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Fragment Impact Modeling and Experimental Results for a 120mm Warhead

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The U.S. Army Combat Capabilities Development Command (CCDC) Armaments Center at Picatinny Arsenal, NJ is working to develop technologies to mitigate the violent reaction of a 120 mm warhead, loaded with an aluminized HMX-based enhanced blast explosive, when subjected to the NATO Insensitive Munitions (IM) Fragment Impact (FI) test. As per NATO STANAG 4496, FI testing is conducted at 8300±300 ft/s with a 0.563" diameter, L/D~1, 160˚ conical nosed mild steel fragment. Reaction violence resulting from FI can be mitigated by the use of liners or barriers applied to the munition itself or its packaging, commonly referred to as a Particle Impact Mitigation Sleeves (PIMS). Previous development efforts for this item focused on a lightweight plastic warhead support which was able to reduce the severity of the input shock sufficiently to prevent high order detonation. However, violent sub-detonative responses were still observed which occurred over several hundred microseconds, consumed part of the explosive charge, and ejected hazardous debris over large distances. These responses are driven by rapid combustion coupled with damage to the explosive as well as mechanical confinement. Quantitative modeling of these scenarios is a challenging active research area. Prior experimental results and modeling guidance have shown that mitigation of these reactions requires a more substantial reduction in the overall mechanical insult to the explosive. In particular, steel and aluminum PIMS have been able to efficiently provide the necessary fragment velocity reduction, breakup and dispersion in typical packaging applications. Packaged warheads were tested at the GD-OTS Rock Hill facility with several PIMS designs incorporated into the ammunition containers. Several designs were demonstrated to provide benign reactions with minimal added weight. Future iterations will attempt to further improve the design using advanced lightweight barrier materials.

1. Introduction

All U.S. munitions are required by international agreement to be made Insensitive Munitions (IM) compliant to the extent practical. This entails that the munition in both its operational and logistical configurations must react nonviolently when subjected to a suite of tests intended to simulate hazards commonly encountered on the modern battlefield. These include Fragment Impact (FI), Bullet Impact (BI), Fast Cookoff (FCO), Slow Cookoff (SCO), Sympathetic Reaction (SR), and Shaped Charge Jet Impact (SCJI). Reaction severity is categorized into detonation (Type I), partial detonation (Type II), explosion (Type III), deflagration (Type IV), and burn (Type V) responses. The determination of reaction severity is made based on photographic evidence, witness plate damage, fragment size and throw distance, and blast gauge pressure readings. Currently, work funded by the Joint Program Executive Office for Armaments and Ammunition is being performed to improve the IM response of a 120 mm warhead packaged in its logistical configuration. This paper documents several modeling and experimental results for this configuration subjected to the NATO standard fragment impact test.

2. NATO Fragment Impact Testing

The NATO Standardization Agreement (STANAG) 4496 Ed. 1 [1] describes the NATO standard FI test of interest in this work. It specifies a 287 grain, 0.563” diameter, L/D ~ 1, 160° conical-nosed mild steel cylindrical fragment with a Brinell hardness of less than 270, which impacts the item under test at a velocity of 8300±300 ft/s. Two aim points are specified in STANAG 4496: the center of the largest presented area of explosive, and the most shock-sensitive location. In the U.S., a smooth bore 40 mm powder gun is typically used to propel the fragment, which is mounted in a plastic sabot. Velocity is measured using time-of-arrival gauges and/or by high speed camera. Figure 1 shows the fragment, sabot, and a typical testing setup [2].

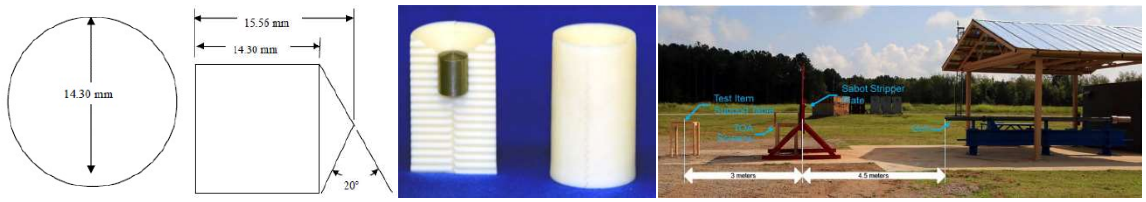

Figure 1. NATO standard fragment (left), typical sabot (center), and 40 mm smoothbore gun (right)

