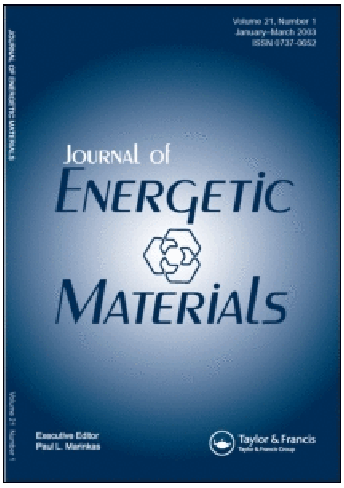

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Non-Solid Explosives for Shaped Charges. Part II. Target Penetration with Metal Liner Devices Using Sensitized Nitromethane Liquid Explosive

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Non-Solid Explosives for Shaped Charges. Part II. Target Penetration with Metal Liner Devices Using Sensitized Nitromethane Liquid Explosive

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In an attempt to overcome the inconsistencies of plastic explosive–filled shape charges in EOD operations we have explored the use of sensitized gelled nitromethane liquid as a filling for a number of shaped charge devices. The ability to penetrate munition casings and induce deflagration is not only dependent on the velocity of detonation of the mixture, investigated in previous papers, but also on the geometry of the devices used and in some cases the confinement present in the device. In this article a range of nitromethane-based explosive fillings, with a range of velocities of detonation, was used to investigate the performance, in terms of target penetration, of both conical and dished metal liners and

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flat-bottomed cup liners mounted in cylindrical tubes. A number of unexpected results were obtained when copper dish devices were mounted in metal tubes and demonstrated a penetration dependence on standoff to the target. These observations were confirmed by flash X-ray investigation of the functioning devices. Some discussion of the critical parameters controlling the liner behavior has been undertaken.

Keywords: liquid explosives, shaped charges, target penetration

Introduction

Military shaped charges are designed for maximum efficiency against armored targets and hence are filled with high-density solid explosives possessing high velocity of detonation. Consistent performance depends on the homogeneity of the filling and is vital to ensure correct functioning of the device [1]. Consistent device filling is difficult even for melt cast fillings. In an earlier paper [2] we discussed the problems resulting from imperfect fillings and reported some unpublished results that illustrated these difficulties, even for experienced operators (A. Doig, RMCS, personal communication, 2003). Our earlier paper reported the performance of sensitized nitromethane (NM) fillings and the results obtained demonstrated their consistent behavior.

Ideally, for ordnance disposal the device should penetrate the munition case and initiate a burning mode in the filling, with deflagration being the final objective and detonation being the least desirable result. Shaped charges filled with plastic explosive, PE4 (88% RDX, 12% wax) [1], require performance degradation to achieve deflagration in attacked munitions. Degradation is produced either by increased stand-off, allowing the jet to start to break up by extended travel, or reduced explosive content, to avoid the common detonation induced by these devices. As an example the injector explosives ordnance disposal (EOD) device, ‘‘Baldrick,’’ described later, has three charge fill levels indicated on the tube body for such situations. Because usually there is no simple way for calculating in the field the degradation required, using the option of liquid explosives becomes attractive. The appropriate properties of nitromethane and its sensitization have been discussed by other authors [3,4]. Addition of chemical reagents maintains the density and hence generally produces relatively higher performance systems. In an earlier paper [2] we investigated the performance parameters of sensitized nitromethane as an explosive. This article reports some of our measurements of the penetration achieved with the sensitized NM-filled systems. Results obtained with some of the dish liners in metal cases were somewhat surprising in that their penetration showed a stand-off dependency not expected for explosively formed projectile (EFP) devices. Flash X-ray photography of functioning devices confirmed our initial suppositions. Events when munitions are attacked will be described in later publications.

Experimental

Materials

Nitromethane, 95% pure, polyethylene oxide, mean molecular weight 300,000, and diethylenetriamine, DETA, were supplied by Aldrich Chemical Company (Gillingham, Dorset, UK). Three different types of glass microballons, all with the same particle size distribution but requiring different collapse pressures, were supplied by 3 M Limited (Harlow, Essex, UK) and trialed in this study. A range of polymer foams, identified in the first paper, were supplied by Caligen Foams (Accrington, Lancashire, UK). Polypropylene plastic pipe, 35 mm o.d. and 1.5 mm wall thickness, manufactured by Marley Plumbing and Drainage Ltd. (Lanham, Kent, UK), was purchased from the local D.I.Y. store. Epoxy resins manufactured by Huntsman Advanced Materials (Basel, Switzerland) were supplied by Radio Spares. The 30-mm-diameter, 60° cone angle, copper liners, with 1.25 mm wall thickness, were supplied by B.Ae. Defence Systems (Glascoed, Usk, UK). Copper dishes were manufactured in the engineering workshop at the Defence Academy of the U.K. using oxygen free copper sheet supplied by Goodfellow Metals U.K. Ltd (Huntingdon, Cambridgeshire, U.K.)

