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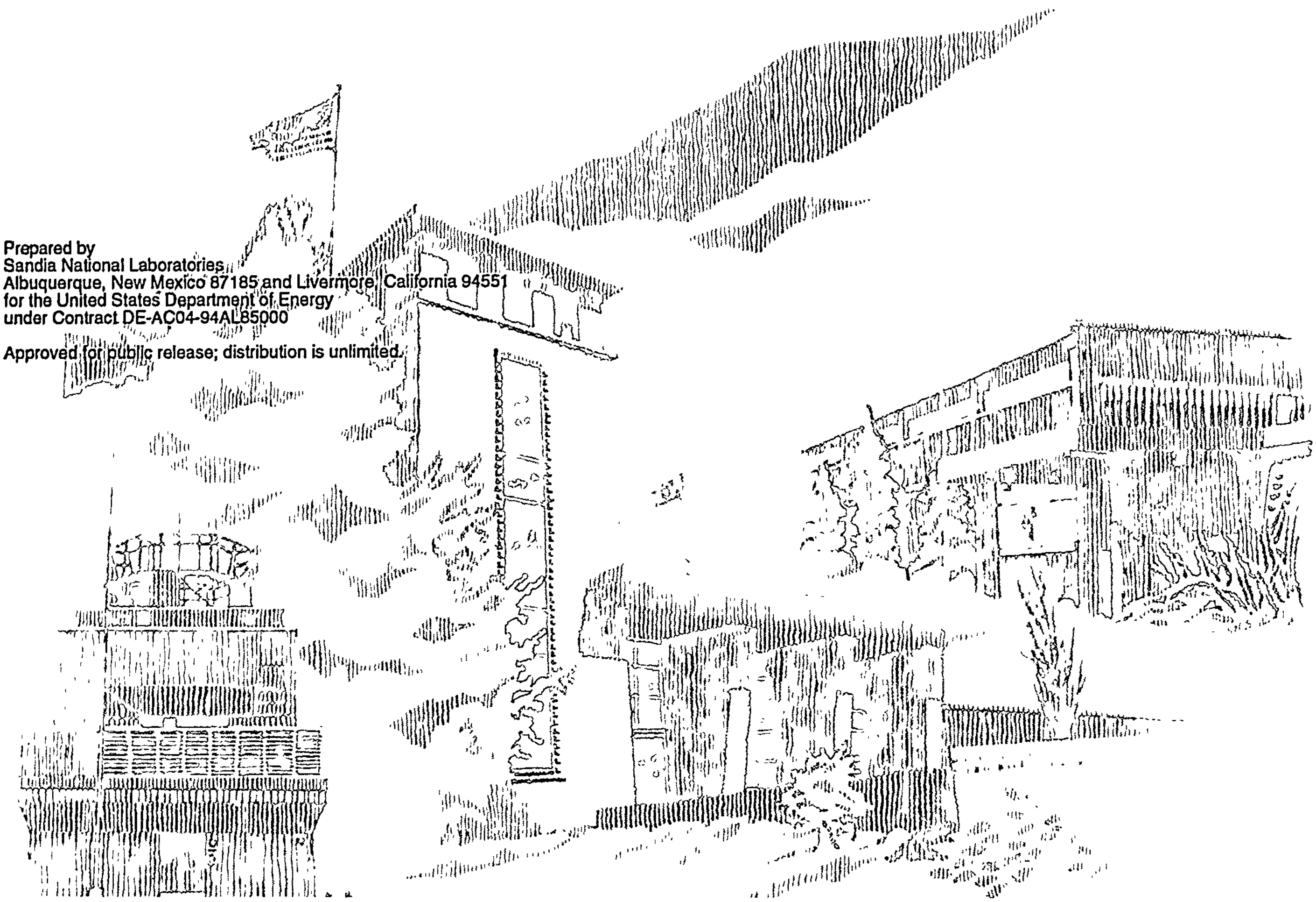
Investigations of Emergency Destruction Methods for Recovered, Explosively Configured, Chemical Warfare Munitions

Interim Emergency Destruction Methods Evaluation Report

M. R. Baer, P. W. Cooper, M. E. Kipp, M. E. Larson, V. M. Loyola,
W. C. Replogle, and K. L. Tschritter



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INVESTIGATIONS OF EMERGENCY DESTRUCTION METHODS FOR RECOVERED, EXPLOSIVELY CONFIGURED, CHEMICAL WARFARE MUNITIONS

INTERIM EMERGENCY DESTRUCTION METHODS EVALUATION REPORT

by
Melvin R. Baer, Paul W. Cooper, Marlin E. Kipp, Marvin E. Larson,
Vincent M. Loyola, William C. Replogle and Kenneth L. Tschritter
Sandia National Laboratories
Albuquerque, New Mexico
Livermore, California

ABSTRACT

At the request of the U.S. Army Non-Stockpile Chemical Materiel Office, the Sandia Explosives Containment System Design Team investigated mature destruction systems for destroying recovered chemical warfare munitions (CWM). The goal of the investigations was to identify and examine available techniques for the destruction of recovered CWM. The result of this study is a recommendation for an interim solution, a solution for use on any munitions found while an optimal, long-term solution is developed. Sandia is also performing the long-term solution study to develop a system that destroys CWM, contains the blast and fragments, and destroys the chemical agent without insult to the environment.

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Program Manager for Non-Stockpile Chemical Materiel
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Engineering Research and Development Center
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CONTENTS

FIGURES

TABLES

INVESTIGATIONS OF EMERGENCY DESTRUCTION METHODS FOR RECOVERED, EXPLOSIVELY CONFIGURED, CHEMICAL WARFARE MUNITIONS

Executive Summary

Over a three-month period, the Explosives Containment System Design Team investigated five emergency destruction methods. The methods investigated were: the explosive overcharge method currently used, tailored explosive overcharge systems, steel blast mitigation, steel containment, and foam mitigation. The design team reached the following five conclusions:

1. The undesired blast effects from a 5:1 explosive overcharge can be reduced if the explosive charge is placed in a steel cylindrical barrier.

2. The explosive in the 5:1 overcharge can be reduced by tailoring the explosive to the agent fill of the recovered munition.

3. Off-the-shelf steel containment/mitigation systems will not contain all of the agent, and would be difficult to decontaminate after explosive destruction of the recovered munitions.

4. Foam mitigation systems currently used by Explosive Ordinance Disposal (EOD) units would be effective for protecting property from the blast used to destroy CWM, but would require subsequent clean-up of chemical agent, water and surfactant.

5. Scale tests must be performed to utilize any alternative to the standard 5:1 overcharge.

Details of the examination of each technology is described in the report. After performing the investigations described in this report, it is the team recommendation to stay with the 5:1 explosive overcharge, in the absence of any testing. Additionally, we recommend evaluating the effectiveness of a steel cylindrical barrier in noncritical tests; i.e., tests in remote areas on recovered munitions or using agent.

Introduction

This report examines and recommends the best methods available for mitigating adverse effects associated with destroying recovered, explosively-configured chemical warfare munitions. In remote areas the Army currently uses a 5-to-1 explosive overcharge (explosive to agent mass ratio) to destroy recovered chemical munitions that are unsafe for transport or disassembly. Using this explosive overcharge for chemical munitions with a large quantity of fill agent, requires an excessive amount (up to 140 pounds) of explosive for effective destruction. In an effort to reduce the hazards associated with destroying recovered chemical munitions, Sandia was tasked to investigate on-site emergency destruction methods that minimize damaging blast effects and the hazards of spreading chemical agents. The task is two-phased. In the first phase Sandia will investigate mature destruction technologies that could be used if a chemically filled munition is found today; i.e., an interim solution. In the second phase Sandia will develop a long term solution that destroys CWM, contains the blast and fragments, and destroys the chemical agent without insult to the environment. This interim solution report is the result of the investigations of the first phase.