3. General Phenomenology and Previous Work

The 8300 ft/s NATO FI test is intended to simulate a heavy bomb or artillery fragment. At this impact velocity, extremely strong shock waves and hydrodynamic deformation due to pressures well above material flow strength are commonly observed. The typical strategy for preventing violent response of high explosive warheads under such conditions is to buffer out the initial impact shock, and secondarily to reduce the mechanical insult to the explosive by providing sufficient fragment velocity reduction, breakup and dispersion. To achieve this, Particle Impact Mitigation Sleeve (PIMS) technology is normally tailored to the munition of interest. PIMS are specialized mechanical barriers designed to mitigate the FI threat by addressing the aforementioned physical phenomena. The use of a thin plastic PIMS internal or external to the warhead body has been observed to prevent shock initiation of high order detonation in a variety of munition items [3]. However mitigation of the violent sub-detonative responses which usually still occur typically requires substantially heavier barriers.

The phenomenology of sub-detonative response due to high velocity impact is extremely complicated, and outcomes are challenging to quantitatively predict. These responses are driven by rapid combustion coupled with damage to and fracture of the explosive, conductive and convective heat transfer, as well as mechanical confinement, and can occur over relatively long timescales, e.g., several milliseconds. Typically some of the explosive charge is left unconsumed, large fragments are projected over long distances, and pressures which develop are relatively low. Modeling challenges include (but are not limited to) production of damage and porosity changes, ignition criteria, reaction rates, flame propagation in damaged reactant, equations of state and constitutive models for the solid explosive reactant and gaseous products (as well as mixtures of both), interaction with confinement, and possible transition to detonation, shown in Figure 2 [4, 5]. All of these phenomena need to be experimentally quantified in a consistent theoretical framework which must have a robust numerical implementation that can be used for practical length and time scales, and this remains a challenging active research area. Some material models which have been developed for this purpose include Coupled Damage and Reaction with Kinetics (CDAR-K) [5] and High Explosive Response to Mechanical Stimulus (HERMES) [6]. In any case, no such models have been parameterized for the explosive of interest or anything similar, to the authors’ knowledge. Additionally, other modeling challenges such as prediction of dynamic fracture for the inert materials might limit the utility of such an explosive model in many applications. As a result, while computer modeling can currently provide some useful qualitative and quantitative information, testing is still relied upon for IM design.

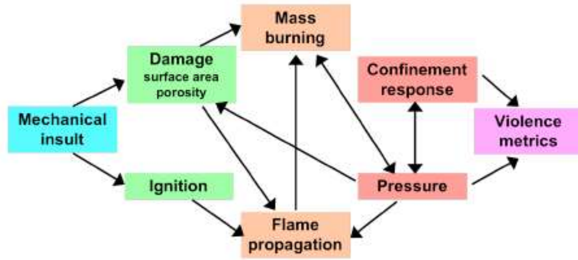

Figure 2. Sub-detonative response phenomenology (from [4, 5])

Much work has been performed in the past to mitigate the 8300 ft/s NATO FI threat for a variety of larger caliber explosive warheads. Several experimental programs have found PIMS consisting of steel and/or aluminum layers several millimeters thick to provide the necessary fragment velocity reduction and dispersion to pass the FI test criteria, although this obviously varies to some extent with the munition case and explosive fill. Examples include recent IM programs for the TOW2B missile [7, 8] and the M72 LAW [9]. Testing of the 8300 ft/s NATO fragment against inert flat plates of these materials has also been performed. A recent CCDC Armaments Center experimental program [10, 11] obtained residual velocities for FI against a variety of steel plates using flash radiography. Some results from this study are shown in Figure 3. This work demonstrated that hardness of steel plates at the thicknesses of interest had a minor effect on the residual velocity but a significant effect on the fragment debris mass distribution. Similarly, high speed video (HSV) has been used to obtain residual velocities for a variety of protection schemes under the aforementioned TOW2B program [12]. These tests have shown that successful designs provide velocity reductions of 1000-2000 ft/s and result in significant fragment breakup, which is clearly an essential feature of the problem. Other more exotic materials have been able to achieve the same velocity reduction for somewhat less areal density, e.g., [7-8, 12]. However these may not make good packaging materials, which must generally be inexpensive and endure extreme environmental and rough handling conditions. Additionally, the extent to which the PIMS thermally insulates the warhead is an important consideration from the standpoint of mitigating cookoff response.

