-piercing tungsten carbide projectile to penetrate the case, forcing a burning pyrotechnic into the filling. Armor-piercing high-explosive incendiary (APHEI) rounds contain an incendiary composition and a secondary explosive composition, typically RDX, to assist the penetration. In both cases, when the projectile impacts a target, the incendiary mixture ignites and the collapsing steel body seals the surface of the target and forces the burning explosive into the hole created by the penetrator. Because of the extended

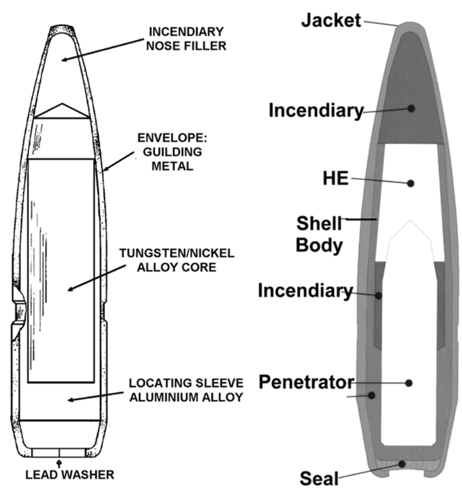

Figure 1. 0.5″ Armor-piercing hard core incendiary bullet (left) and armor-piercing hard core high-explosive incendiary (right) rounds (courtesy NAMMO SA, Raufoss, Norway).

range area required for the firing of the gun, this method can only be used in very open country with minimum surrounding infrastructure.

Short-range methods use either a pyrotechnic or an explosively produced projectile to attack the munition. The pyrotechnic devices "FireAnt" [7] and "Dragon" [8] use the thermochemical reaction of aluminum with an oxidizer to create enough heat to burn through thin-cased munitions, particularly plastic bodies, and start deflagration in the explosive contents. In the former case, the oxidizer is either iron oxide, a "thermite" charge, or an oxoanion such as perchlorate or nitrate. In the Dragon device the oxidizer is calcium sulphate, a stable non-toxic oxidizer. When used against thicker walled munitions, the contents have cooked off before the case has been opened and violent deflagration and/or detonation can result.

Short-range deflagrator [9] attack uses either shaped charge jet or explosively formed projectile devices to attack the munition. The current U.K. in-service issue devices, described in our earlier publication [13], are the container charge demolition, X1E1, or point focus charge; and the injector, EOD, L5A1, known colloquially by operators as "Baldrick." The former uses a 60° copper cone in a metal tube and the latter uses copper dish liners also in a metal tube. Both devices use plastic explosive, PE4 (88% RDX, 12% wax), charges to induce a reaction within the explosive fill. Once initiated, gas pressure inside the munition increases until it either exceeds the tensile strength of the munition case, when rupture occurs, releasing the pressure, or the reaction may transition from deflagration to detonation. This undesirable outcome has been observed with both devices when filled with PE4 [10,11]. The copper jet impact can result in prompt detonation when high-performance explosives such as HMX (VOD of $9300\,m\,s^{-1}$) are used in the filling.

To overcome the detonation difficulty, the performance of the PE4 is degraded by adjusting the stand-off, or reducing the quantity of explosive (note: Baldrick has three levels for filling marked on the body for such occasions), or by the insertion of an inert block into the explosive above the liner. An alternative explosive filling for Baldrick and point focus charge, which guarantees to transfer less energy to the shaped charge than PE4, should result in a deflagration rather than a high-order detonation event. In earlier papers we have investigated the performance parameters of sensitized nitromethane as an explosive [12] and its potential use in production of shaped charge jets [13] and found that its penetration performance matched the criteria for safe EOD work. In this article we examine the performance of nitromethane-filled devices against time-expired munitions. Usually in the EOD situation the devices are only filled immediately prior to use to minimize operator hazards.

Requirements for Field Filling Systems

The particular requirements for field filled shaped charges used in the EOD environment can be summarized as:

1. Pose minimum risk to the operator
2. Produce consistent performance
3. Contain the minimum number of explosive components
4. Can be filled rapidly in a safe manner with the minimum number of operations
5. Readily adapted for unforeseen circumstances without sophisticated calculations
6. Easily decommissioned if not required
7. Cheap to manufacture and use

Although plastic explosive, PE4, meets many of these requirements for field filling of shaped charges, its variable performance, even in the hands of a skilled operator (A. Doig, RMCS, personal communication, 2003), and the risk of induced detonations are problematic. Liquid nitromethane explosive systems give good filling integrity with consistent performance with an added attraction of being easy to fill. They also meet all the above requirements and nitromethane systems are more environmentally friendly than the RDX in PE4 [14]. Unsensitized NM is not an explosive and hence can be carried under less stringent conditions. Any unused material can be readily decomissioned by mixing into an excess of warm water.