The Army currently uses a mass of explosive 5 times the mass of the chemical agent (5:1 overcharge) to destroy recovered CWM. This destruction method may be effective for destroying the munition and fill, but there can be undesirable blast effects depending on the mass of agent and location of a recovered munition. For example, if a chemically filled munition is recovered in an urban environment the explosive overcharge destruction method will require evacuating people, and the blast will likely cause damage to buildings, windows and other property. In performing this study we assumed a worst case scenario (a recovered munition in a populated area) and investigated options that are available today. During a three month period the team investigated the following five destruction methods:

1. The 5:1 explosive overcharge method currently used
2. Means for reducing the explosive in the current method
3. The use of a cylindrical barrier around the recovered munition and overcharge
4. Commercially available containment systems
5. The use of aqueous foam for blast and agent dispersal mitigation

The intent of this report is to contrast these five options. We determined there is not a single option best for all circumstances. Each has strengths and weaknesses to be considered in selecting the best option for a given scenario. In the evaluation of the technologies we asked ourselves several questions: Will the agent be destroyed? If not destroyed, what form will it be in? How can we mitigate the blast effects? Given all the trade-offs, what is the best solution available today?

In the remainder of this document the investigation of each destruction option is discussed; the strengths of the systems are compared and contrasted, and recommendations are made.

Investigation 1

The 5:1 Explosive Overcharge Destruction Method

The 5:1 explosive overcharge destruction method currently used serves as a baseline against which other options can be measured. The Army has experience with a 5:1 overcharge and is confident that it is effective. This option is already used by Emergency Ordinance Disposal (EOD) teams. Army experience shows that an explosive charge of about 5 times the mass of chemical agent contained in the device will effectively destroy the agent and the device. In order to use this experience as the baseline a complete understanding of the thermal kinetics of the explosion and subsequent fireball is required.

The next section describes the modeling of the 5:1 explosive overcharge. The purpose of this investigation is to understand the existing destruction method and establish it as a base-line for evaluating the alternatives. This investigation consists of scaling the fireball created by the explosive overcharge, calculating the products of the reactions within the fireball, and comparing the results to historical laboratory experiments.

Scaling Estimates

The explosive destruction of an agent in a chemical weapon occurs in the inferno of the fireball that accompanies a detonation event. Thermochemical detonation calculations of well mixed explosives and filling agents produces a high fraction of reactive product gases that may undergo secondary combustion with entrained air. To investigate the nature of this event, we estimated the quantity of air that is violently mixed with the explosive and agent hot product gases. A first principles calculation of the turbulent mixing and entrainment of air with reactive gases is a formidable computation, thus, estimates are made using empirical correlations from the open literature.[1] Based on field tests with varied quantities of propellants, High (1968) correlated fireball diameter (D_f) with explosive mass (M_x) and determined a 1/3 scaling law, $D_f \sim 3.76\ M_x^{\ 1/3}$, where the fireball diameter is given in units of meters and the explosive mass in kilograms. If one assumes that this diameter corresponds to a spherical volume of air entrained in the fireball, the amount of air mass in the fireball, M_{air}, can be scaled to the explosive mass according to $M_{air} \sim 32\ M_x$. With the above scaling a specified ratio of explosive mass to agent mass yields a relative mass of entrained air such that thermochemical calculations can be performed corresponding to an explosion state.

Thermochemical Analysis of Explosion States

This study centers on the agent phosgene. Phosgene and mustard are the two most common fills for the munitions of interest in this study and for the reactions discussed here the chemical properties are similar. All of the appropriate thermochemical data were taken from Lange's Chemical Handbook.[2] The baseline explosive material used for the overcharge is C4. All of the thermochemical data for this explosive and other candidate energetic materials are taken from Dobratz.[3]

Thermochemical calculations were performed using the CHEETAH (an updated version of the TIGER code) computer program using the complete library developed at Sandia National Laboratories.[4] The fireball mixture density is calculated by summing the masses of explosive, chemical agent and entrained air and dividing by the volume of the fireball. Results from these calculations yields the product species (gaseous and condensed) and the thermodynamic state of the reacted mixture. The fireball temperature and overpressure induced by the secondary combustion are the states of most interest. For the baseline case of C4 and phosgene (5-to-1 mass ratio), the calculated fireball temperature is roughly 2000 K. Interestingly, this corresponds to a temperature near the freeze-out condition (~1800 K) observed in detonation calorimetry work. The freeze-out temperature corresponds to temperatures where chemical kinetics rates are comparable to the acoustic time scales associated with gas expansion. At lower temperature conditions, one expects incomplete reaction with the potential for unreacted chemical agent.

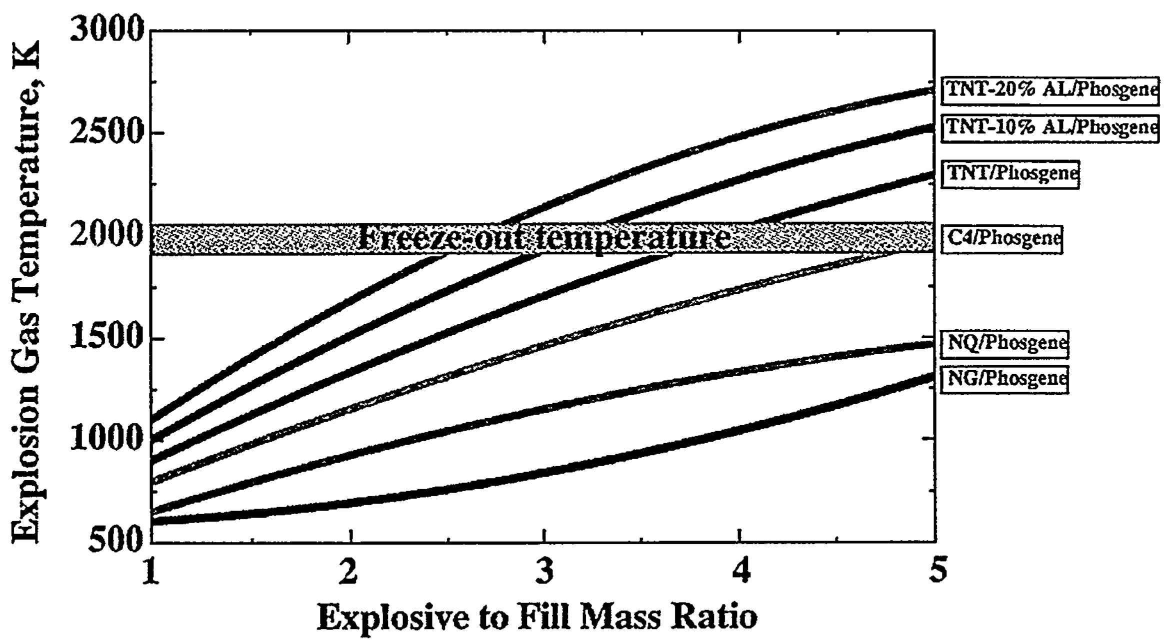


Figure 1. Destruction effectiveness of various explosives on phosgene.

Experimental studies at Lawrence Livermore National Laboratory (LLNL) with confined and unconfined explosives have demonstrated that additional energy release occurs along the expansion isentrope and that fireball products are distinctly different than those corresponding to the detonation state.[5] Equilibrium analysis shows that detonation of the explosive and agent materials yields a high degree of reactive gases like H_2, CO and CH_4 - which will readily react when mixed with air. This secondary combustion is fast and complete if the gas temperatures are sufficiently high (above 1800 Kelvin). These results suggest that the 5:1 ratio of explosive mass to chemical agent mass is consistent with detonation calorimetry and establishes a formal basis for the destruction method.

The Need for Alternative Destruction Methods

The 5:1 overcharge may be effective but is not an optimum solution. For the Levins projectile, adopting the 5:1 charge ratio, 140 pounds of C4 are required for an effective explosive destruction. Depending upon the scenario, the collateral damage to assets in the area due to the blast effects of a 140 pound charge may be prohibitive. The principal appeal of the 5:1 overcharge is that it doesn't involve new technology. EOD units around the country can take this approach using only existing skills. The principal failing of this concept is that if the device location is populated with people or immovable assets the resulting destruction may not be acceptable.

