IDA

Effectiveness of Small Warheads

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PREFACE

This document was prepared under a task titled "Track 2 Anti-Personnel Landmine Alternatives" for the Defense Advanced Research Projects Agency/Advanced Technology Office.

CONTENTS

Effectiveness of Small Warheads

Application of Energetic Warhead Materials Explored for the Self-healing Minefield to Other Munitions

Introduction

This study was commissioned by the DARPA Self-Healing Minefield (SHM) program. The goal of the SHM program was to increase minefield effectiveness by adding communication and mobility functions to individual mines. This would enable a deployed field to self-organize as a network and detect breaching. Once detected, breaches would be sealed by mines "hopping" into the breach using their mobility capacity.

To produce such mines in the current mine form factor, a smaller warhead was needed to make space for the communications and mobility subsystems. The warhead under consideration used a pyrophoric material, Zr, in the liner. The specific task of this study was to determine whether using pyrophorics or energetic materials such as Al-Teflon would enhance lethality against lightly armored or thin-skinned vehicles. Given the very limited data, assessments were made based on the underlying science of the various lethality mechanisms.

Status

The results presented here were briefed internally at IDA, to the DARPA Program Manager and to warhead experts at Picatinny Arsenal in anticipation of an Army program based on the DARPA work. The self-healing minefield program, however, did not transition to the Army as a funded program. The results of our lethality study are documented here to provide a starting point for future investigations. Atlhough the context of the presented work is the self-healing minefield, the lethality discussions (pp. I-22–I-50) should be relevant to any attempt to use this approach to penetrate lightly armored or thin-skinned vehicles.

Summary of Results

We found two mechanisms where warhead lethality would be increased by the use of pyrophoric or energetic (e.g., Al-Teflon) warheads:

1. Increased probability of detonation of explosives or deflagration of propellant materials.

2. Increased crew casualties as a result of burns.

We expect only slightly improved ignition of fuel to result from the use of pyrophorics. We encountered anecdotal reports of Zr warheads shorting out electronics. The mechanism is not understood. This is an area that warrants further study.

The arguments supporting these results and the underlying science are summarized on the next chart. This is followed by the detailed briefing that applies the argument to the self-healing minefield.

Basis of Results

- Chemical energy delivered to target is large compared with jet kinetic energy.
    - (See p. I-26).

- Resulting Temperatures are high.
    - (See p. I-28).
    - Second-degree burns on crew likely (p. I-36 ff).
        - Overpressure injuries also are likely in confined compartments, but not analyzed here.
    - Initiation of energetics likely (p. I-38 ff).

Effectiveness of Small Warheads

Reducing Warhead Size to Enable Smart Mines with Lethality against a Broader Target Set

The briefing given at Picatinny Arsenal to IDA and the DARPA Program Manager follows. Minor corrections resulting from formal IDA review have been incorporated.

Global Question

- To what extent can mine warhead size be reduced while preserving antitank lethality and, if possible, improving lethality against lighter vehicles?
- Size constraints imposed by
  - Room for electronics, mobility.
  - Volcano delivery.
  - Desire for 120 mm OOD system.

OOD is "obstacle on demand," one of the concepts explored to provide maneuver protection for Future Combat System-equipped forces.
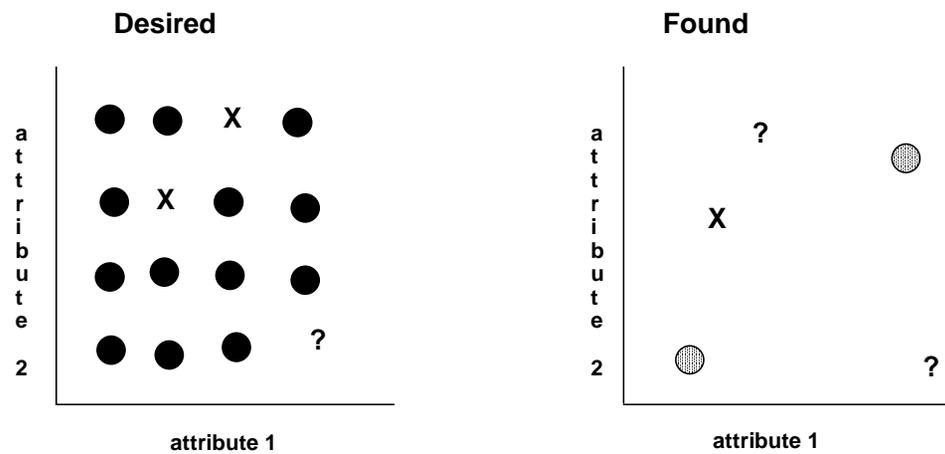
Initial Question