Sensitization of Nitromethane

The only chemical sensitization used in this study for comparison purposes was 5% diethylenetriamine, DETA, $NH_2C_2H_4NHC_2H_4NH_2$ [5], which was used as a standard to compare against the performance of the sensitized gelled NM. The major disadvantage of this material is its toxicity, which increases the hazards for the operator. An additional difficulty is that 24 h after mixing the detonator sensitivity is greatly reduced, often requiring a booster charge for reliable detonation and a dark oil layer is produced at the bottom of the sample. Hence, this mixture was used within minutes of mixing. Desensitization and decommission of the chemically treated NM, in the event of non-use of the device, involves treatment of the NM phase with aqueous acid, preferably hydrochloric, to form salts with the free amine.

Our previous paper described the sensitization of niromethane with polymer foams or glass microballons suspended in polymer-thickened NM and this latter is the principal method used in this study. The sensitization mechanism operating when the microballoons are used has been ascribed to a number of different processes [6].

GEL Preparation

The gelled NM samples, with different concentrations of the ‘‘polyox’’ thickener to give 1, 2, 5, and 10% polyox by mass, were prepared in bulk as indicated previously [2] and stored in plastic bottles until required. Sensitization of the gelled NM was achieved by incorporation of the appropriate weighed quantities of microballoons to give 1, 5, or 10% by mass formulations. The microballoons were wetted with NM before addition to avoid dusting problems. The mixture was vigorously stirred for 2 min, using a wooden tool, before pouring into the charge device immediately prior to use.

Devices Trialed

A number of devices were investigated. The service issue short range deflagrator, injector EOD 1.5 A1, known colloquially by operators as ‘‘Baldrick’’ [7], was supplied by DERA (Fort Halstead, Kent, UK) and was designed as an EFP device. It consists of an alloy metal tube, 150 mm long by 50 mm o.d. and 4 mm wall thickness, with a copper dish 1.5 mm thick either glued to the lower end or held in position by a rolled-over lip on the metal tube; see Fig. 1. The detonator holder is a plastic sleeve, which fits inside the alloy tube, and has a 7-mm axial hole designed to accept a standard L2A1 electric detonator. Also supplied is a solid plastic piece, which can be fitted between the detonator and the copper dish to reduce the detonation pressure developed and to shape the impacting shock wave on the dish liner, thus reducing the chances of detonation in the attacked munition.

The standard U.K. service issue ICM92 container TX113A, also known as the point focus device, X1E1, was supplied by Ammunition Branch, Defence Academy of the U.K. and shown in the lower part of Fig. 1. This device consists of a painted steel metal cylinder, 67 mm long by 28 mm o.d. with 0.8 mm wall thickness and a 60° copper metal cone of 0.8 mm wall thickness. The copper cone is an interference fit into the cylinder and is retained by a lip at the lower end of the tube. Correct alignment of the cone is ensured by using an appropriately shaped former to drive the liner into complete contact with the retaining lip. For the gelled NM this was liquid tight but, when using the liquid NM with the foam or chemical sensitizer, the copper liner had to be sealed into the tube with a rapid-setting epoxy resin glue to render the system leakproof. The plastic detonator holder doubles as a filling tamper, when plastic explosive PE4 is used as the filling and three metal rods, which are attached to the outside of the tube body by a plastic retaining ring, support the device at a suitable stand off distance from the target.