Local terrain, weather conditions, and the distribution and durability of collateral all affect the extent of damage that will be realized from the detonation of large quantities of HE (High Explosive). Atmospheric effects such as focusing of blast waves due to a thermal inversion can magnify blast effects. These effects can increase distances predicted for specific blast overpressures from either mitigated or unmitigated blasts. The International Association of Bomb Technicians Institute (IABTI) safe standoff distance associated with 140 pounds of explosive is 1560 feet. The 5:1 explosive overcharge destruction method may destroy the chemical agent but blast effects and evacuation areas are large. Alternatives that reduce damaging blast effects and potential for down wind dispersal of chemical agent are needed. In the next section we report on the possibility of reducing the explosive overcharge required to destroy the agent in recovered CWM.

Investigation 2

Methods for Reducing the Explosive in the Overcharge

Given the hypothesis that the 5:1 explosive overcharge using C4 effectively destroys the chemical agent fill, we asked the question, "is it possible to reduce the overcharge using a different explosive that is tailored to the chemical agents under investigation?" To investigate this option, alternative explosives were used in subsequent calculations and compared to the baseline C4 explosive fireball temperature.

Since C4 is an underoxidized explosive, the first candidate energetic materials considered are oxygen balanced or oxygen rich. Figure 1 displays calculations for the two explosives nitroguanidine (NQ) and nitroglycerin (NG). Interestingly, lower fireball gas temperatures are predicted. This is because excess oxygen is entrained in the fireball which dilutes the secondary combustion.

For destroying agent the most effective explosive would provide fuel, rather than oxygen, for the secondary combustion in the expansion process. Next we examined underoxidized explosives like TNT. As expected, higher fireball temperatures were predicted, reducing the required overcharge mass yielding performance comparable to C4. To greatly reduce the quantity of explosive, one must consider materials that will have high combustion temperatures. High temperatures can be realized in explosives that are mixed with metal powders like aluminum or magnesium; these are commonly used as underwater explosives. Figure 1 shows a comparison of two blends of TNT/A1 mixes. As the fraction of A1 is increased, higher fireball temperatures are predicted and the required mass of explosive to fill agent can be reduced. For the 20% Al-TNT mixture (known as Tritonal) roughly 2.5:1 ratio of explosive to agent mass yields similar fireball temperatures as the 5:1 ratio for the baseline C4. At higher fractions of Al, other studies have shown that a large fraction of the additive remains unreacted and a performance improvement limit of the material is expected.[6] For the explosives evaluated in this study, Tritonal is the best explosive for destroying phosgene.

This analysis suggests that explosives can be tailored to significantly reduce the required quantity of explosive mass for the destruction of chemical munitions. The caveat is that we made assumptions in performing these calculations, such as evenly distributed explosive in the overcharge and complete mixing in the fireball. Consequently, although the results are promising, other agent fills must be modeled and scale tests with explosives and surrogate agent must be performed before a reliable recommendation can be made.

Investigation 3

The Use of Barriers Around an Overcharge

Whether the explosive overcharge ratio is 5:1 or 2.5:1 a simple barrier will reduce undesirable blast and fragment effects. The barrier under investigation in this section is a right circular cylinder. The purpose of the cylinder is to mitigate the blast and fragments from the explosive overcharge without interfering with the chemical reactions in the fireball. The investigation consists of sizing the cylinder and determining the effectiveness of mitigating the overpressure generated by the explosion.

Cylinder Dimensions

The cylinder should mitigate blast and fragments but not interfere with the destruction of agent. If the cylinder diameter is smaller than the fireball it requires thicker walls due to the high pressures in the fireball, and may interfere with the agent destruction. Therefore, the diameter of the barrier should be the same as, or greater than the diameter of the fireball. From classical scaling data (Kinney & Graham [7]) the fireball radius for a TNT charge detonated at sea-level and room temperature is $R_{fb}=1.5W^{1/3}$ - where R_{fb} is the fireball radius in feet and W is the weight of the charge in pounds. This leads directly to the volume of the fireball (assuming it's a sphere) to be $(4/3)\pi r^3$; $(4/3)\pi(1.5W^{1/3})^3$; or $V_{fb}=14W$ where V_{fb} is in cubic feet and W is in pounds. If we provide for confinement - a right circular cylinder whose diameter equals its' height and we size that cylinder such that its' volume equals that of the fireball, then the volume of the cylinder is $(\pi/4)D^3$ and this equals 14W. This analysis leads to a cylinder diameter (and height) $D(\text{or } H)=2.6W^{1/3}$, where D and H are in feet.

Wall Thickness of the Cylinder

From Kinney and Graham's scaling data, the peak overpressure at the edge of a TNT fireball at sea-level is about 150 psi. If the charge were lying on the floor inside the cylinder, then the pressure at the nearest point of the wall would be larger than if the charge were suspended in the center of the cylinder. This, and the fact that the cylinder diameter may be somewhat less than the free fireball diameter, leads us to assume that the maximum pressure approaching the inside wall is around 300 psi. The hoop-stress in a thin walled cylinder is $S=Pr/t$, where S is the hoop stress, P is the internal pressure, r is the radius and t is the wall thickness. Assuming the maximum allowable stress in the wall is around 30,000 psi (carbon steel), then the wall thickness must be greater than r/100. High strength steels can be used resulting in thinner walls and reduced weight.

The above analysis was used to calculate the minimum size of an open-ended confining cylinder assuming the destruct charge HE weight is around five times the weight of the chemical filler. The results of those calculations are shown in the following table:

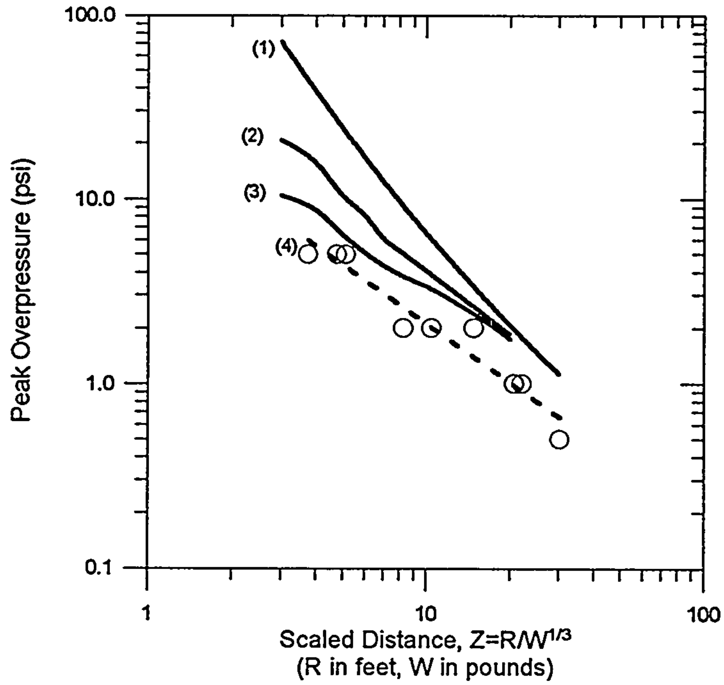
ITEM	Fill Weight (pounds)	5:1 HE Weight (pounds)	Cylinder Diameter (feet)	Min. Wall Thickness (inches)	Min. Weight (pounds)
French Hand Grenade	0.7	3.5	4	0.25	170
75 mm Artillery Shell, Mk II	2	10	5.5	0.33	415
5 inch Artillery Shell, Mk VI	7	35	7	0.42	850
4.2 inch Mortar	7.5	37	8	0.48	1275
4 inch Stokes Mortar	9	45	9	0.54	1815
6 inch Artillery Shell, Mk III	13	65	10.5	0.63	2880
155 mm Artillery Shell, Mk II, IIA, VII	15	75	11	0.66	3315
8 inch Artillery Shell, Mk III, and Livens - Mk II	30	150	14	0.85	6915

Table 1. Cylindrical barrier sizing for various munitions.