- Does the use of a pyrophoric warhead increase lethality?
  - "Reactive warheads" considered as well.

Nature of Data

Desired

attribute 2

attribute 1

Found

attribute 2

attribute 1

● Good Data

X Ambiguous Data

? Conflicting Data

▨ Anecdotes

For system-level vehicle assessments, lethality modeling is based on size of the hole made by the munition. Potential for fire is not usually treated, hence pyrophoric effects cannot be modeled. Further, the "research" data behind these models is old. Program-specific data is sketchy and not encouraging about the efficacy of pyrophorics. Finally, the basic physics and chemistry of ignition are poorly understood.

Context

- Two casualties/penetrated tank:
  - 40% die.
  - Of 60% who survive,
    - 40% have burns,
    - 50% fractures.
  - Half of the wounds occur outside the tank.
  - Secondary explosions lead to 20% of casualties.

    COL Ron Bellamy, USA,"Historical Perspective of Combat Casualties," *Proceedings of 1988 LFT Crew Casualty Assessment Workshop*

Crew tries to escape a tank that's been hit.

Secondary explosions are not that easy to trigger or to trigger quickly enough to hurt the crew directly.

For a four-man crew, the numbers above indicate that roughly two would escape harm, one would be killed, and one would be injured, with fractures or burns most likely. We will show below that a pyrophoric that combusts completely inside a compartment generates enough heat to severely burn the crew. This would significantly increase casualties. By contrast, the Stark experience had an "all or nothing nature":

- 54 casualties—
    - 37 killed outright,
    - 15 received first aid and returned to duty,
    - 2 required admission to medical facility.

Roughly speaking, it would appear that on the Stark either you were killed or you escaped harm (with only two real exceptions). In this regime it is not clear that adding pyrophorics would increase casualties appreciably.

Classification Schemes

Warhead Type	Damage Mechanism	"Target" Component	Target Vehicle
HE	Perforation	Structure	Tanks
Jet (SC)	Spall	**Crew**	APCs
EFP	Blast	Electronics	Trucks
Rod	Heat/Fire	**Fuel**	
	Toxic Gases	**Energetics**	

From the Live Fire Test Crew Casualty Assessment conference in 1988, six categories of crew injury were used. These are listed at the left below. Listed on the right are the damage mechanisms from the chart.

Penetrating Injuries   (Perforation and Spall)

Burns   (Heat/Fire)

Toxic Gases   (Toxic Gases)

Blast/Overpressure   (Blast)

Directed energy

Blunt Injury/Acceleration

Directed energy does not seem to apply, and although blunt injury/acceleration is unlikely to be affected by pyrophoric or reactive warheads, it is likely to be relevant, given the large number of fractures.

"Crew," "Fuel," and "Energetics" are discussed below. The warhead type is assumed to be jet.

How do we know if we care?