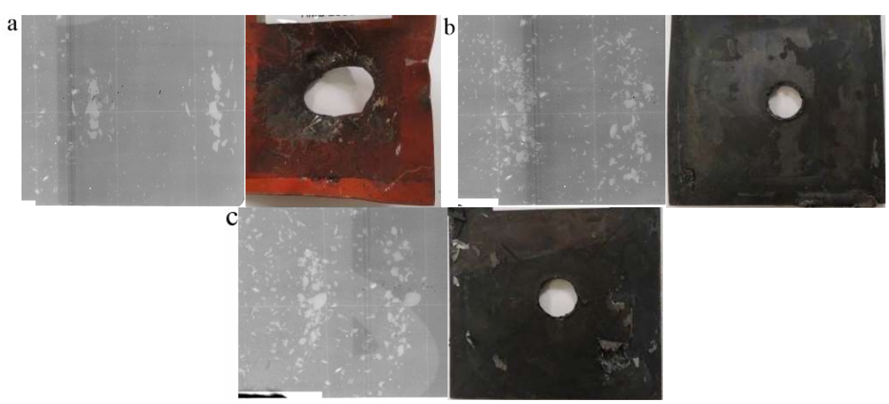

Figure 3. 8300 ft/s NATO FI test radiographs for (a) ~0.04” thick steel ammunition container (velocity reduction of 500 ft/s); (b) 0.118” thick steel plate (velocity reduction of 950-1200 ft/s); (c) 0.236” thick steel plate (velocity reduction of 1975 ft/s)

4. Item and Configuration Description

The configuration of interest in this work, shown in Figure 4, is a 120 mm warhead packaged in a ~0.04” thick sheet steel ammunition container. The steel warhead was designed by the CCDC Armaments Center and is loaded with ~4.5 lb of an aluminized HMX-based enhanced blast explosive (65% HMX, 20% Al, 15% binder). Its wall thickness is approximately 0.4”, and it is mounted in a 0.35” thick high density polyethylene (HDPE) warhead support which slides over a recess on the warhead body, introducing a small air gap. In previous work, this configuration was demonstrated to prevent high order detonation of the warhead when subjected to FI. However, it was not sufficient to2 address the violent sub-detonative responses which still occurred. It should be noted that the container is expected to break up the incoming fragment (see Figure 3a). This test series experimentally evaluated several PIMS designs which were downselected with the aid of high rate continuum modeling, past experience and engineering judgment. Approximately 5/8” of space is available between the OD of the warhead support and the ID of the container to incorporate PIMS. These could be attached to the container, the warhead support, or both to achieve a multi-layer design. Cylindrical steel nose and aft simulants were threaded onto the warhead. The PIMS and HDPE support were placed over the warhead, and the entire assembly was centered in the container by laser cut acrylic discs, shown in Figure 5.

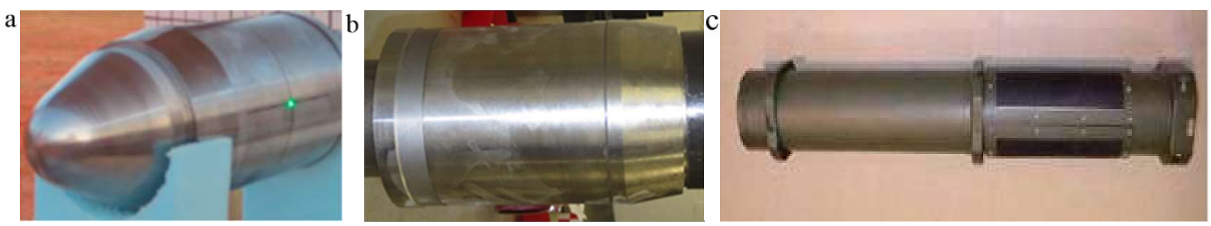

Figure 4. (a) 120 mm Warhead; (b) Nose and tail simulants; (c) Ammunition container