Some low cost in-house-manufactured devices, designed to mimic the cone and dish devices, were assembled from cheap, readily available components. The first device consisted of a

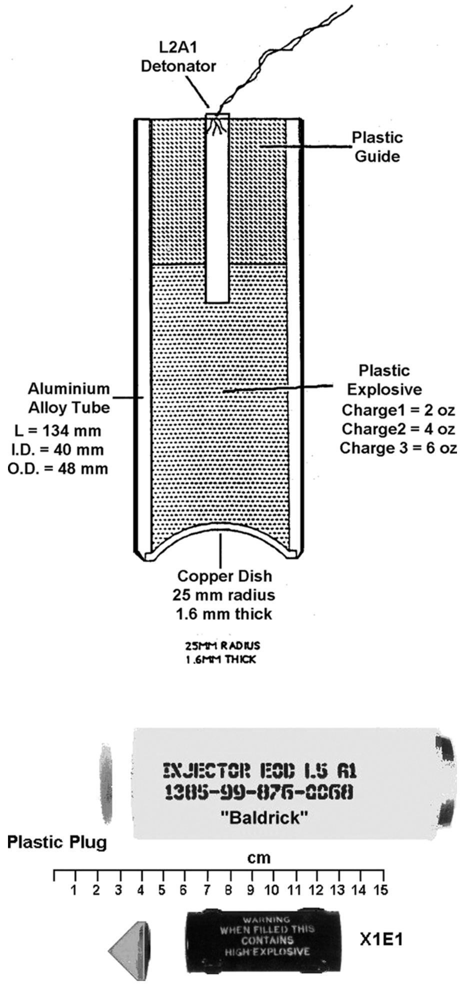

Figure 1. Schematic of Baldrick (top), Baldrick components (middle), X1E1 (lower).

100-mm length of a 41-mm o.d., 4-mm wall thickness light alloy tube that had a either a 60° copper cone, 1.25 mm thick, or a copper dish fitted to one machined end, which was then rolled onto the insert to provide a liquid-tight seal to the liner. The improvised devices consisted of a 100-mm length of a low-density polypropylene pipe into which the copper cone or dish could be easily hand-pressed, if the pipe had been previously warmed in hot water, to produce a liquid-tight seal. With both the metal and the plastic tubes the dish liner was retained by a supporting lip at the lower end. A further device used a flat-bottomed, parallel-sided cup, normally used by engine manufacturers to plug casting holes in engine blocks, as the metal liner sealed into the metal tube. The in-house-manufactured and improvised devices were supported on cheap adjustable metal wires or polymer tube to produce the appropriate stand-off as required; see Fig. 2. All improvised systems used rigid polyurethane foam sections at the top as detonator holders.

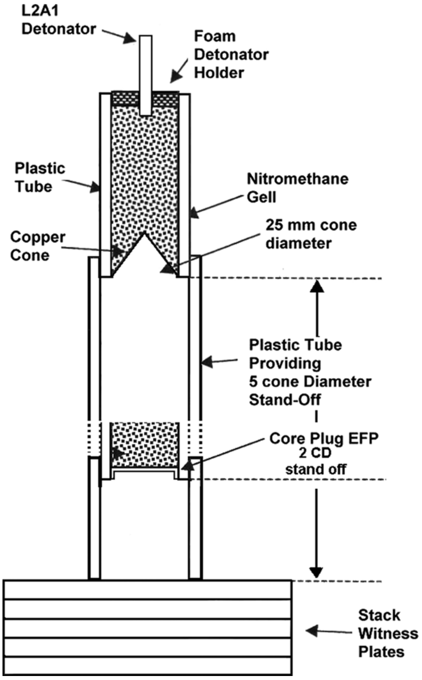

Figure 2. Showing test assembly for the cone and the plug devices. The schematic shows the location of the core-plug relative to the target plates.

Assembled devices were filled with either the microballoon sensitized gelled NM or pure NM poured onto a sample of foam, which extended from the detonator to the top of the copper liner, immediately prior to use and the detonator inserted into foam holder. Similarly shaped charge devices filled with either PE4 or chemically sensitized (DETA, 5% by mass) NM, prepared immediately prior to the trial, were also tested for comparison.

Targets

The principal targets used were stacks of mild steel plates, 100 × 100 × 10 mm, held together with adhesive tape. This enabled simple values for the penetration performance to be measured in order to determine the possible success against potential munition casings. Flash X-ray samples used 100-mm-thick steel cube witness plates. The devices were mounted vertically over the middle of these target stacks using either metal rods or garden canes or plastic tubing with an adhesive tape mounting. Cone device stand-off above the top plate was adjusted to the "optimum" 5 cone diameters for each of the devices trialed using a series of metal rod distance pieces. The dish liners, originally expected to produce EFPs, initially used the 2 cone diameter stand-off as indicated schematically in Fig. 2. Additional experiments with the metal cased dishes were performed at the 5 liner diameter stand-off to optimize the penetration. Performance was measured by the number of plates penetrated and the dimension of the holes produced.