Pressure Fields from Firing in a Cylinder

We plotted several sets of data to determine barrier effectiveness in terms of overpressure. The goal of using the barrier is to reduce the damaging blast effects from using an explosive overcharge. In this section we use several plots of pressure as a function of distance to illustrate the effectiveness of a barrier (a right circular steel cylinder).

The plots shown in Figure 2 illustrate data on pressure measurements taken from several sources. The peak overpressure as a function of the horizontal distance from the center of a 5:1 charge was calculated using the scaling curves in Figure 2 for both the free field and the open ended cylinder. The cylinder case used the curve for a charge fired behind a barrier where $H/W^{1/3}=2$; which is quite conservative. In each case shown in Figure 3 the cylinder is the minimum size for the particular chemical weapon designated. The data plotted in Figure 3 can be compared to the free field pressure to evaluate the effectiveness of the cylindrical barriers. Two examples of this are shown in Figures 4 and 5. (Note: In Figures 4 and 5 the pressure curves appear to converge. This is an artifact of the extrapolation method used in these calculations - actually the pressures will converge but at a distance further from the charge than indicated).



(1) Free air blast. Calculated from scaling tables for Explosive Blasts in Air.[7]
(2) Air blast on the other side of a barrier wall where $H/W^{1/3}=1$, and H is the height of the wall in feet and W is the weight of explosive in pounds. From the DOE Manual on Blast Effects on Structures.[8]
(3) Air blast on the other side of a barrier wall where $H/W^{1/3}=2$.
(4) Air blast data from FBI Technical Bulletin 44-72 for small cylinders.[9]

Figure 2. Overpressure from explosives with and without barriers.

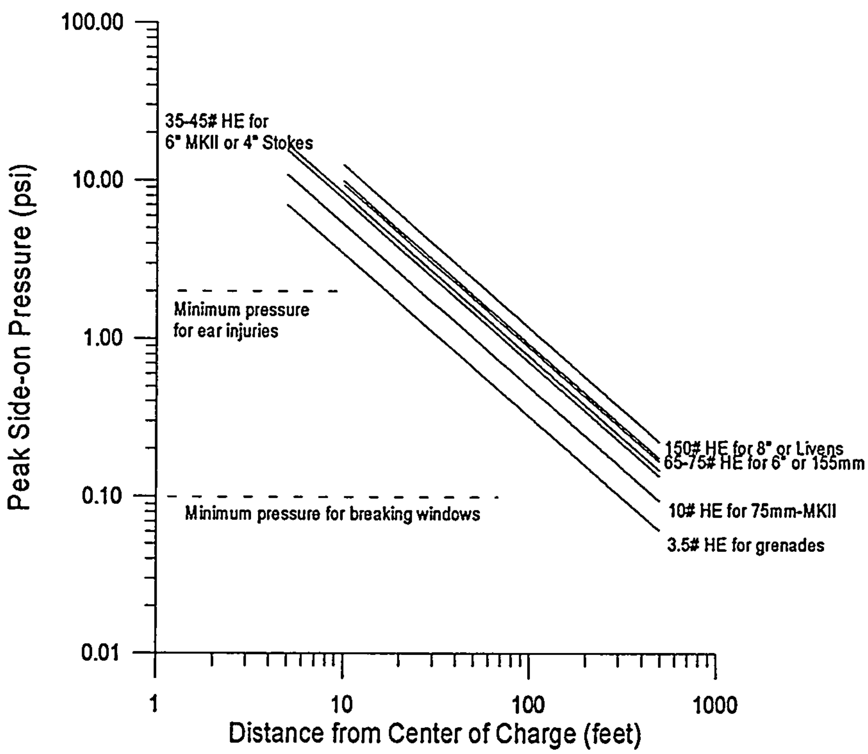


Figure 3. Peak overpressure as a function of distance from the center of a 5:1 charge fired in the minimum size cylinder for each weapon indicated.

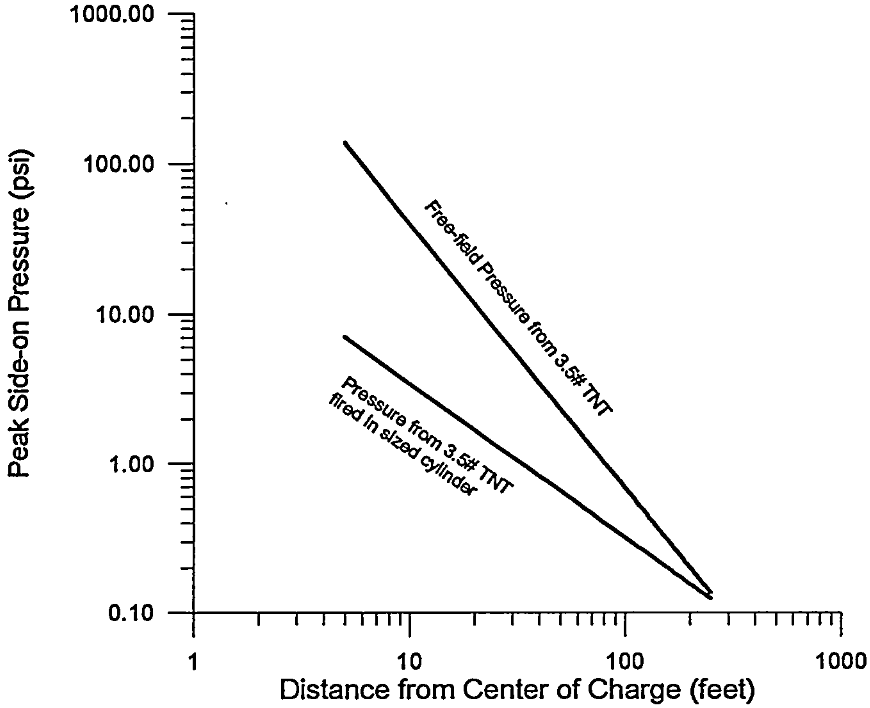


Figure 4. Comparison of peak overpressure from a 5:1 charge destroying a chemical hand grenade with and without a minimum sized confining cylinder.

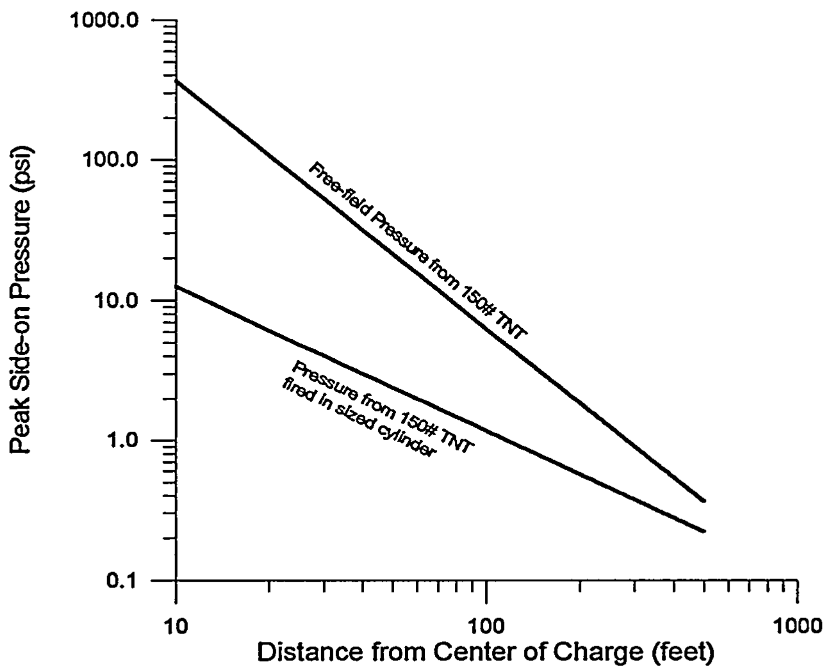


Figure 5. Comparison of peak overpressure from a 5:1 charge destroying an 8 inch chemical shell or a Mk-II Levins with and without a minimum sized confining cylinder.