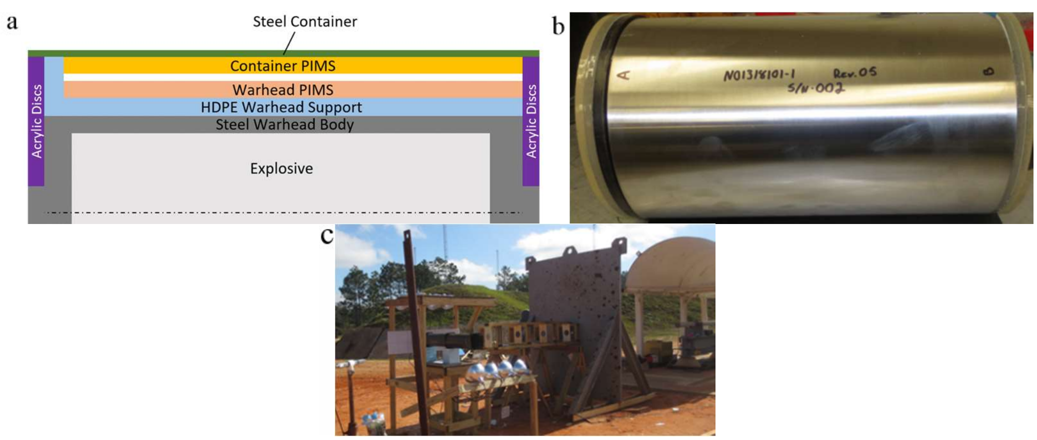

Figure 5. (a) Diagram of packaged warhead with notional PIMS protection; (b) Warhead and sample PIMS assembly prepared for insertion; (c) Test setup

5. High Rate Continuum Modeling

To investigate what kinds of protection designs might be required to fully mitigate FI, several calculations were performed in the multi-material Arbitrary Lagrangian-Eulerian (ALE) hydrocode ALE3D [13]. The ALE formulation allows for severe distortions to arise, while better preserving material interfaces and retaining some of the natural zoning adaptivity a pure Lagrangian calculation would provide. ALE3D advances the solution in time with a Lagrangian step followed by a remap/advection step. A modified equipotential mesh relaxation scheme is used to dynamically move mesh into regions of interest. A second order monotonic advection algorithm is utilized. Standard artificial viscosity is used to spread shock fronts over several zones. The Mie-Gruneisen equation of state (EOS) was used for all of the solid materials. Standard Steinberg-Guinan [14] forms for the flow stress as a function of equivalent plastic strain, strain rate, and temperature (defined using the zero-Kelvin isotherm) with a von Mises yield surface were utilized. Spall failure was approximated using a maximum tensile hydrostatic stress criterion. Failed material is unable to withstand shear or hydrostatic tensile stress, and voids are inserted upon failed material reaching an excessive relative volume. The explosive was modeled as an inert Mie-Gruneisen solid using the unreacted Hugoniot, and was assumed to be elastic perfectly plastic with a small amount of strength; no attempt was made to model its energetic response.

The ballistic limit of the warhead body has been suggested as an approximate threshold for violent sub-detonative munition response in heavily confined charges [15], although such a criterion is clearly independent of the particular explosive. It has also been observed for several common explosives that the transition from essentially no reaction to violent explosion occurs over a fairly narrow range of impact velocities, e.g., less than ~650 ft/s [16]. As such the plan was to computationally identify designs which resulted in relatively minor deformation of the warhead body as an upper bound on the required protection, then hone in on the lightest successful configuration experimentally. Based on experience and logistical considerations, steel and aluminum PIMS were investigated under this effort. Warhead and container PIMS configurations were modeled, and some sample calculations are shown in Figure 6. The calculations indicated that the HDPE warhead support, while not providing a significant amount of penetration resistance, would still easily buffer out the impact shock from the incoming fragment debris. It also appeared that a container PIMS provided noticeably less penetration of the warhead body than a warhead PIMS for the same thickness. Clearly the code does not explicitly model fragment breakup, but the distances in question are so short that the effect is well approximated by the loss of strength due to extensive spall failure. It appeared that a 0.25” thick steel container PIMS would likely be an upper bound on the thickness required to prevent severe penetration of the warhead body. A 0.375” thick aluminum warhead PIMS also appeared viable, with a substantial weight reduction compared to the steel design. As a result PIMS in several appropriate increments up to these thicknesses were downselected for testing.