Flash X-ray Studies

Some of the preliminary results from the target stacks attacked with dish devices in metal tubes were unusual and indicated that the devices were behaving in an unexpected and unpredictable manner depending on the device configuration. As a result a series of devices with different fillings were fired on the D.S.T.L. Porton Down ranges, operated by Hunting Engineering Ltd., and a series of four flash X-rays with different trigger times were recorded for each firing to identify the nature and velocity of the projectiles produced. The range set up is shown in Fig. 3. The X-ray source, a tungsten rotating anode tube operated at 140 Kv, and the film detectors were protected from the explosion effects by 25-mm-thick aluminum sheets supported on rigid steel frames. Distance calibration on the X-ray photographs was obtained from images of a steel threaded rod with nuts screwed onto the rod at various measured distances placed alongside the test assembly.

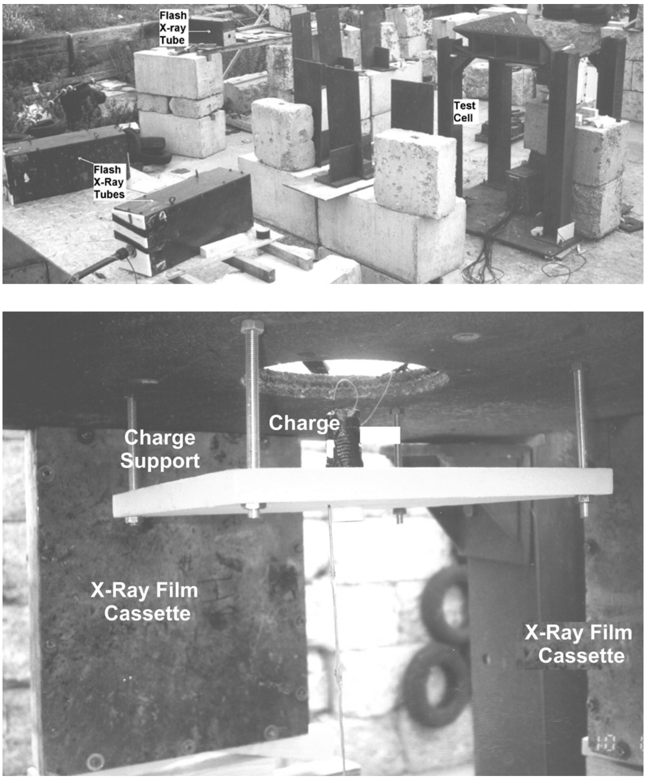

Figure 3. Flash X-ray test facility (top) and close-up of charge firing arrangement (lower).

Results and Discussion

Results from the velocity of detonation (VOD) measurements, reported earlier [2], demonstrated that the velocity of detonation varied with filling density in a linear relationship as predicted by Kamlet and Jacobs or Marshall's formulae [8], with the highest concentration of the highly oxygen-deficient polyox (10%) showing the lowest VOD and deviating most from the predicted formulae. Below 2% concentration of the polyox used, MMW = 300,000, the microballoon dispersion was unstable and the mixture did not fully respond to the detonator output with the lower timing trigger failing to function. This may be due to the microballoons migrating toward the upper surface of the mixture in the time interval between device filling and firing. Changing the mean molecular weight (MMW) of the polymer may circumvent this problem. Because all the tubes used appeared to be above the critical diameter for the explosive fills, confinement did not affect the VOD measured. The penetration results shown in Table 1 (where the gel composition convention 2/5 refers to microballoon content and then polyox content) were consistent and the 5% variation from the NM mixtures, using both physical and chemical sensitization, was less than for the PE4 filled devices; see top lines of Table 1.

All the copper metal cone liner devices trialed functioned by producing jets as expected and their penetrations matched those expected from their cone diameters, angles, and thickness as well as the velocity of detonation of the filling, (Table 1). The smaller diameter and thinner cones produced lowest penetration values as expected from the reduced mass of metal available for jet production. The penetration appeared to be independent of the confining material with the polymer tube–cased devices performing as well as the steel tube–cased devices. The PE4-filled devices showed the highest penetration performance but the DETA-sensitized nitromethane charges also functioned well and exhibited better consistency of performance; see top two lines in Table 1.