As shown in Figures 4 and 5, a barrier around the munition and explosive overcharge will reduce undesirable blast effects. For example, from Figure 5, a 150 pound charge detonated without a barrier produces a side on pressure of close to 10 psi at a distance of approximately 80 feet. The same explosive charge with a barrier produces a side on pressure of approximately 1 psi at the same distance from the charge. The conclusion from our investigation on barriers is they are effective for mitigating damaging blast effects. Careful sizing of the cylinder will eliminate interference with the chemistry in the fireball, without negating the blast mitigation.

Investigation 4

Commercially Available Containment Systems

The purpose of this investigation is to evaluate the use of commercially available explosive containment devices for destroying recovered CWM. In this section we evaluate commercial systems for containing the explosion from the 5:1 overcharge; we consider destroying the burster in munitions using a shaped charge in the absence of an overcharge and fragment mitigation from burster detonation.

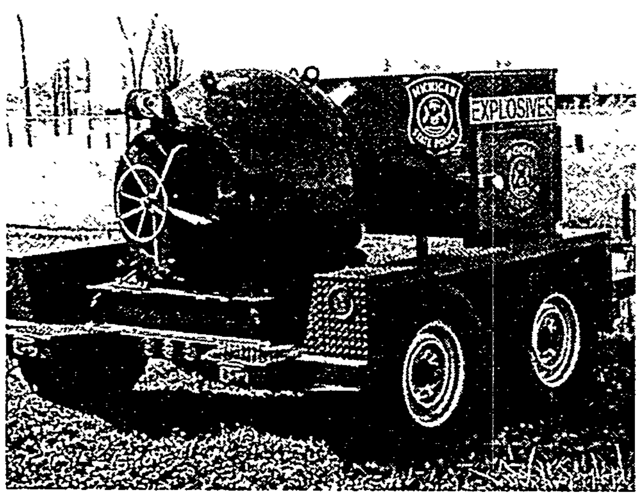


Figure 6. The Nabco bomb containment vessel.

There are commercial blast mitigation devices available which are potentially applicable to the destruction of recovered CWM. Nabco Incorporated is a manufacturer of containment vessels. Their standard total containment vessel is shown in Figure 6. This system is transportable and qualified to contain 10 pounds of C4. Nabco also has a new vessel designed to withstand 26 pounds of C4. Shielding Technologies, Inc. and Weatherly - Dynasafe also manufacture comparable systems. The challenge involved with utilizing these systems lies in assured destruction of the explosive and the subsequent detoxification of the containment vessel.

The munitions can't be destroyed in the commercially available vessels using the 5:1 overcharge. With the exception of hand grenades, the internal dimensions of these containment devices will not allow a sufficient fireball to form for the complete destruction of agent using a 5:1 explosive overcharge. There are alternative scenarios worthy of investigation for utilizing commercial containment vessels.

It is possible to remove the explosive hazard from the munitions without the use of an overcharge. The problem is, chemical agent will remain. If one were willing to assume the risks of cleaning the dispersed agent after eliminating the explosive hazard, a smaller charge, in the form of a shaped charge, could be used to open the munition and remove the explosive hazard. The primary purpose of the shaped charge is to destroy the explosive components in the device, with the inevitable consequence of releasing agent. The reduced explosive energy of a shaped charge, compared to the 5:1 overcharge, will ease the design requirements on the mitigation hardware. Since destruction of agent in a fireball is not the goal in this case, the internal volume of the commercial vessel is no longer a limiting factor. The idea of detonating or destroying the burster in a recovered munition brings up several questions.

1. Can a shaped charge detonate or destroy the burster?
2. How large of a shaped charge is required to destroy the burster?
3. If a burster is detonated, what are the size and velocity of the fragments from the casing?

These questions are examined in the next sections.

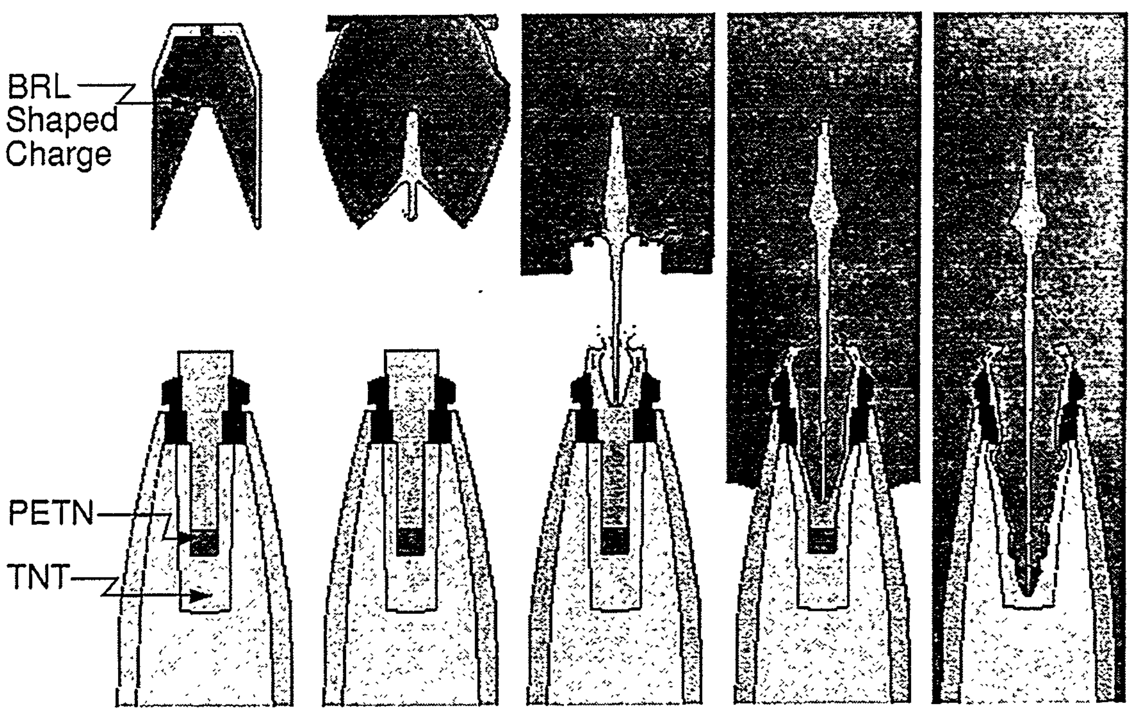


Figure 7. Illustration of a shaped charge jet attack on a 155 mm artillery shell.

Burster Initiation Using a Shaped charge

We investigated the applicability of using a shaped charge for initiating the burster in an artillery shell. This is the first cut at estimating the size of a shaped charge required to initiate detonation in the burster charge of various chemical filled artillery shells. For the purpose of this exercise, it is assumed that the shaped charge must fire axially through the nose of the shell, penetrate the fuse and then enter the burster charge (shown graphically in Figure 7). The important parameters in this case are listed below.

1. Length and average density through the fuse.
2. Critical V^2D for the jet at the entrance to the burster charge(see below).
3. Diameter of the jet at that interface.
4. Velocity of the jet at that interface.

Size and Average Density of the Fuses

The only design information available about the five artillery rounds of interest were the sketches in the manual on old US and foreign chemical weapons.[10] The sketches do not show the fuses so we estimated the fuse length by extrapolating the ojive of the shell to a point and assuming the base of the fuse was at the forward end of the booster well. This method gave the following fuse lengths (the fuse density was assumed to be that of solid steel):

SHELL	FUSE LENGTH (inches)
75 mm	2.6
5 inch	3.6
6 inch	4.1
155 mm	4.1
8 inch	5.1

Critical V^2D

One criteria for initiating detonation in a target explosive by impact of a shaped charge jet is the product of the diameter of the jet times the square of its velocity. This is based on work first reported by Manfred Held in Germany and then expanded at several other laboratories. This theory states that in order to achieve detonation, the jet entering the target HE must exceed a critical V^2D, and the value of this critical parameter is different for different explosives. When the jet must first penetrate a barrier or cover over the HE, the required V^2D is higher than that for bare HE. Little data is available on the quantitative effect of the barrier or on bare HE V^2D values. The values we were able to find are about 4 $(in)(mm^2)/(ms^2)$ for cast TNT and about 1.7 for Tetryl (Tetryl was most likely the booster explosive in these fuse trains). Because we don't know how much higher the V^2D must be to give robust initiation, we calculated the jet requirements at several values of V^2D ranging from 5 to 20.