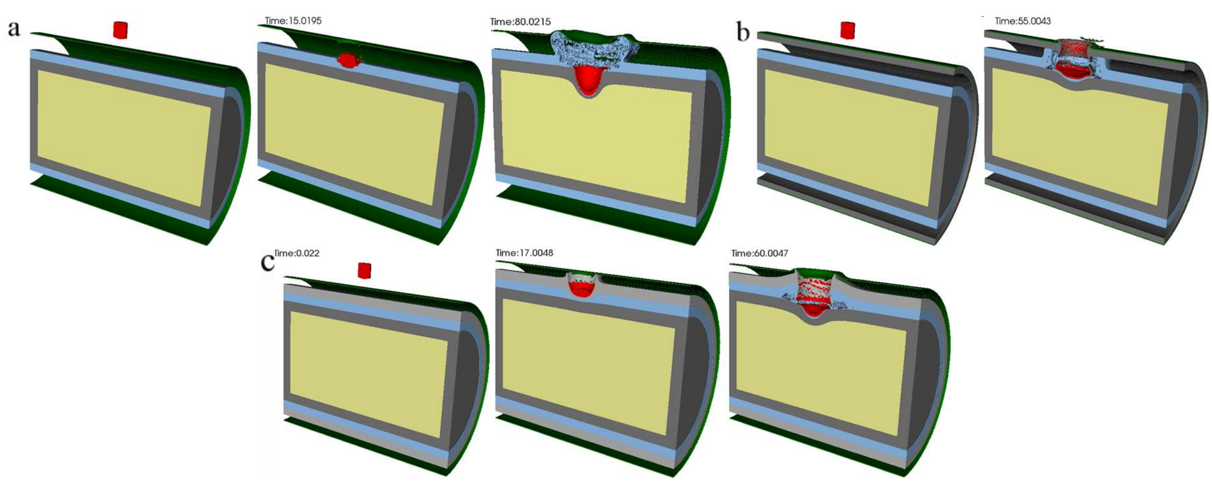

Figure 6. Sample ALE3D FI calculations for (a) baseline configuration at 0 μs, 15 μs, and 80 μs; (b) 0.25” steel container PIMS at 0 μs and 55 μs; (c) 0.375” aluminum warhead PIMS at 0 μs, 17 μs, and 60 μs

6. Experimental Methodology and Results

FI testing was performed at the General Dynamics Ordnance and Tactical Systems (GD-OTS) Rock Hill test facility. Ten warheads were available for this test series. The warheads were to be tested in a configuration most closely representing a potential fielded configuration: in thin steel ammunition containers, inside a plastic warhead support, with full cylindrical tube PIMS applied to either the outside of the warhead support or the inside of the container providing full 360° protection (see Figure 5). This ensures that the confinement from the PIMS and ammunition container is taken into account in the test results. Because it was not practical to test against the entire munition, the warheads and the rest of the hardware had to be mounted concentrically within the containers, which were not modified. The PIMS can be split into arcs if more practical from a manufacturing standpoint, but the test results from the tubes should be conservative as the strength of the metal will add confinement. To conserve test assets, a significant amount of extra hardware for different PIMS designs was obtained to provide flexibility in terms of testing configurations which it seemed logical to evaulate, or repeating a configuration for any no-tests. Several thicknesses of 4140 steel and 6061-T6 aluminum warhead and container PIMS were obtained, as these materials were readily available in the geometries of interest. Additionally, it was hypothesized that strength of the PIMS might appreciably affect fragment breakup, as well as penetration since full deceleration of the fragment debris is desired. To evaluate whether this would provide any improvements, some of the steel PIMS were heat treated to as high of a hardness as was practical. In addition, a limited quantity of 7075-T6 aluminum PIMS were fabricated. The hardware selection turned out to be very good, with most of the PIMS being used and hardware availability only slightly constraining testing decisions. Additionally, very good aimpoint accuracy and impact conditions [2] were achieved throughout this test series, resulting in consistent and valid tests which allowed for optimization of the design to progress quite satisfactorily. Accordingly, this data is tabulated in Table 1, along with peak blast overpressures (BOP) which were comparable to those produced by the gun, even for violent sub-detonative responses. Comparisons of modeling predictions with the results are also shown for several of the configurations.

A baseline shot (test number RT18592) was conducted first, shown in Figure 7. A violent deflagration was observed. This reaction launched the aft simulant into the berm surrounding the test arena, and it was found buried several feet into the soil. The warhead body broke up into several large pieces, most of which were recovered. The remaining debris was likely launched outside the test facility, at least several hundred yards. During several test series with this item where such reactions were observed, isolated chunks of explosive were found at such distances and further. Gouging was also noted on the witness plate, which occurred for all of the deflagrations.