The copper dish liners and the core plug cup devices produced some surprising results, which depended on the nature

Table 1
Penetration results cone shaped charge devices

Device	Filling (%μb/% Polyox)	VOD (ms^{-1})	Pentration (mm)	Comments
X1E1		±120		
	PE 4		50 & 47	Jet hole diameter decreasing
	NM/DETA		48 & 47	Jet
	Foam 8173	5700	37	Jet
	Gel 1/2	6500	38	Jet
	Gel 1/5	6369	35	Jet
	Gel 1/10	5376	30	Jet
	Gel 5/5	4880	25	Jet
	Gel 5/10	4785	20	Jet?
	Gel 10/5		18	Poor jet. Cu spatter on plate
	Gel 10/10	4292	15	As above
Copper cone in plastic	PE 4		58	Larger diameter cones higher performance
	NM/DETA		52	Jet
	Gel 1/5	6369	38	Jet
	Gel 1/10	5376	32	
	Gel 5/5	4880	30	Jet
	Gel 10/5		20	
	Gel 10/10	4292	15	Copper spatter on plate

of the confining material (Table 2). When fitted to a plastic tube, because the liner was uniform thickness, the dishes produced backward folding EFP, whose penetration was independent of device to target stand-off but directly proportional to velocity of detonation [9]. This was in keeping with dish liner collapse theory [10], shown schematically in Fig. 4. A typical EFP recovered from the target plate is shown in Fig. 5.

Table 2
Target penetration dish liner devices

Device	Explosive	Penetration (mm)	Comments
Baldrick metal tube	PE4	38	Jet reducing diameter hole
	NM/DETA (5%)	35	As above
	Gel 1:5	35	Jet
	Gel 5/5	30	Jet
	Gel 10/5	25	Jet
	Gel 5/10	15	EFP? Constant diameter hole
	Gel 10/10	15	EFP? As above
	Foam 8173	27	Jet-reducing diameter
	FoamX6276AC	20	Thick jet
Dish liner in plastic tube	Gel 1:5	12	Constant diameter
	Foam 8173	8	Projectile caught 2nd plate

However, when the dish liners were fitted into metal tubes, the target penetration, although of a larger diameter than that produced by the true cone jet, was dependent on device-to-target stand-off distance. The penetration perforations decreased in diameter as expected for a jet impact rather than the constant diameter perforations expected of an EFP or self-forging fragment. The target penetration was greater than for the plastic-tubed devices. The cup liners (core plugs in Fig. 2) fitted into steel tubes appeared to give distinct jet-type penetrations when used with PE4 and DETA-sensitized NM mixtures but only produced EFPs with all the other formulations.

In order to clarify this situation, flash X-ray images of the detonation process were taken. The X-ray images showed the

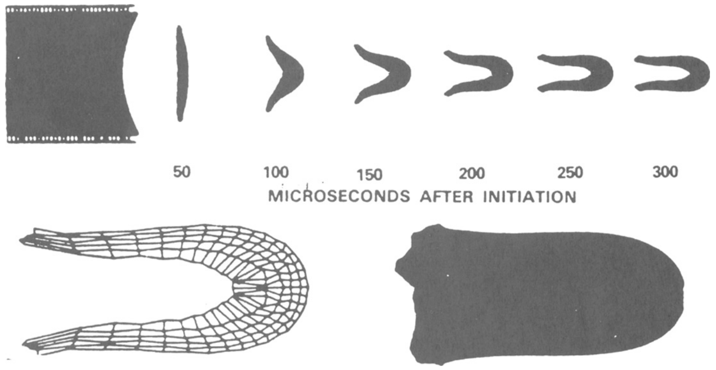

Figure 4. Showing computer model of EFP generation (top) and enlarged computer image of final EFP (lower left) and X-ray image of the EFP projectile (lower right).

formation of a typical thin jet with the cone liners and thick jets with the dishes in metal tubes; see Figs. 6 and 7. The PE4-filled devices produced the thinner longer jets, shown in Fig. 6, but the gelled NM-filled devices still produced a jet-like projectile and formed an identifiable slug and cone rim characteristic of jet performance, Fig. 7. The jet stretched as it traveled and at ~5 cd stand-off achieves the optimum target penetration. The L/D ratio is greater than the 2.8 ratio found for EFPs produced by high VOD HMX fillings (Table 3). Figure 8 shows the variation in the profile of the EFPs formed with VOD of the

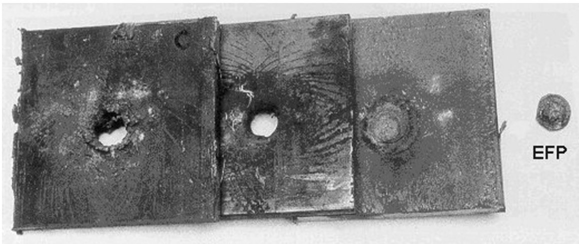

Figure 5. Target plates from trial using plastic-tubed Baldrick with gelled NM (2/5).