Effectiveness vs. Challenge
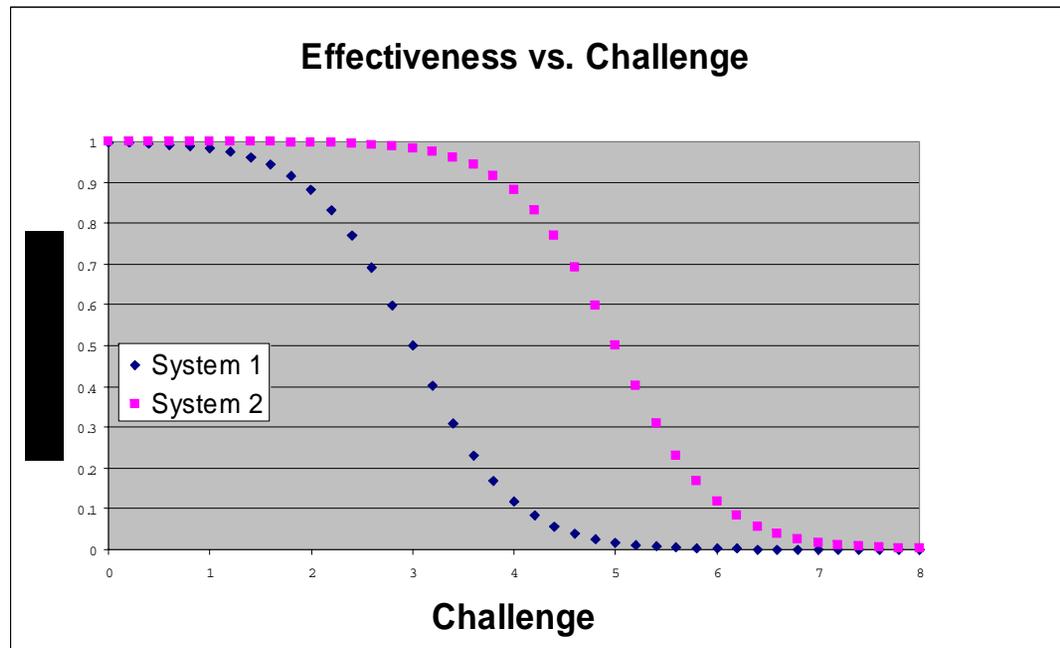
This notional chart compares the effectiveness of two systems against the varying difficulty of the challenges they face. A simple example would be two warheads against increasing thicknesses of armor plate. Thin plate they both penetrate; thick enough plate neither penetrates. The question for the analyst becomes, Is the region where one penetrates and the other does not of sufficient interest to warrant investment or so rare that it does not? We will refer to the area enclosed by the two curves as the "interesting regime," where one approach works significantly better than the other.

What will pyrophorics do?

- Ignite energetic materials:
  - Explosives, propellants, fuel.
- Start other fires.
- Burn crew.
- Generate toxic gases.

The question is, Do any of these things happen in the "interesting regime" from the previous chart?

Experience Base

- "Incendiary" munitions:
  - Questionable historic effectiveness.
  - Shells/fragments not reliably ignited on impact.
- Antitank depleted-uranium rounds:
  - Why scorch the corpse?
- VAMPIRE:
  - Penetrate mines and ignite to neutralize.
    - Burnout times as long as minutes!

With respect to depleted-uranium rounds it is important to recognize two facts. First, the effectiveness of the depleted-uranium rounds is not a function of their pyrophoric nature. Second, the regime of interest for depleted-uranium—main battle tank frontal armor—is not the regime of interest for "small warheads."

VAMPIRE fired a shaped charge into a mine to neutralize it. Burnout times were too long to be regarded as an interesting lethality mechanism in combat.

We have not looked at the burdens that might be imposed by using pyrophoric materials. In general, they may be more expensive than conventional materials, difficult to work with, or lacking in other desirable features, such as density or ductility.