Impact Initiation Theory

‘‘Critical energy criteria,’’ first proposed by Walker and Wasley [15], was for the projectile impact to induce a prompt detonation response. The critical energy condition for initiation of a specified explosive by either a shaped charge jet or a long rod penetrator is V^2d [16], where V is the jet tip/projectile velocity and d is the jet/projectile diameter. In order to achieve munition deflagration, devices need to penetrate the casing and deliver just sufficient energy to the HE filling to induce the burning reaction without providing sufficient energy to enable the filling to suffer prompt detonation or undergo a DDT [17]. Explosives can withstand much higher pressure without initiating if the pressure load is slowly applied; therefore, for a nondetonation response, the rate of energy deposition is important rather than the actual energy level. It is the rapid pressure rise accompanying projectile impact that can cause deflagration or detonation. The critical power density criteria, watts per kilogram ($W\,kg^{-1}$)—i.e., the rate of energy deposition per unit mass of explosive has been postulated [18,19]—is the important parameter. The impact can be described by the following equation [19]:

$$\frac{p}{\rho} + \frac{V^2}{2} = H$$

where p/ρ is the pressure per unit mass, $V^2/2$ is the kinetic energy per unit mass, and H is a constant.

On impact with the target, assuming that the jet flow behaves as if constricted through a nozzle, the variation of pressure as a function of time is the differential of this equation w.r.t. time

$$\frac{1}{\rho} \times \frac{dp}{dt} = -V\frac{dv}{dt} \tag{1}$$

This expression yields power input per unit mass quoted above and is equivalent to V^3/d.

Using this criterion in conjunction with data from a number of experimental studies, Lee [19] demonstrated that the critical power density can be divided into three approximate categories

$1 \times 10^{8}\,\mathrm{W\,kg^{-1}}$ Initiation of deflagration DDT unlikely
$1 \times 10^{11}\,\mathrm{W\,kg^{-1}}$ Initiation of deflagration likely to lead to DDT
$1 \times 10^{14}\,\mathrm{W\,kg^{-1}}$ Prompt shock initiation of detonation

Application to Current Study

Calculations were performed on the shaped charge devices used in this study to determine the energy density delivered by the devices. Jet tip velocities were measured from the flash X-ray images of functioning devices described in a previous paper [13] and the penetration hole diameter was used as a measure of the jet dimension. No allowance was made for the energy expended in penetrating the munition casing. For the point focus X1E1 device filled with PE4, the standard field fill, the measured jet tip velocity by flash X-ray was $5600\,\mathrm{m\,s^{-1}}$ $\pm 10\%$ and the jet tip diameter was 5 mm. Substituting these figures into Eq. (1) above and assuming a composition B target filling at a density of $1.65\,\mathrm{g\,cm^{3}}$, a power density of $2.13 \times 10^{13}\,\mathrm{W\,kg^{-1}}$ was obtained. At this power density it is highly likely that initiation will lead to DDT and close to the prompt detonation regime. The short-range deflagrator filled with PE4, although it produced a slower moving, thicker projectile, still yielded a power density of $\sim 5 \times 10^{10}\,\mathrm{W\,kg^{-1}}$, which is lower than the point focus device but still in the range for which DDT may occur. Both devices have produced DDT reactions in attacked ordnance. A critical factor may be the energy that is dissipated by the jet penetrating through the casing. Thicker casings will absorb more energy from the jet and produce a reduced impact on the explosive filling, diminishing the possibility of DDT. On the other hand, the lower VOD of the nitromethane-filled shaped charge will produce a lower jet tip velocity and also an increased jet diameter. Hence, the nitromethane filling should reduce both the power density and the possibility of

DDT occurring. Using the data for the measured VOD of the NM systems (earlier paper [13]) and the jet diameters and velocities, measured from flash X-ray images, power densities of around $10^8\,\mathrm{W\,kg^{-1}}$ should be produced and hence deflagration would be expected.