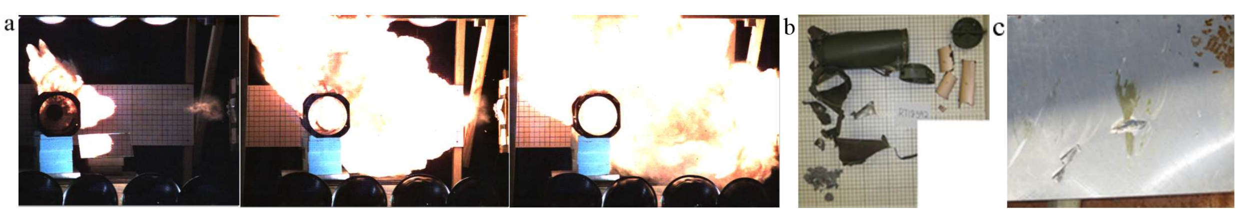

Figure 7. Baseline (RT18592) (a) HSV at 310 μs, 895 μs, 1517 μs from impact; (b) Recovered debris; (c) Witness plate gouging

The next test (RT18591) was a 0.125” steel container PIMS. A violent deflagration was observed, shown in Figure 8. Interestingly, little reaction was observed until an explosion occurred some 2ms after impact. What appeared to be a plug of warhead body material was also recovered. The PIMS fractured longitudinally through the impact point and was blown through the container in one piece, straightened into a flat plate and thrown ~20 yards. Thus one disadvantage of using a metal PIMS is that if it is overmatched, it can itself become hazardous debris, although one large hazardous fragment is always better than several. In IM testing, fragments over 0.66 lb found past 50 feet are generally considered hazardous [17]. The next test (RT18593) was a 0.1875" steel container PIMS. The packaged warhead was knocked off the test stand onto the ground. The warhead was pulled from the packaging intact with a large indent in the warhead body that contained some of the residual fragment, shown in Figure 9.

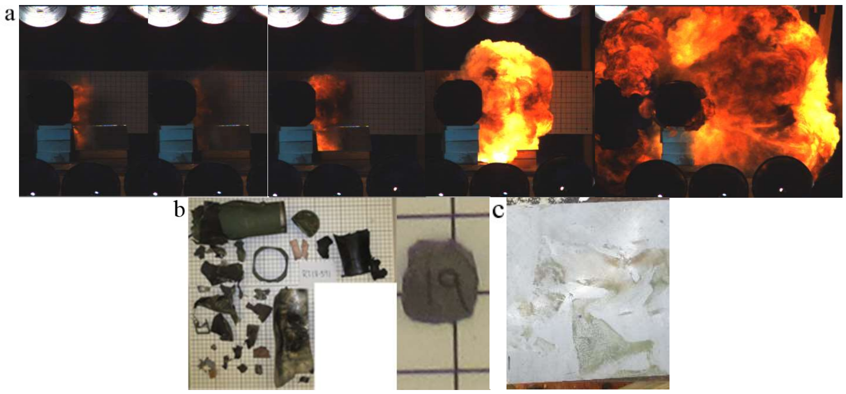

Figure 8. 0.125" Steel Container PIMS (RT18591) (a) HSV at 310 μs, 1206 μs, 1517 μs, 1828 μs, 2412 μs from impact; (b) Recovered debris; (c) Minor witness plate gouging

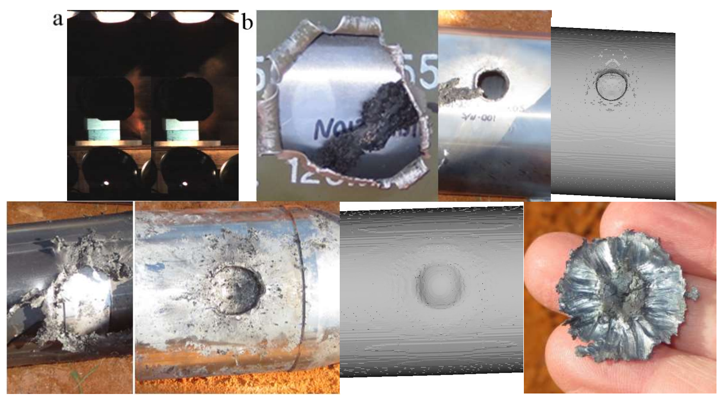

Figure 9. 0.1875" Steel Container PIMS (RT18593) (a) HSV at 310 μs, 2723 μs from impact; (b) Recovered debris, intact warhead, model comparisons