New Regime

- Antitank mine produces jet for bottom attack.
  - Liner is pyrophoric.
    - Jet production or penetration ignites liner.
  - Floor/armor is thin. Spall not always relevant.
  - Complex (selectable?) initiation possible.
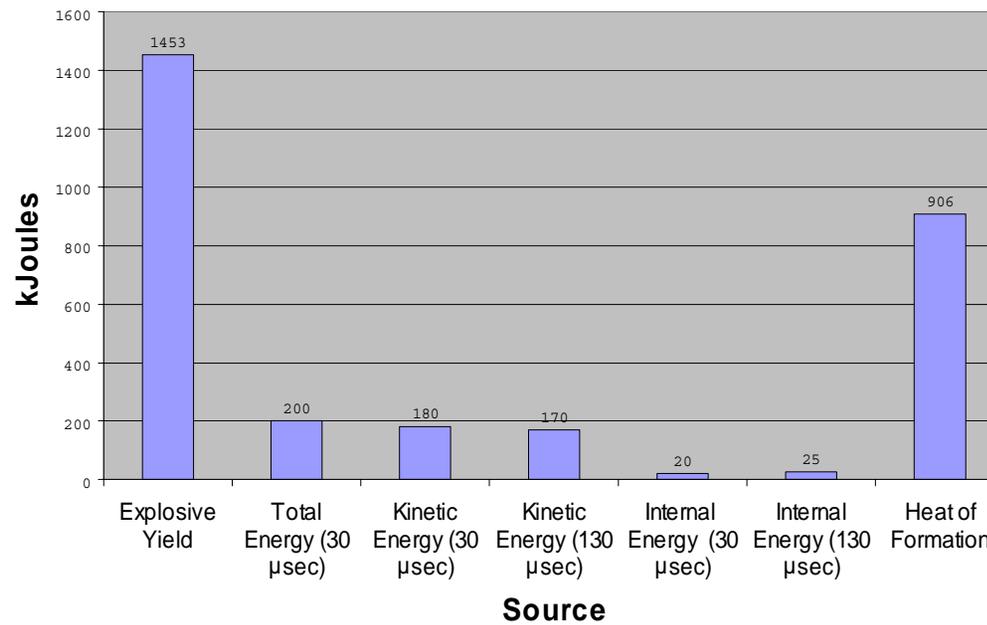 - Multiple jet or multiple slug possible.

Couple Energy to the Target

- For example, penetrator/spall combination.

- Obviated by:

  – Bottom attack.

  – Desire to extend target set to APCs, trucks.

> Without spall, energy in penetrator may not couple to target.

Where's the energy?

These numbers are for a particular 92 g Zr jet, created with 261 g of high explosives.

The heat of formation of ZrO_2 when it forms is huge compared with the kinetic energy of the jet. In fact, it is nearly as great at the explosive yield that created the jet.

For metal Teflons a similar combustion energy is available, with the exact comparison depending on how completely the carbon burns. Numbers are given below for Al-Teflon. Al-Teflon would have a lower density, and hence a lower volumetric loading. Other available metal Teflons have densities comparable to Zr.

Note that 92 g of Al-Teflon has a heat of combustion of 808 kJ. This combustion releases 1.5 moles of carbon. If that is burned to CO_2 another 532 kJ is released. Combustion is usually not complete. Fine carbon powder has other damage mechanisms though.

A figure we will use for further estimation is 100 g of Zr or 100 g of Al-Teflon (with one-third of the carbon burned) both yield about 1 MJ.

How hot is that?

- Adiabatic flame temperatures:
  - Stoichiometric pure O2:   15,000 K
  - Stoichiometric in Air: 5,400 K
  - Half Stoichiometric in Air: 3,100 K
  - 1/3 Stoichiometric in Air: 2,300 K
  - 92 g Zr in 1 m^3 of air: 1,060 K
  - 92 g Zr in 7 m^3 of air: 420 K
- Jet temperature range   500–850 K

Adiabatic flame temperatures are computed assuming complete combustion and no energy loss.

The jet temperature is approximately 500 K at 30 µsec and 850 K at 130 µsec. The additional energy comes from the jet stretching as the tip outpaces the tail.

1 m^3 of air is about 45 moles, or 9.8 moles of O_2. Starting at 300 K, we add 2,000 K at 1/3 stoichiometric and 760 K at 1/10 stoichiometirc.

Note that the estimates of the heat in the ZrO_2 extend beyond the database at about 2,100 K, and the gases beyond it at 3,000 K.