Devices Trialed

A series of devices were trialed. The standard service issue ICM92 container TX113A, also known as the point focus device X1E1, and Injector, EOD, L5A1, or "Baldrick," were both supplied by Ammunition Branch, Defence Academy of the U.K. at Shrivenham. Alternative alloy steel-cased copper cone and dish devices were manufactured in-house, and improvised devices assembled from cheap components using polymer pipe casing with the copper cone and dishes were also trialed. The details and dimensions of all these devices have been given in our earlier paper [12].

Explosive Filling

The principal explosive filling used was thickened NM containing 3–5% by mass of polyethylene oxide, "polyox" (mean molecular mass 300,000), and 2% by mass of hollow microballoons. Preparation and properties of this system have been described in earlier publications. Comparisons were also made with devices containing polyurethane foam sensitizer (supplied by Colligen Foams Ltd., Accrington, Lancashire, U.K.) filled with NM. Some devices were filled with DETA-sensitized NM, prepared immediately prior to use, and others with PE4 for comparison purposes only. One device was also filled with powdered HMX explosive turned into a paste with nitromethane, which did not require any sensitization.

Targets Attacked

Preliminary targets attacked were simulated small-scale shells manufactured from steel, EN24, tubes. One end of a cut length,

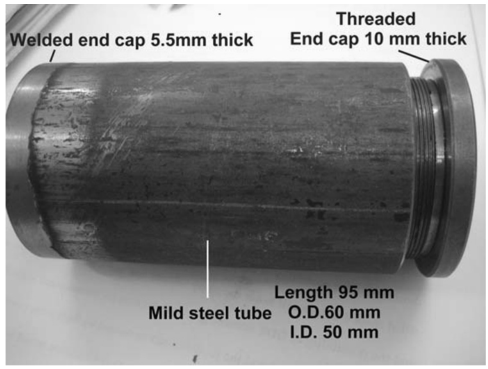

Figure 2. Manufactured simulated mortar bomb for initial trials.

95 mm, of the tube 60-mm o.d. and 5-mm wall thickness, was sealed by welding a closing plate over the end and the open end was screw-threaded to take a screw in the sealing top; see Fig. 2. This arrangement enabled the target to be sealed after filling with 200 g of either plastic explosive PE4 or composition B (60:40 RDX:TNT), thus simulating the confinement within a shell casing. The response of these targets should mimic the anticipated behavior of a typical field gun shell but with the provision that it contained only a limited amount of explosive compared with the 2500 g found in a typical field gun shells. Should the shaped charge device initiate detonation in these targets, the damage could be confined within the test cell on the ERDA range, at the Defence Academy Shrivenham, used for the experiments. These targets were placed on a witness plate and the devices led at the optimum stand-off distance of ~5 cone diameters from the target as shown in Fig. 3.

Following successful trials with these synthetic mortar shells containing plastic explosive, PE4, disposal of time-expired munitions was undertaken. Three types of munitions were targeted. Standard 81-mm mortar shells and two sizes of standard NATO-issue HE artillery shells, 105-mm and 155-mm caliber. These shells were filled with either TNT or Comp B (RDX and TNT 60:40). A series of shells was attacked at different

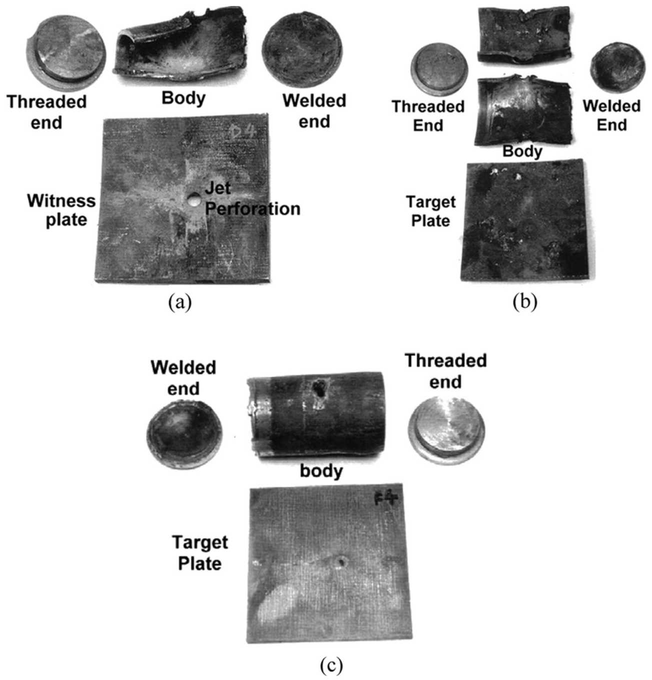

Figure 3. Fragments from synthetic "mortar bomb" trials (a) attacked with X1E1 filled with gelled NM showing jet penetration through witness plate beneath the synthetic target, (b) attacked with plastic-tubed "Baldrick" filled with gelled NM 2:5 and (c) 5:10 mixture.