At this point a mitigation solution was found, eliminating a fraction of the available hardware from consideration. As a result all of the following tests attempted to further reduce the weight per unit length of the PIMS with the remaining hardware, in light of currently available test data. Since a hardened steel 0.125" container PIMS was not available, it was decided to test a 0.1875" steel warhead PIMS (RT18594). A violent deflagration was observed, shown in Figure 10. Again, the PIMS fractured longitudinally and straightened into a flat plate, which was found ~100 yards away. The warhead body split into several pieces, all of which were recovered. The next design tested was a 0.25" 6061 aluminum container PIMS (RT18595). This was much lighter than the steel designs, but significant penetration of the explosive charge was observed in the models. A deflagration was observed, shown in Figure 11. The PIMS fractured longitudinally along the impact point and peeled open into a flat plate, which was thrown ~30 yards. The warhead body was split into two halves, both of which were recovered ~50 yards from the test stand. The next configuration tested was a 0.1875” thick hardened heat treated steel container PIMS (RT18597), which was intended to investigate whether the choice of steel for a practical fielded design would result in a significantly different outcome. The warhead was pulled from the packaging intact with a large dent in the warhead body that contained some of the residual fragment, shown in Figure 12.

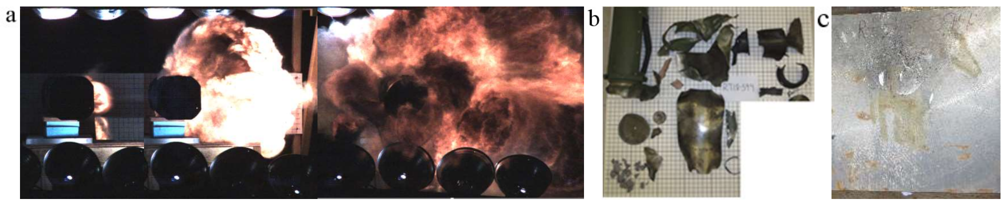

Figure 10. 0.1875” Steel Warhead PIMS (RT18594) (a) HSV at 622 μs, 1206 μs, 2101 μs from impact; (b) Recovered debris; (c) Witness plate gouging

Figure 11. 0.25” 6061 Aluminum Container PIMS (RT18595) (a) HSV at 310 μs, 895 μs, 1517 μs, 2101 μs from impact; (b) Recovered debris; (c) Witness plate gouging

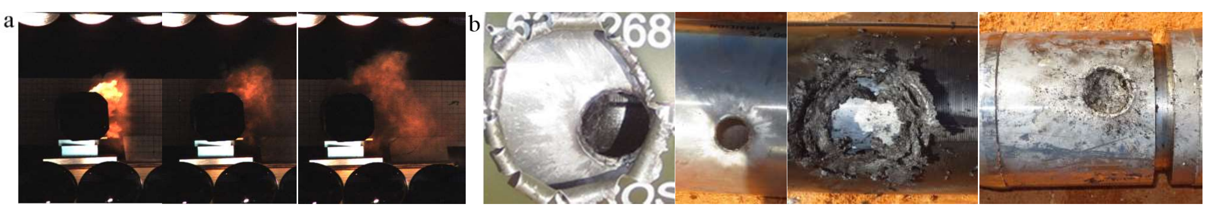

Figure 12. 0.1875” Hardened Steel Container PIMS (RT18597) (a) HSV at 311 μs, 2101 μs, 4202 μs from impact; (b) Recovered debris and intact warhead