The estimate is for a 92 g Zr warhead in a 1 m^3 compartment, which has 10 times the oxygen needed for complete combustion. Combustion with Zr is normally very fast. Times scales for burning skin are short or comparable to other transport mechanisms. (This is discussed in more detail later.)

The main point is that a 100 g warhead would release intense heat if the energy were confined to a small compartment. An Abrams tank crew volume is approximately 7 m^3. Even spread uniformly over this volume, crew members would sustain serious burns if they did not evacuate quickly.

Although not analyzed in detail, air-blast overpressure is likely to have an effect as well. Burning 92 g of Zr in 7 m^3 of air increased the temperature by a factor of 1 ½, with no increase in the number of moles present. (In contrast, explosives or propellants would increase the number of moles.) This factor of 1 ½ would thus translate to an equilibrium pressure increase to 1 ½ atmospheres with transients much higher. This is clearly sufficient for injury. How serious, we have not determined.

How hot, again?

- The burning Zr is much hotter as a result of combustion than a jet would otherwise be.

- There is more than enough chemical energy to substantially heat the crew compartment air.

- How do we determine whether or not it will matter?

What will pyrophorics do?

- Ignite energetic materials:
  - Explosives, propellants, fuel.
- Start other fires.
- Burn crew.
- Generate toxic gases.

The question is, Do any of these things happen in the "interesting regime" from the earlier chart?

Are the effects large?

- Generate toxic gases.
  - Probably; quantitative analysis difficult.
    - Not treated.

- Start other fires.
  - Probably; quantitative analysis difficult.

- Burn crew.
  - Certainly, if energy is contained.

- Ignite energetic materials.
  - See below.

Inside the confines of an armored fighting vehicle, any sustained fire or deflagration involving explosives or propellant is accompanied with extremely toxic fumes. These fires are not suppressed by automatic fire extinguishing systems and the suppressive agents used interact with the burning explosive or propellant to create even more toxic fumes. Hence, for lethal effects, causing such a fire is frequently a success.

Start Other Fires

- Heat Transfer by Radiation or Convection.
  - Radiation (light):
    - Cotton ignites above 1.25 W/cm^2 radiant intensity; time to ignite dependent on fabric areal density.
    - Transient flaming on wood, starts at 300–410 °C radiant, quiescent atmosphere.
  - Convection (heated air):
    - Polymers: Ignition delay of 2–10 sec. for hard to degrade polymers at 1,200 K, 1 atmosphere.
    - Transient flaming on wood starts at 450 °C.

Energy deposition and temperature are high enough to start fires—sustained burning will depend on details of event.

Predicting ignition by pyrophorics is complicated by two factors. First, the division of energy into radiation and thermal components is not known. Second, the ignition mechanisms are complicated, and while they are similar for most solids of interest, the energy required varies from material to material.

In general, heated solids (wood, polymers, organic fibers, etc.) outgas flammable materials. Ignition usually takes place in the gas phase. For self-sustaining combustion, rather than transient flaming, the material must continue to outgas—this requires either an elevated average temperature (320 °C for wood) or continued input of heat.

All these materials appear to be in a regime where they might or might not ignite, depending upon the details of the event.

Burn Crew

- Second-degree burns begin as body temperature is elevated to 44 °C to a depth of 80 μm.
  - At 44 °C proteins are permanently denatured.
  - 80 μm is the nominal epidermis-dermis boundary.

- Clothing affords some protection.
  - Typically about a factor of 2 increase in exposure time.
  - Values range from 1.3 to 3.0.

- Burn can be generated via radiation or convection.
  - Radiative processes penetrate more deeply than convection.
    - Heating to 44 °C at 80 μm requires more radiative energy than convective, because the temperature profile is much flatter.
      - A second-degree radiative burn deposits 3/4 the energy required for a third-degree burn.

Burn Crew

- **Injury via radiant energy on skin:**
  - Second-degree burns for short exposure (delivered in <10 s).
    - Bare skin 3.9 cal/cm^2; clothed 6–10 cal/cm^2.
    - 100 mcal/cm^2/sec injury in 14 sec; extreme pain in 33 sec.
    - 400 mcal/cm^2/sec injury in 2 sec; extreme pain in 5.5 sec.