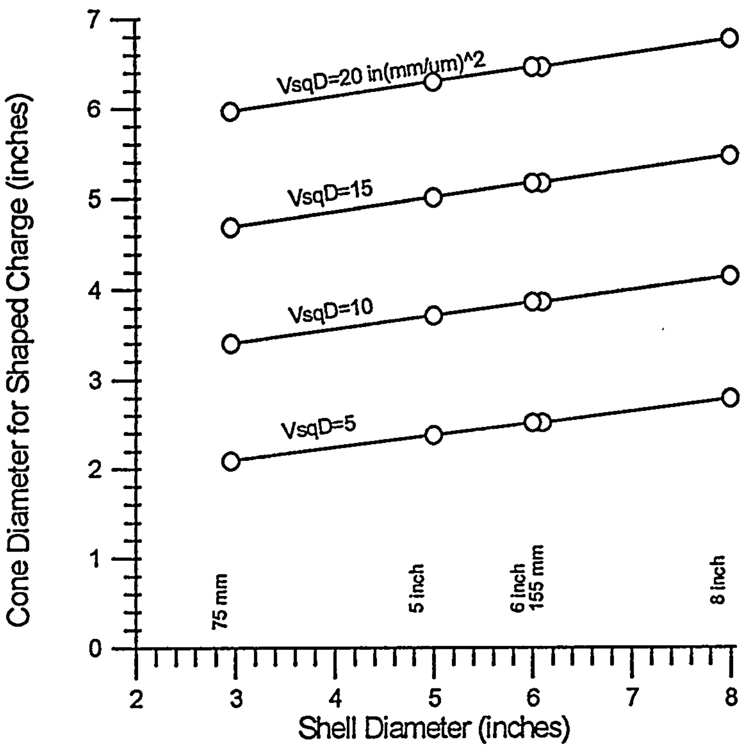


Figure 8. Cone diameter sizing for shaped charge detonation of bursters.

When a jet penetrates a target material the jet is eroded or consumed. The amount of the jet consumed depends upon the target thickness penetrated and upon both the jet and target densities. Consequently, after penetrating the fuse a certain length of the jet is lost (from the front end). The jet has a velocity gradient along its length because it is faster at the front; therefore the portion of the jet which exits the base of the fuse and enters the burster HE is considerably slower than the original tip of the jet.

The diameter of the jet is smaller at the tip and increases toward the rear. So, as more jet length is lost in penetrating a target, the remaining front end is slowing and the diameter is growing. For the purpose of this analysis the jet was considered to have a constant diameter.

Scaled Properties of Shaped Charges

In order to estimate the size of a shaped charge which will provide the required V^2D, we correlated a limited data base of various experimentally derived shaped charge parameters. These correlations were:

Jet length as a function of base cone diameter:

L_j=4.5D_c (L_j is jet length and D_c is base cone diameter).

Jet diameter as a function of base cone diameter:

D_j=0.07D_c (D_j is jet diameter).

Jet velocity gradient:

V_x=1.5+6x/L_j (V_x is jet velocity in mm/µs, x the remaining length of the jet in inches and Lj is the original jet length in inches).

Shaped charge HE weight as a function of base cone diameter:

W=0.35$D_c^{3.3}$ (W is charge HE weight in pounds and D_c is in inches).

Shaped Charge Size Estimates

Using the above correlations, parametric calculations were performed which yielded the shaped charge base cone diameter (and hence the charge weight) for initiating detonation in the five artillery shells of interest. The shaped charge size was parameterized for a range of critical values of V^2D. The diameter and explosive mass for the range of shaped charges investigated are plotted in Figures 8 and 9 respectively. Until we obtain better data on all of the parameters mentioned above, we will assume that we've bracketed the real values.

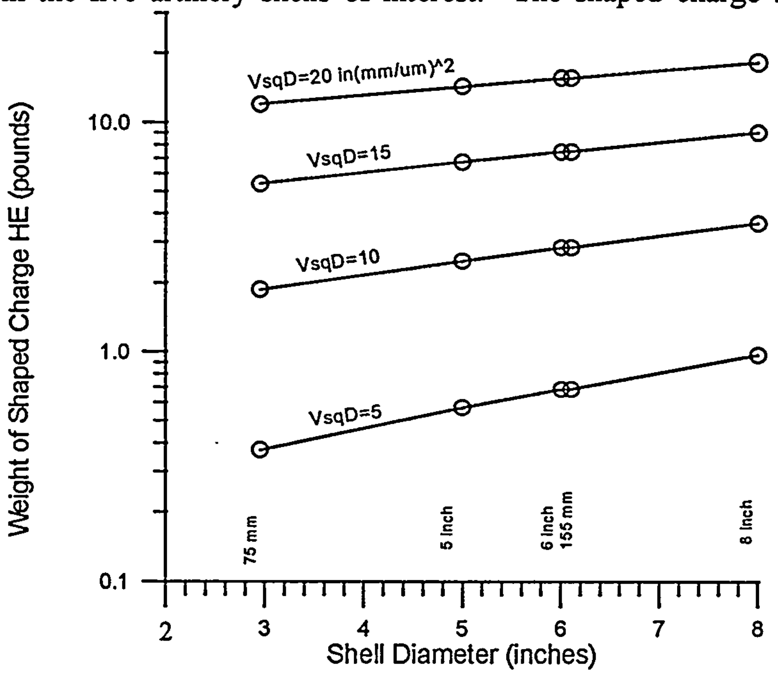


Figure 9. Explosive mass required for shaped charge detonation of bursters.

The result of this first cut analysis is that the shaped charge required to detonate the burster in these munitions is between two and seven inches in diameter and will require as much as ten pounds of explosive.

To utilize a shaped charge for removing the explosive hazard of a recovered munition the containment device needs to contain the explosive from the shaped charge and burster and contain the fragments from the shell. In the next section we investigated the fragments generated by detonating the burster in an artillery shell.

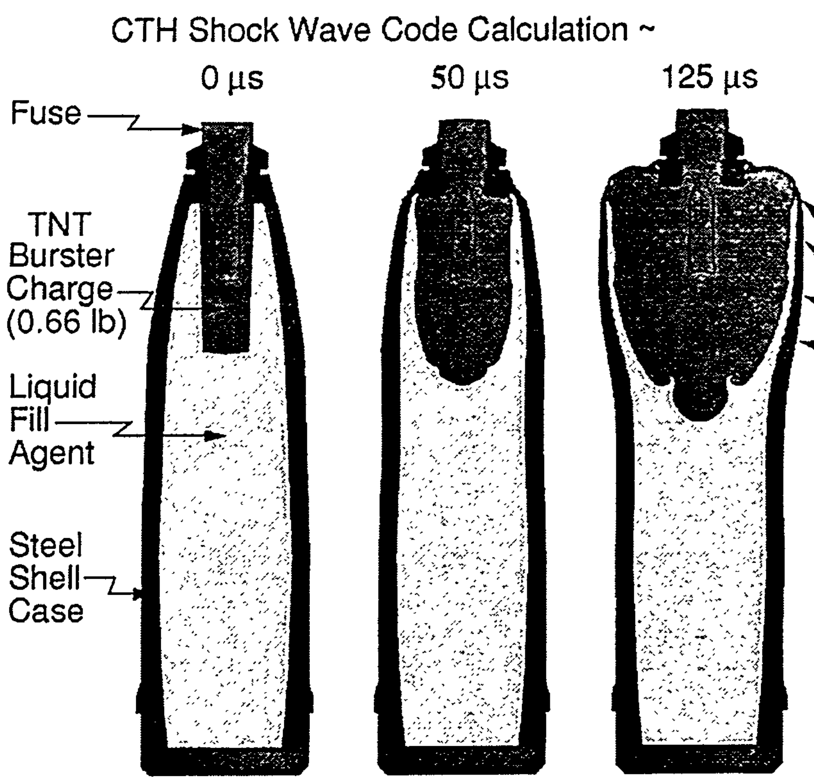
Fragment Size and Velocity from an Artillery Shell

The next step in the investigation was to model the detonation of a burster in an artillery shell to determine the fragment size and velocities and ultimately fragment mitigation requirements. We used a 155 mm artillery shell for a first cut at fragment modeling since it represents the greatest fragment hazard. The following assumptions were made to perform the calculations.