positions on the casing, where the case thickness was different. Some of the shells were fitted with their alloy blanking plugs and others had this blanking plug removed. None of the target shells contained live fuses. The third type of munition attacked was 1000-lb (450-kg) bombs filled with Comp B or aluminized Comp B and again there were no fuses present.

Range Measurements

Trials with munitions of up to 155-mm caliber were performed on the West Lavington ranges in the Salisbury plain training area (limit 25-kg high explosive) and 1000-lb bombs were trialed on the Defence Science and Technology Laboratory trials ranges at Shoeburyness, Essex. In both cases the range setup was identical. The targets were arranged at the center of a 10-m radius circle predicted by CONWEP [20] programs as the fireball radius and a series of fast response thermal measurement gauges, supported on metal frames, were arranged at the edge of this circle at 1.5- and 3-m heights above the ground. This arrangement represented a worst-case scenario for personnel exposed to an event. Blast gauges were mounted on metal poles at 23 and 46 m from the device because the protective shelters for the preamplifier electronics were fixed and this gave the shortest input cabling from the gauges to electronics. The outputs from both sets of gauges were recorded by a fast storage oscilloscope fitted with a data capture board operating at 100 MHz that should indicate how the munition had responded; i.e., deflagration or detonation. Fragments from the destroyed shells were collected and their metallurgy examined by optical and electron microscopy to identify whether the casing had ruptured from a pressure burst or from a detonation [21].

Results and Discussion

The simulated shell targets showed interesting behavior. The PE4 and DETA-sensitized NM-filled shaped charge cone liner and copper dish devices initiated detonations within the PE4 filling, reducing the target to a myriad of small fragments and punching out the center of the witness plate the target was resting on. The gel-filled and the foam-sensitized filling only initiated partial deflagrations in the filling, even though the jet had sufficient energy to penetrate through a steel witness plate on which the simulated target was mounted; see Fig. 3a. For the high polyox filling in a copper dish device the target was opened by the deflagration, with the center section being split in two (Fig. 3b), but most of the filling was unconsumed and scattered around the test facility. The metal dish device in the plastic tube produced an EFP that had only penetrated the top wall of the target but was retained within the opened vehicle as shown by the recovered vehicle (Fig. 3c).

The shells attacked with the X1E1 and ''Baldrick'' devices filled with PE4 explosive detonated unless attacked near the base of the shell where the metal casing is thickest. The effect is shown for the 81-mm mortar shell (Fig. 4). In the upper part of the figure is shown the experimental arrangement and in the middle section of the figure, the debris for PE4-filled Baldrick shows that a large section of the witness plate underneath the munition was removed by the detonation wave induced in the main mortar bomb filling. The small size of the casing fragments recovered and the signals from the blast gauges confirmed the visual observations that detonation had occurred. The lower section of Fig. 4 shows the results from Baldrick filled with gelled NM attack on the mortar bomb. Only deflagration was induced, even though the ''jet'' penetrated the supporting witness plate. The other two in-house-manufactured devices, both metal and plastic cased, gave similar results with PE4 filling.

The 105-mm shells attacked with copper cone devices filled with DETA-sensitized NM produced detonations when the jet struck the thinnest part of the shell casing. Only when the attack was in the regions close to the nose or the base of the shell, where the metal casing was thicker, was deflagration produced. The copper dish devices, when filled with the DETA-sensitized NM, also produced detonations when attacking the thinner wall regions and again away from this region deflagrations were produced. In this case the observation of a fireball indicated the continuing deflagration of the shell filling after the casing had ruptured. The larger 155-mm shells with their thicker wall thicknesses were only particularly vulnerable near the waist region with the copper cone devices in metal or plastic tube devices.