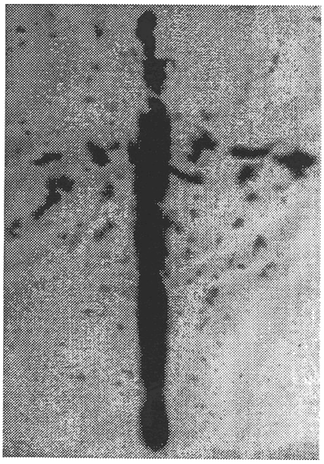

Figure 6. Flash X-ray image of Baldrick device in steel tube, without plastic plug, filled with PE4 explosive.

filling. A composite of a series of flash X-ray images taken at varying times, 28–128 µs, after detonation for an NM gel-filled metal tube Baldrick is shown in Fig. 9. Starting at the top,

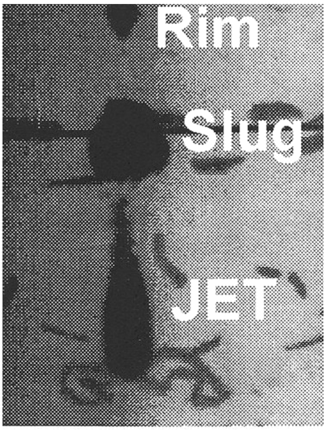

Figure 7. Flash X-ray image of Baldrick device in steel tube, without plastic plug, filled with thickened NM mixture.

Table 3
EFP shape and velocity as a function of VOD of explosive

Explosive	VOD (ms^{-1})	Velocity of fragment (ms^{-1})	Fragment (L/D)
TNT	6900	1650	0.84
Composition B 60:40 RDX:TNT	7800	1950	1.65
Octal 75/25 HMX: Al	8600	2130	2.40
HMX	9100	2160	2.65

the first stage is the collapse of the liner and then the distortion to form the three separated components of the cone rim, the slug, and at the lower part the fat jet. Regions of debris from the case have been indicated in Fig. 9.

Hemispherical liners have been previously shown to produce shaped charge jet [11] projectiles (Fig. 10), but there is no indication in the literature of this effect for simple dish liners. Even the smallest diameter dishes (30 mm) used in this study produced thick jets with the most energetic fillings. The proportion of the hemisphere at which the liner ceases to form a jet does not appear to have been elucidated. Current liners used in this

Figure 8. Shape of EFP as a function of velocity of detonation. TNT (top), Octal, 75/25 (middle), and HMX (bottom). Additional data are given in Table 3.