- Details of the geometry were scaled from drawings in the <u>Old Chemical Weapons: Munitions Specification Report.</u>[10]

- The explosive burster charge (.66lb) of TNT is point initiated at the base of the "fuse" and detonates from that point.
- A solid aluminum fuse was assumed, to fill the void.
- The internal volume was assumed to have a 100% liquid fill.
- A barrier wall thickness of .6 inches (typical for the cylindrical barriers described in investigation 3; commercial containment vessels have thicker walls.)

The local stretching strain rates at time of fracture are determined from a shock wave physics code calculation, CTH in this case (McGlaun, et al., 1989[11]), that models the expansion of the case resulting from the detonation of the burster charge. The fragment velocities are also determined from this same calculation. For example, as illustrated in Figure 10 the 155mm Howitzer shell with a 0.66 pound burster charge accelerates the steel shell casing (and potential fragments) to about 330 m/s in the axial vicinity of the charge. Based upon fragmentation theories developed over the past few years[12], and using generic material properties for steel, an average fragment geometry is obtained. The lower rates of stretching induced along the axis of the shell relative to the circumferential stretching rates, result in the formation of elongated fragments and can lead to the formation of "pedals" as the projectile is burst open. These analyses predict that the burster will cause the shell to fragment in strips approximately 10 mm wide and anywhere from 15 to 45 mm long. The velocity of the fragments range from 115 to 330 m/s.



Fragment Size ~

Average steel fragment dimension is estimated from the local strain rate.

V_R (m/s)	$\dot{\varepsilon}$ (1/s)	S (mm)
330	7930	8
320	6400	9
330	5530	10
115	1660	22

V_R is case velocity, $\dot{\varepsilon}$ is circumferential strain rate, S is average fragment size, determined from

$$S = \left(\frac{\sqrt{24}\,K_c}{\rho c \dot{\varepsilon}} \right)^{2/3},$$

where ρ is density, C is sound speed, and K_c is fracture toughness.

Figure 10. Example of a burster charge detonation in a 155mm Howitzer shell.

Requirements for containment of these fragments by steel barriers is determined based on available perforation data (limit velocity data), for the impact of steel projectiles on steel targets. If the fragment is treated as a compact projectile with 10 mm characteristic dimension, then the velocity required to perforate 0.6 inches (15mm) of steel ranges from 1200 m/s for mild steel spherical projectiles onto mild steel targets[13] to 2000 m/s for hard steel cylindrical projectiles onto hard steel targets[14]. If the fragments rotate during transit from source to the target, and behave as rod penetrators, then the limit velocity is lowered for the same target plate. Data of Lambert[15] suggest that for a fragment with length to diameter ratio of 5, the limit velocity would be about 700 m/s to perforate a steel target of 15 mm. If the fragment could form into a length-to-diameter ratio of 10, then the limit velocity begins to approach 400 m/s.[16] All these data assume machined projectiles with controlled impact conditions rather than jagged fragments with random impact angles and orientations. In all these configurations the 0.6 inch steel appears to provide adequate protection to contain fragments from this source.

This investigation reveals that the commercial systems evaluated are not suitable for use with a 5:1 overcharge. The vessels are all over 1 inch thick and should contain the blast and fragments from a 155mm shell, but some agent would be vented. Assured decontamination of the remaining device will be a challenge. There would be bulk agent as well as trace contamination in vents, to be dealt with. Fragment mitigation would also need to be confirmed. An alternative to attempting to contain the blast in a vessel is to mitigate the blast with aqueous foam; a method which is described below.

Investigation 5

The Use of Aqueous Foam for Blast and Agent Dispersal Mitigation

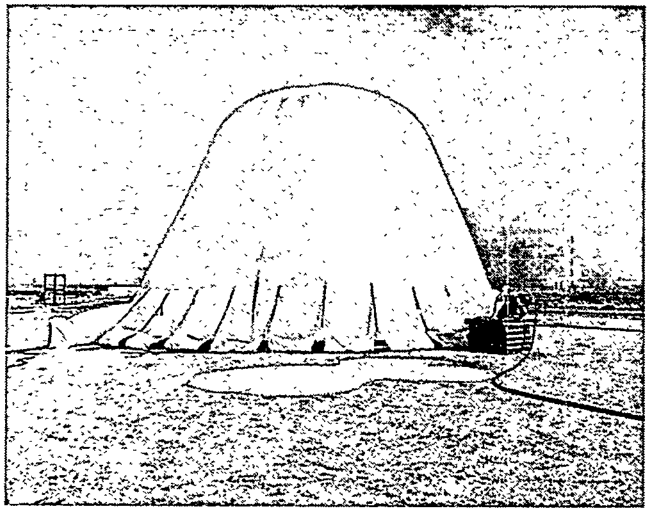
In this investigation we examine the use of aqueous foam for blast mitigation. The foam can be used with the shaped charge burster detonation method or to mitigate the blast from an explosive overcharge. In this section we describe previous use of aqueous foam, it's application with an explosive overcharge and with a shaped charge.

The adverse effects of the explosive overcharge method can be profoundly reduced with the use of aqueous foam mitigation. The efficacy of aqueous foam in suppressing blast damage has been demonstrated numerous times. Results of testing performed in support of the Nuclear Emergency Search Team (NEST) and various experimental demonstrations show we can quantify the mitigation of blast strength associated with the use of aqueous foam mitigation. Effective foam concentrates, field-erectable foam-containing structures, and field-deployable foam generation equipment have been developed and extensively exercised in the NEST program. Figure 11 shows a photograph of the NEST 50-foot cone. This foam containment system could be employed to mitigate the blast effects associated with a 140 pound destruct charge. Table 2 includes estimates of the equipment size and personnel requirements to deploy this system.

As indicated in Table 2, a crew of 8 is appropriate for this assembly and if they are experienced, the entire cone deployment can be accomplished in approximately one hour.

System Parameter	5:1 Explosive Overcharge	Explosive Overcharge With Foam	Shaped charge With Foam
Total explosive wt. (lbs)	140	140	3
Agent wt. (lbs)	28	28	28
Containment volume (ft^3)	not applicable	28,000	300
Containment base area (ft^2)		3,000	105
Foam Expansion ratio		150:1	100:1
Water for base (gal.)		3,600	0
Water for foam (gal.)		1,500	21
Total water (gal.)		5,100	21
Concentrate required (gal.)		100	1
Installation time (min.) (experienced crew)		60	5
Crew required (people)		8	2
Stowed kit volume (ft^3)		200	8
Stowed kit wt. (lbs)		1,600	100
Capture effectiveness		99.8%	99.5%
Post-shot cleanup area (ft^2)		7,000	250
IABTI safe distance (ft)	1560	1560	900
Distance to 1 psi overpressure (ft)	250	50	13.2
Distance to 5 psi overpressure (ft)	76	24 (in foam)	6.3

Table 2. Worst case destruction logistics for an explosive overcharge and foam mitigation



In April of 1989 the system pictured in Figure 11 was used in Florida at the defunct Sooner Defense Inc. plant. A blast from over 50 pounds of explosive in a small shed was successfully mitigated using the foam filled cone. The cone was deployed by EOD personnel (who were familiar with the cone because of their NEST affiliation) in about 1.5 hours, with oversight from Sandia personnel. The mitigation system worked well and there was no damage to nearby structures.