All of the devices filled with either gelled or the foam-sensitized NM produced deflagrations in the shell filling regardless of the point of attack. The fragments produced (Fig. 5) and the measurements from the gauges indicated only deflagrations. In one trial with a 105-mm shell, the jet from the X1E1

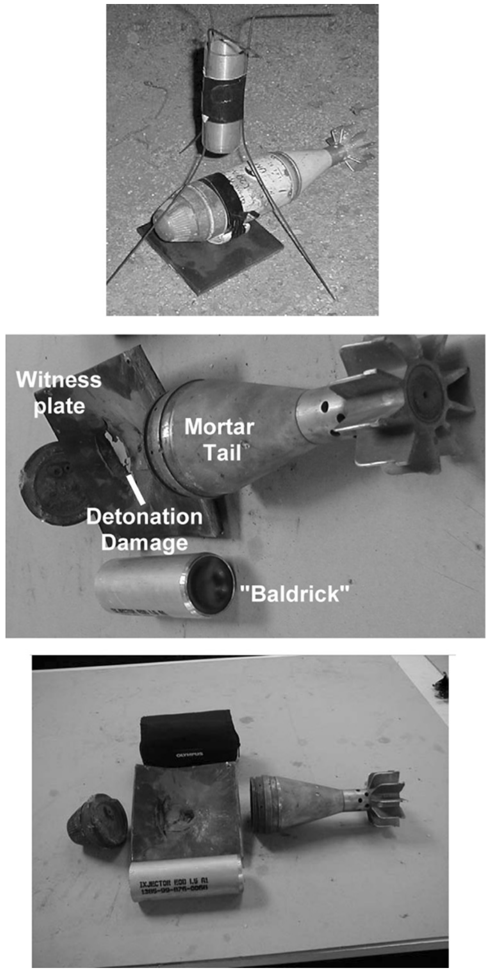

Figure 4. Experimental arrangement for 81-mm mortar trials (top) and effects of filling composition on steel-tubed Baldrick performance; Baldrick filled with PE4; munition fully detonated (middle), Baldrick filled with gelled NM (2:5); munition did not detonate (lower).

penetrated the casing and initiated a propellant-type burn of the filling, which ejected the nose blanking plug and projected an unruptured casing some 50 m down range. When recovered, this

Figure 5. Two 105-mm shells after attack by NM-filled X1E1 either side of an original shell.

casing was complete, apart from the jet penetration hole, but the filling had completely burned. If the 155-mm shell was attacked near the base, then not all of the filling was combusted and the separated front section contained some unconsumed filling with only limited charring on the exposed surface. Similar results were obtained when the point of attack was close to the nose of the shell. Metallographic examination of the shell fragments from attack with the gelled NM-filled devices showed clear evidence of a pressure burst on the grain boundaries of the steel fabrication with none of the small, high-energy, shear dimples expected from a detonating system [22].

Because of the serious outcome should the 1000-lb bombs detonate, they were not attacked with the PE4-filled device. All the devices, X1E1, Baldrick, and in-house-manufactured systems, when filled with gelled NM mixture, only induced deflagration in the contents of the 1000-lb bombs. The composition B-filled bombs usually produced a violent deflagration between 1 and 5 s after initiation of the attacking device and the deflagration lasted for varying times between 2 and 5 s. In one firing, the deflagration occurred 28 s after the attack. This was just sufficient time for a misfire to be declared and showed the importance of the >30-min soak time when the higher polyox and microballoon mixtures failed to initiate immediate deflagration in the bomb filling. The failure surfaces of typical fragments produced by the event, shown in Fig. 6, were also subjected to optical and SEM metallographic

Figure 6. 1000-lb Bomb (TNT/RDX) ready for test firing above and below fragments following attack by improvised explosive device copper cone in plastic pipe using gelled NM filling (2:5). The white wire shows the penetration hole.

examination and showed characteristics of ductile failure associated with a pressure burst.

The fireball produced by the deflagration was approximately 20 m in diameter and just covered the nearest sensors. The blast wave observed was less than that obtained from the calibration value from 5 kg of plastic explosive PE4 and values are given in Table 1. The figures for the calibration agreed with values calculated using the CONWEP suite of programs. The heat doses delivered to the measuring sensors depended on the prevailing wind and are shown graphically in Fig. 7. This was unsurprising because the fireball could move several meters during the burning phase driven by the prevailing wind. Thus, the upwind sensor could be engulfed in the fireball and experience a heat dose greater than the limit value for second degree burns [23], as shown in Fig. 7. Those sensors downwind of the event