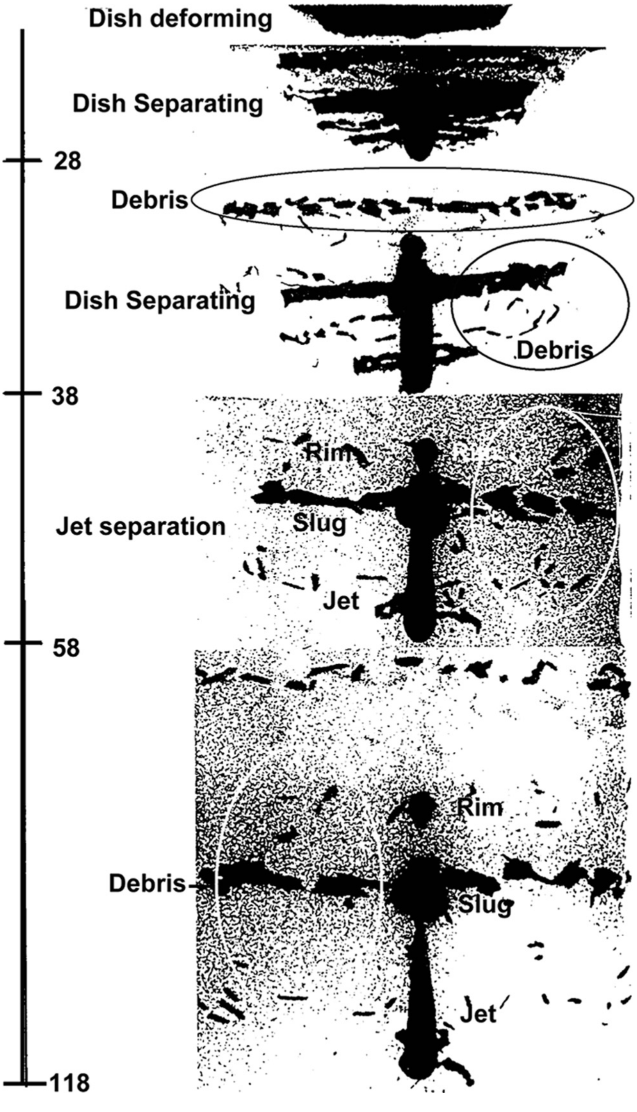

Figure 9. Flash radiograph sequence from gel (2/5) filled steel tube Baldrick. Scale on the left side is microseconds after initiation.

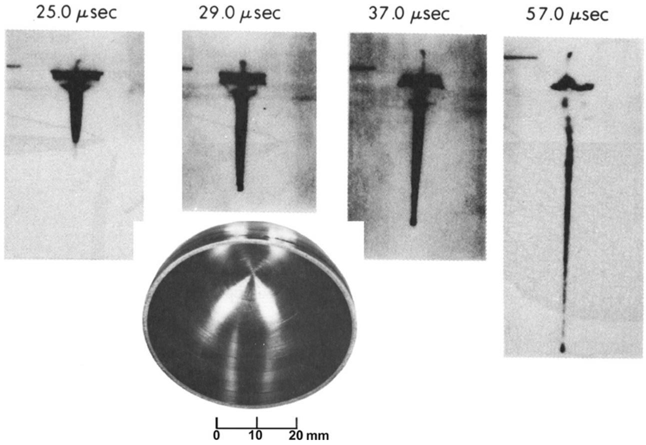

Figure 10. Flash X-ray images of copper hemisphere liner shown at various times after initiation of detonation. Adapted from Kronman and Walters [11].

work represent <1/4 of a hemisphere and all produced the jet characteristics with the metal casing except for the lower VOD gels, where an EFP may have been produced, but there was also considerable copper splatter on the top target plate, indicative of inhomogeneity in the shock wave. All the dish liners have a common curvature at their highest point, cf. the hemispherical dishes, and this may be the critical parameter dictating the jet formation for all the dishes used. This jetting effect was found to be independent of the attachment of the liner to the metal tube. Examining the curve for the formation of jets and EFPs with liner geometry as a function of liner angle and VOD (Figs. 11 and 12), then the dishes in the plastic tube produce EFPs at VODs well above the critical jet line and the metal-encased liners produced comparatively slow-moving thick jets. Velocity determined from the flash X-ray images gives the slowest jet velocity of $\sim$2300 ms^{-1}.

This difference between metal- and plastic-encased dishes may be due to the extra confinement and shock wave reflection from the metal container walls augmenting and shaping the shock wave impinging on the dish. When the metal tube

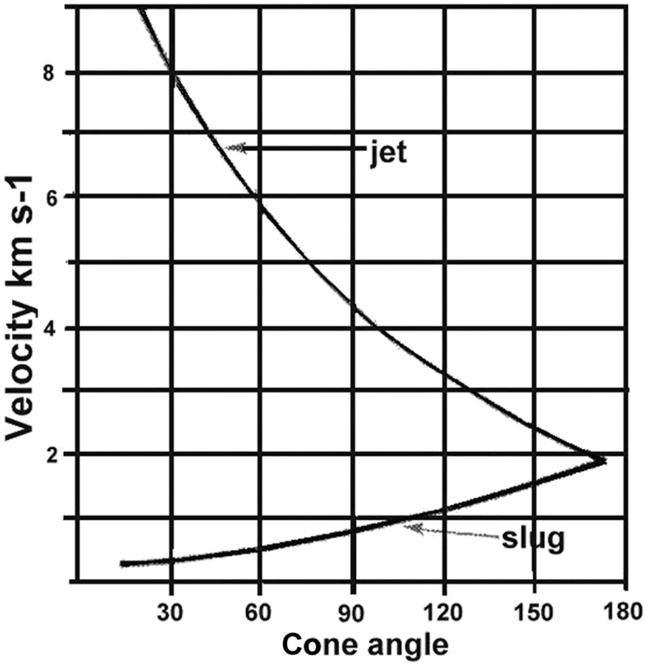

Figure 11. Variation of jet and slug formation with VOD and cone angle.