- **Injury via convection from air to skin:**
  - Second-degree burns in 1 sec., 1,100–1,650 °C; 3 sec., 370–480 °C; 15 sec., 100 °C.
    - 1,300 °C–sec. is a figure of merit for integrated exposure.

> Estimated "flame temperature" of small warheads in crew compartments exceeds requirements for severe burning, whether energy is primarily heat or light.

The scientific literature is replete with decomposition studies of the cyclic nitramines [HMX and RDX] but their critical reaction steps and overall chemical mechanisms are still subject to spirited scientific debate. Depending on how one counts them, as many as 8–13 chemical mechanisms have been proposed, and collectively, they eventually identify each type of covalent bond in the HMX molecule as being an important participant in the decomposition process.

—S. A. Shackelford et al*., J. Phys. Chem.* **89**, 3118 (1985)

Effects on Explosives

- Secondary explosives designed to be shock initiated only.
  - Heat or friction may start chemical reactions, but *usually* not detonation.
    - Shackleford quote indicates limited understanding of basic processes.

- Physics must relate to energy delivered at a given rate in a given volume.
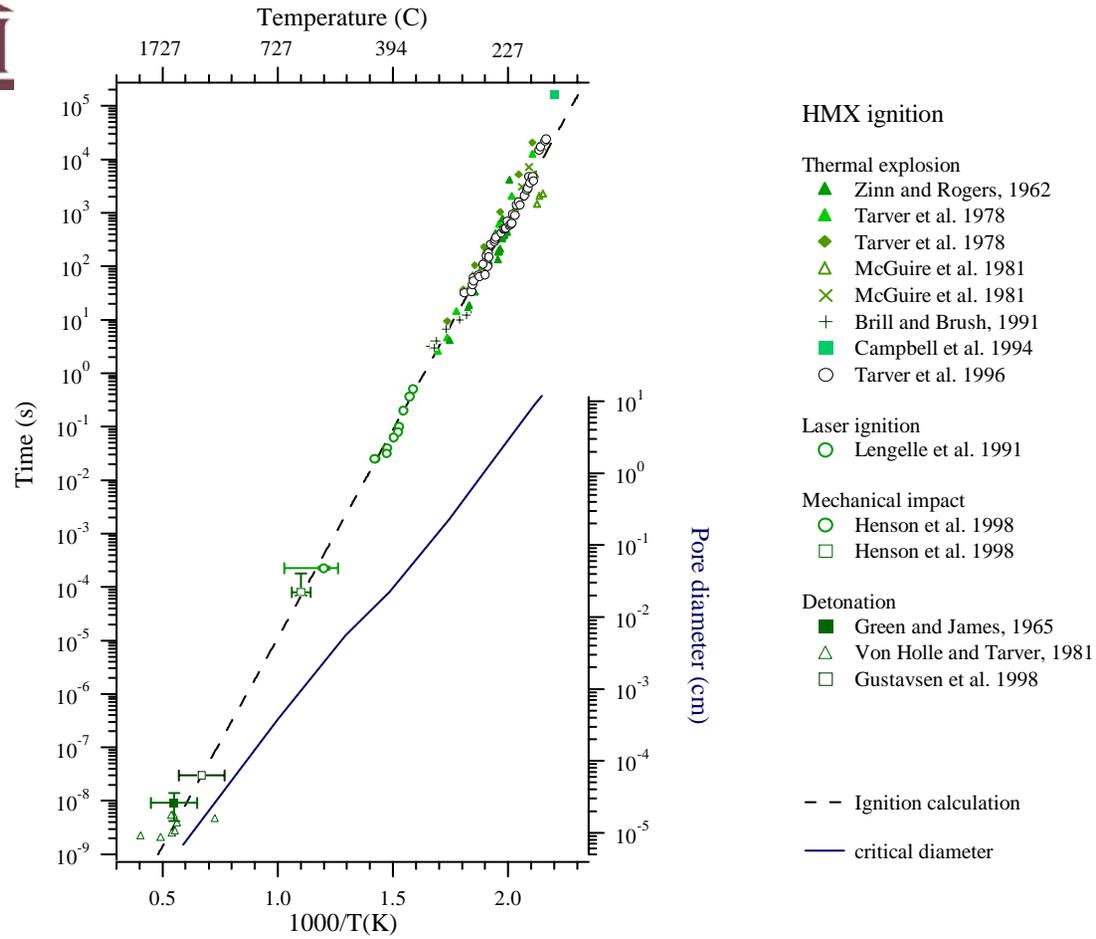
The chart above and the text below are from Henson et al (2002). For our purposes, heating a 1 µm size sample to 2,000 K will result in detonation. At 650 K, a 1 cm size object heated for 10 ms may not suffice. TNT numbers seem similar. This suggests that a pyrophoric jet or energetic warhead might trigger detonation thermally.