Table 1
Blast overpressures (OP) from 1000-lb bomb (Comp B fillings) deflagrations

Firing	Device pressure (kPa)	Gauges 23 m (OP kPa)	Gauges 46 m (OP kPa)	Delay to deflagration (s)
Caliber[n] PE4 5.25 kg		12.38	4.78	
CONWEP		10.7	4.44	
1	1.78	10.69	3.71	3.54
2	1.46	5.87	3.25	0.003
3	1.21	7.02	3.05	0.003
4	1.78	8.84	2.62	0.005
5	1.5	4.65	3.20	28
6	1.73	7.85	2.80	3.34

The device used in these tests was the 60° copper cone mounted in a polymer tube. The device pressure is the OP measured by the blast gauges when the shaped charge device is initiated.

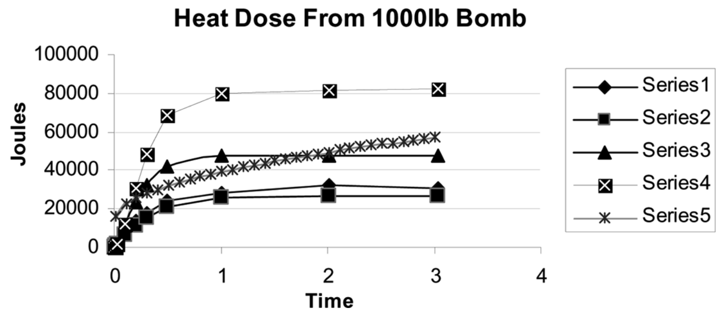

Figure 7. Heat dose from deflagrating 1000-lb bomb. Series 1 and 3 are cross-wind sensors; series 2 is downwind sensor. Series 4 is upwind sensor, and series 5 is standard second degree burn line from the literature [23].

received thermal doses less than the second degree burn line. Based on the figures determined in this work, personnel at 30 m downwind of the event would survive with limited burns. The blast overpressure measured at 23 m is on the threshold for eardrum damage in some people [24]. Normally, personnel are evacuated from the safety zone for full detonation prior to applying the procedure. In the case of the aluminized fillings, the contents continued to burn for 10–20 min after the casing was ruptured with very little uncombusted residue. The thermal output and blast overpressures were only just detectable and thus have not been included in the data table [21,22].

Throughout 60 trials of both 105- and 155-mm shells and 10 trials on 1000-lb bombs, no detonations resulted when gelled NM, sensitized with either microballoons or foam, was used in any of the three devices tested in these trials. Simple calculations based on comparisons with measured detonation and jet velocities of PE4 and gelled NM indicate that the energy deposition range is very much in the region of the induced deflagration as indicated earlier in this article. The higher performing DETA-sensitized NM may well produce energy deposition levels in the region of the deflagration to detonation transition response and hence the energy dissipated by passage through the casing is critical. If the shell is attacked at the thinnest part of the casing, then after penetrating the casing, the jet may have sufficient residual energy to initiate a burn but insufficient to produce a deflagration to detonation transition. Unfortunately, in these trials no distinction can be made between DDT and a prompt detonation. The one firing of the HMX paste–filled copper cone device induced an immediate violent response adjudged to be a prompt detonation.

Conclusions

The ease of manufacture of the nitromethane-based filling and the consistent performance of both copper cone and copper dish devices has provided a reliable method for initiation of munitions.

The energy delivered to the munition filling by impact of the projectile produced by gelled NM-filled devices was calculated to be below the threshold for DDT. No detonation events were observed with any of the devices filled with microballoon-sensitized nitromethane. Similar devices filled with plastic explosive initiated detonation in the simulated and real shells up to 155 mm as predicted by the critical power density theory. Deflagrations from 1000-lb bombs produced blast waves with lower peak pressures and impulses than the detonation of 5 kg of PE4. The heat dose observed from these bombs could cause second degree burns for personnel less than 30 m upwind from the event. The blast overpressure could cause injury to personnel standing within the 23-m circle. Unused NM fillings can be easily decommissioned by washing with warm water.

Acknowledgements

The authors gratefully acknowledge assistance from staff of COTEC for assistance with the firings against the standard shells on the West Lavington ranges. Similar thanks go to Maj. G Evans and staff of DSTL Shoeburyness for help with the 1000-lb bomb disposals and Dr. Michael Williams, of DASSR at DCMT, for help with the heat dose and blast overpressure measurements.

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