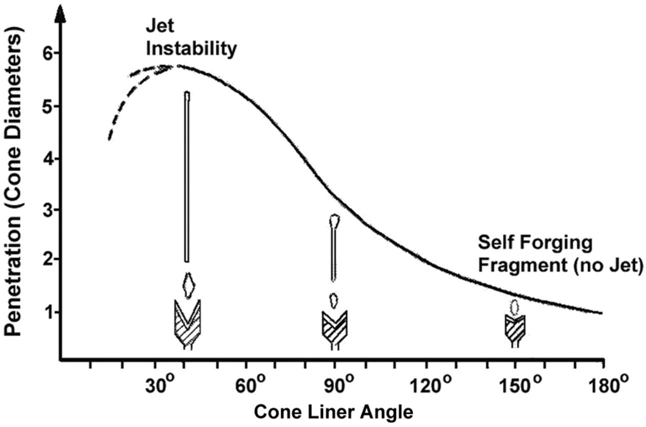

Figure 12. Penetration from cone liner devices as a function of liner angle constant VOD.

"Baldrick" device had the thick plastic washer plug inserted in the middle of the explosive filling between the detonator and the dish, a true EFP was formed as evidenced by the target plate results already seen in Fig. 5. The effect of relative location of plug and liner was not investigated. This effect could have two origins: a velocity of detonation effect and also the nature of the shock wave impinging on the liner. In the absence of the plastic insert, the VOD for the PE4 filling would be above 6900 ms^{-1}, whereas with the plastic insert simple calculations on the reduction in VOD expected from the presence of the barrier indicated that the VOD could be less than 4500 ms^{-1}. This is about the same magnitude as the worst performing NM gel. The shock wave after the plastic inert plug will have the profile indicated schematically in Fig. 13 and will impinge on the outer edges of the dish in advance of the center, which is the normal contact point. This will make a significant difference to the liner collapse. Also, if the quantity of explosive filling in the device was reduced below a depth of 1.5 tube diameters, then again an EFP was formed. The shock wave would be still essentially spherical again, indicating a shock wave shape effect.

The fillings with high concentrations of polyox and microballon, which produced low VOD, gave poor jet formation with inconsistent target penetration. This may be an indication of a minimum detonation velocity requirement for effective penetration performance. Most of these firings produced penetration attributable to either an EFP or a jet. The top plate indicated

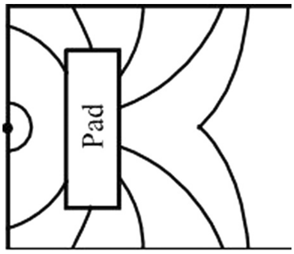

Figure 13. Schematic of the effect of an inert pad on the shape of the detonation wave for metal-cased device.

copper spatter, which may be indicative of the problem of keeping the very high microballoon compositions homogeneous due to cavitation, induced by the mixing process in these viscous gels, being slow to disperse. Further work on the shape and velocity of the detonation wave may need to be undertaken to clarify this aspect. The resulting detonations were still above the low-order detonation mentioned by Usselstein [12] for NM initiated by an insufficient shock wave stimulus.

Conclusions

Sensitized nitromethane gels give outstanding, consistent performance in a number of shaped charge devices. Metal cone liners produced shaped charge jets when contained in both metal and plastic tube confinement. Copper metal dish liners when contained in a metal tube support unexpectedly produced target penetration consistent with shaped charge jets. The jets formed by the dish liners were fatter and shorter than those produced from the cone liners and the target penetration was correspondingly less. The results were confirmed by flash X-ray imaging of functioning devices. Flat-bottomed cup liners in metal tubes with high VOD explosive fillings (PE4 and DETA-sensitized NM) produced a jet-type projectile but with the gel NM fillings only produced EFP-type projectiles even in the metal tube.

The mixtures trialed here should give the correct performance parameters for munition disposal by deflagration induced by projectile impact and because they have a lower environmental impact and toxicity than conventional munition fillings [13] should reduce the safety hazard for field operators.

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