The results of the ignition calculation with the first-order decomposition step included are shown above. The…[dashed] line is the time to ignition as a function of temperature and the…[solid] line the critical ignition diameter, d.

This calculation clearly reproduces the linear ignition behavior observed in the data. In addition, the critical diameters that result from the calculation are also in quite good agreement with observation, with diameters in the thermal explosion regime approximating the normal size of samples required to generate thermal runaway and diameters in the regime of laser ignition approximating the depth of heating in those experiments and diameters in the regime of detonation approximating reaction zone lengths.

It is important to note that the critical diameter is the only free parameter in the calculation, with all kinetic and thermochemical constants determined independently. The time is then fixed by the ignition time for the critical diameter.

It is thus quite promising that, even in such a simple calculation, both parameters reproduce observation over the entire range of energetic response in HMX based materials.

Effects on Explosives

- Physics must relate to energy delivered at a given rate in a given volume.

  – Henson results indicate that pyrophoric or energetic materials may heat explosives to the point where detonation proceeds.

- Pyrophoric/energetic warheads appear hot enough to trigger detonation.

  – However, thermal transport may occur primarily in cases where shock initiation would also occur.

Effects on Propellants

- Propellants (generally) do not detonate.
- Rule of thumb is ignition by fragments requires a speed of 250–400 m/s.
- Nevertheless, high temperature may be sufficient to induce deflagration, even in insensitive propellants.
- Need to research propellants further.

Effects on Fuels - 1

- Fuels ignite, but do not detonate.
- In the absence of an oxidizer, they will not ignite, not matter how hot.
- Ignition is a two-step process:
  - Spill the fuel.
  - Hit it with something hot or burning.

Effects on Fuels - 2

- Joint Munitions Effectiveness Manual rules of thumb:
  - Burning particles will ignite fuel spray if:
    - Vrel < 200 ft/sec for gasoline,
    - Vrel < 150 ft/sec for diesel.
      - For diesel, ignited spray rarely propagates.

- Where's the temperature dependence?

Effects on Fuels - 3

- Data from system tests indicate fires are hard to start.
  - Needed contact time (flattened t vs. 1/T curve) seems to be a likely explanation.

- Time lines for jet and spill do not support two-step process.
  - Exception is violent rupture of fuel container.

- Follow-up needed here as well.

Effects on Electronics

- Complete instrumentation failure reported by GDOTS (General Dynamics Ordnance and Tactical Systems, Inc.) in attempts to measure ΔT, ΔP in Zr-penetrated compartment.
  - Fine (ZrO_2?) powder observed everywhere.
  - Hypothesized shorting by dielectric material.
    - ZrO_2 is an excellent insulator to high temperature.
      - Thermal damage mechanisms more likely.
    - Carbon from metal Teflon might create shorts.

ZrO$_2$ has resistivity in the range of 10^{13}–10^{14} (10 to 100 trillion) ohm-cm at room temperature, and 10^7–10^8 (10 to 100 million) at 1,000 °C. This suggests that the onset of thermal damage mechanisms will occur at lower temperatures than electrical effects. This may not be the case for carbon powder from reactive materials.