Figure 11. A foam filled blast mitigation cone.

Foam Mitigation with a 5:1 Overcharge

Foam placed over a munition will mitigate the fireball as well as the blast. The water in the foam will cool the fireball and limit destruction of the agent. If the explosive overcharge method is to be used with foam a standoff for the fireball is required. One option is to use a steel cylindrical barrier along with the foam. The cylinder would establish a volume for the fireball and the foam would mitigate the blast effects. Field verification testing of the effectiveness and scaling of this solution is required. This option could supply the benefits of both destroying the chemical agent in place and acting to capture the products of the reaction. Remediation of foam mixed with chemical agent would be required.

We know from the NEST program results that the aftermath of a 140 pound charge detonating in the 50 foot cone is a very untidy mess. The volume of the foam will be greatly reduced and the resulting water-surfactant-agent mixture will cover an area of perhaps four times the original base area of the cone. The degree to which this poses a problem will be heavily dependent upon the particular scenario. The most favorable circumstance would be a situation in which the resulting slurry is retained in a local depression. The least desirable circumstance would be for existing features, such as a city storm sewer, positioned to receive liquid from the working point.

In NEST experience, these messes have been allowed to sit until the water evaporates and minimal residue remains. It is possible that the aftermath could be allowed to dry either naturally or with the assistance of heating systems leaving only dry material to be finally discarded as potentially toxic waste. The extent of this form of waste will depend upon how effectively the agent is destroyed, which must be established in the foam environment. If we expect substantial volume of toxic material to remain, this option is probably unacceptable. Experience in NEST has demonstrated that foam cleanup operations are generally unpredictable and problematic.

Foam Mitigation with Shaped Charge Initiation

Another option is to use the foam with a shaped charge. This option would greatly reduce blast damage to nearby structures. The distance to which a 1 psi overpressure (an approximate condition for breaking common windows) is experienced would be reduced by a factor of 5 which corresponds to decreasing the associated area by a factor of 25.

The principal advantage of this option is the small amount of explosive that would be utilized and the correspondingly small blast effects. The principal disadvantages of this method are that a mess remains to be cleaned up at the working point and that the destruct charge must be aimed and applied in a device-dependent fashion. Confidence that the explosive potential of the device will be destroyed must be established.

As summarized in Table 2, the shaped charge with foam mitigation is more convenient to deploy than that of foam mitigation with a 5:1 overcharge, and the resulting cleanup area is smaller. It is clear that captured agent will be concentrated around the working point. If the remaining foam can be allowed to evaporate prior to final disposal, the cleanup problem may be reduced. If it is deemed important to clean up the resulting mess promptly some sort of wet vacuum system might be employed. At best, there will remain an unpleasant cleanup for the foam-mitigated options even if they are thoroughly successful at blast mitigation and confining the agent to the immediate vicinity of the working point.

Conclusions and Recommendations

This report provides a general description of the investigation of five options, and combinations of those options for emergency destruction of chemical munitions using explosives. Equipment, expertise, and experience supporting all of these options exists and any one of them could be attempted. The common thread to any option other than the 5:1 explosive overcharge is that field testing for verification of the predicted results is required.

The best near term improvement to the 5:1 overcharge method is the addition of a steel cylindrical barrier for blast mitigation. Field tests using a properly designed steel barrier can be performed on recovered munitions in remote locations, to verify its effectiveness. Beyond the steel barrier no one option can reasonably be promoted as the best remedy for all potential situations. It seems clear that this will remain true even with further development and understanding of the interim solution options. In Table 3 we illustrate the strengths of each option depending on the destruction priority. For example, if the primary goal is to destroy chemical agent an explosive overcharge is the best approach. If the goal is total containment of blast and minimal down wind dispersal of agent a commercial vessel with shaped charge initiation is the best method.

The problem with shaped charge initiation, reduced overcharge using tailored explosives, and foam mitigation is that they need some development. They meet the criteria of available technologies but their application to this problem requires further testing.

Performance consideration	*Most Effective Destruction Method*	*Alternative Destruction Method*	*Alternative Destruction Method*
Agent destruction	5:1 Overcharge	Reduced Overcharge	Overcharge With Foam
Blast damage	Vessel or Foam	Reduced Overcharge With Barrier	5:1 Overcharge With Barrier
Fragments	Vessel	Foam with Barrier	Overcharge With Barrier
Agent containment (minimized potential for down-wind dispersal)	Vessel	Foam	Reduced Overcharge
Sure kill of explosive in device	5:1 Overcharge	Reduced Overcharge	Overcharge With Foam
Post Shot Cleanup	Reduced Overcharge	5:1 Overcharge	Foam or Vessel
Ease of deployment	Overcharge Without Barrier	Overcharge With Barrier	Foam or Vessel

Table 3. Preferred method to achieve selected objectives.

Table 3 illustrates that the best destruction system is priority dependent. A containment vessel may be preferable in situations where an explosive overcharge is unacceptable. Aqueous foam or a containment vessel might also be preferred over an overcharge where minimizing the threat of down-wind dispersal is deemed overwhelmingly more significant than that of contamination at the working point. The strengths and weakness of each option are summarized in the tables below.

Recovered Munition Destruction Using a 5:1 Explosive Overcharge

Strength	*Weakness*
No New Technology	Blast and fragment damage may be prohibitive
No Significant working point cleanup required after shot	Adverse publicity associated with a very big event
	Evacuations required over a large area

Recovered Munition Destruction Using a Tailored Explosive Overcharge

Strength	*Weakness*
Reduced blast and fragment effects	Needs proof of concept testing
Reduced by-product plume and evacuation area	Evacuations required over a large area

Recovered Munition Destruction Using an Explosive Overcharge in a Cylindrical Barrier

Strength	*Weakness*
Reduced blast and fragment effects	Needs proof of concept testing
	Evacuations required over a large area

Recovered Munition Destruction Inside a Commercial Containment Vessel

Strength	*Weakness*
Minimal blast and fragment effects	Needs proof of concept testing for blast and fragment mitigation
No plume	Assured destruction of explosive hazards is questionable
Containment vessels are available	Burster charge initiation needs development
Minimized evacuation area	Vessel detoxification after the event will be difficult

Recovered Munition Destruction Using an Explosive Overcharge in a Cylindrical Barrier With Foam Mitigation

Strength	*Weakness*
Reduced blast and fragment effects	Needs proof of concept testing
Reduced by-product plume and evacuation area	Evacuations required over a large area
Foam dispersion technology is available	Maximum hazardous cleanup effort at working point

Recovered Munition Destruction Using a shaped charge and Foam Mitigation

Strength	*Weakness*
Greatly reduced blast and fragment effects	Needs proof of concept testing
Greatly reduced by-product plume and evacuation area	Evacuations required
	Shaped charge initiation needs development
	Hazardous cleanup effort at working point

It is clear that no optimum system for destroying recovered chemical munitions is available today. There are a variety of options available; each with specific trade-offs. Our modeling and calculations predict the 5:1 explosive overcharge destroys most of the agent and it is our recommendation to continue using this method unless some proof of concept tests are performed. The simplest tests to perform are on the application of cylindrical barriers surrounding the explosive overcharge and munition. The reduction of overcharge using a tailored explosive is promising, but further modeling of agent reactions in the fireball and verification tests in the field with surrogate agents, are required. The foam mitigation over an explosive overcharge requires slightly more investigation due to the chemical interactions between the foam and agents. We need to evaluate the environmental impact of using foam mitigation with chemical agents. Investigations on burster initiation with shaped charges and containment vessel qualification require extensive testing. The shaped charge initiation requires development of a statistical database of shaped charge effectiveness on various fuse/burster configurations.

It is our recommendation to stay with the 5:1 explosive overcharge. Additionally, we recommend evaluating the effectiveness of a steel cylindrical barrier in non-critical tests; i.e., tests in remote areas on recovered munitions or using agent surrogates. We stand ready to consult, conduct analysis and/or testing of the interim solution options at the customers' request.

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