Stoplight!

	Plain	Pyrophoric	Reactive
Energetics	Moderate Y	Good G	Good G
Fuel	Poor R	Slightly better R	Oxidizer rich? R
Crew	Slug Y	Plus high Temps G	Plus high Temps G
Electronics	Slug Y	Plus high Temps Y	Temp and C Y

This chart represents in qualitative form the differences in plain (e.g., Cu), pyrophoric (e.g., Zr), and reactive (e.g., Al-Teflon) liners for the warhead.

For energetics, both explosives and propellants, the elevated temperatures will increase the probability of explosion.

For fuels, we believe there will be little advantage—the two-step process, mix with air and ignite—is unlikely to be greatly affected by pyrophoric or reactive warheads. The possible exception would be a tailored, oxygen-rich reactive compound, which might enable combustion to begin simultaneously with the spilling. There may be better approaches to targeting fuels than this.

For crews inside vehicle compartments, the energy released by either pyrophorics or reactive materials is so great that severe burning would result if the energy was contained in the compartment.

For electronics, the elevated temperatures or the presence of fine, conducting powders might be a significant damage mechanism. We believe this is plausible, but to our knowledge not yet established.

Needed Measurements

- Completeness of combustion.
- ΔT, ΔP in compartments.
- Electronic effects of oxides, carbon.
- Ignition of fuels.
  - Especially with reactive materials.
    - Oxidizer-rich reactive materials.

Structural Response Test Results (Example)

Fragment Mass (grains)

600   1,200

1,800   2,400

Needed Theoretical Work

- High explosives, propellant initiation.
  - Study in terms of energy transport rather than $P^2\tau$ or other empirical rules.

- ΔT, ΔP in compartments.

- Ignition of fuels.
  - Especially with reactive materials.
    - Oxidizer-rich reactive materials.

Smart Mine Premise

- Sensors provide target type, aim point.
- Complex initiation system can be tuned to target type, aim point.
  - Jet easily penetrates hard vehicle.
    - Jet can be used to cut track.
  - Jet can be contained in soft vehicle.
- Mobility can enhance antipersonnel lethality.

Programmatic Issues

- Self-healing minefield to replace GATOR.
  - Mine lethality of with smaller Cu warhead may be decreased.
  - Minefield effectiveness may increase.
- Warhead size enables mobility.
- Mobility may thwart breaching.

Will the Army accept lower
lethality of individual mines?

Programmatic Issues

- Can the lethality community give appropriate credit for pyrophoric or reactive warheads?

- Can the target set of the mines be expanded?

> Can anyone be induced to fund the data collection and model building?

A Possible Block Structure

- Block 1: Cu warhead; mobility; basic communications.
- Block 2: Zr warhead; mobility algorithm, multiple initiation methods, target typing.
- Block 3: Hf -Teflon; antijam communications.
- Block 4: Soft-target bounding; aim-point selection.

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14. ABSTRACT

This study was commissioned by the DARPA Self Healing Minefield (SHM) program. The goal of the SHM program was to develop mines that could self-organize as a network and detect breaches, which would be sealed by mines "hopping" to the exposed area.

To produce such mines in the current mine form factor, a smaller warhead is used to make space available for the communications and mobility subsystems. The warhead under consideration uses a pyrophoric material, Zr, in the liner. The specific task of this study was to determine whether using pyrophorics or energetic materials such as Al-teflon enhanced lethality against light armor or thin-skinned vehicles. Given the very limited data, assessments were made based on the underlying science of the various lethality mechanisms.

We found two mechanisms where warhead lethality would be increased by the use of pyrophoric or energetic (e.g., Al-Teflon) warheads: (1) increased probability of detonation of explosives or deflagration of propellant materials and (2) increased crew casualties as a result of burns.

We expect only slightly improved ignition of fuel to result from the use of pyrophorics.

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