The next configuration tested was a spaced plate design: a 0.125” 7075 aluminum warhead PIMS inside of a 0.125” steel container PIMS (RT18598). This produced about as much of a weight reduction as using the 0.1875” steel warhead PIMS. The warhead was pulled from the packaging intact with a large dent in the warhead body that contained some of the residual fragment, shown in Figure 13. The next configuration tested (RT18599) was a spaced plate design: a 0.25” 7075 aluminum warhead PIMS inside of a 0.125” 6061 aluminum container PIMS. This would provide a higher areal density than the 0.25” aluminum container PIMS, and a substantially higher flow strength for the aluminum. The warhead was pulled from the packaging intact with a smaller dent in the warhead body that contained some of the residual fragment, shown in Figure 14. The observed deformation compared well with modeling predictions. This spaced aluminum PIMS design produced a 33% weight reduction compared to the 0.1875” steel container PIMS demonstrated to produce a benign reaction. The next configuration tested was a 0.25” 6061 aluminum warhead PIMS inside a 0.125” 6061 aluminum container PIMS (RT18620). This was done to determine whether the grade of aluminum made a difference, and also since the 0.25” 6061 aluminum container PIMS was unsuccessful. A completely benign reaction was observed, shown in Figure 15. Unfortunately the warhead could not safely be removed for visual inspection.

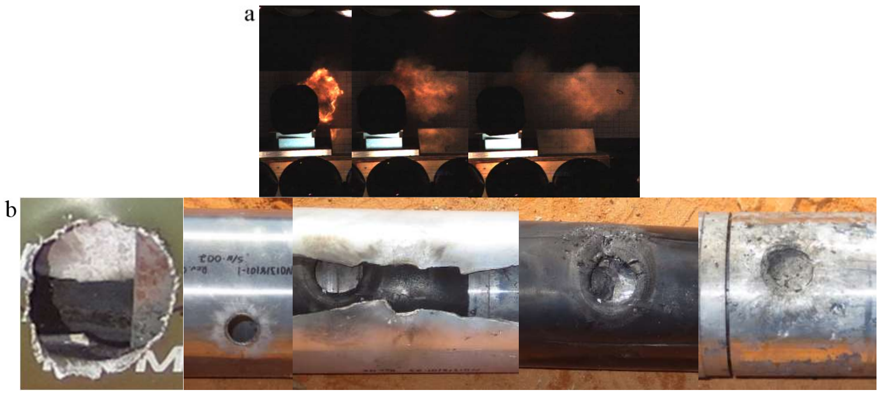

Figure 13. 0.125” Steel Container PIMS with 0.125” 7075 Aluminum Warhead PIMS (RT18598) (a) HSV at 622 μs, 2101 μs, 4202 μs from impact; (b) Recovered debris and intact warhead

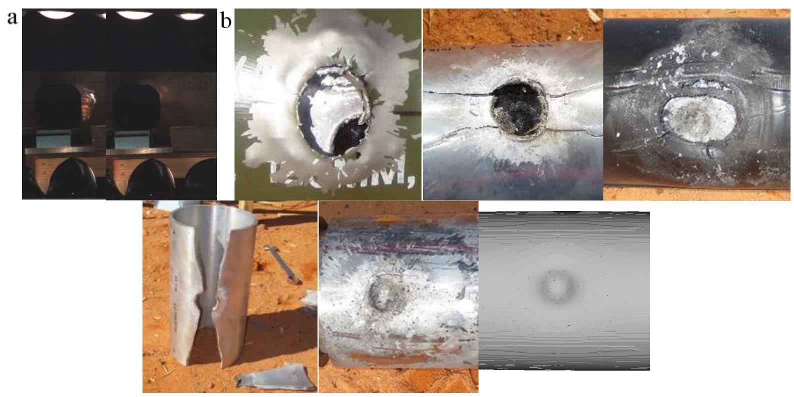

Figure 14. 0.125” 6061 Aluminum Container PIMS with 0.25” 7075 Aluminum Warhead PIMS (RT18599) (a) HSV at 622 μs, 2101 μs from impact; (b) Recovered debris and intact warhead, modeling comparison

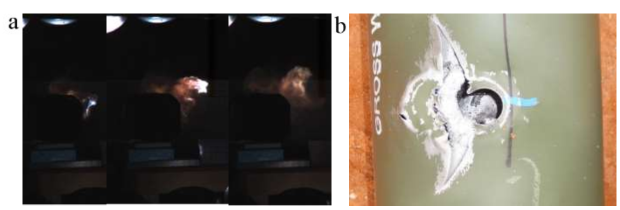

Figure 15. 0.125” 6061 Aluminum Container PIMS with 0.25” 6061 Aluminum Warhead PIMS (RT18620) (a) HSV at 622 μs, 1206 μs, 2101 μs from impact; (b) Recovered debris

The final test was a 0.125” hardened steel warhead PIMS (RT18621). This would achieve another 5% weight reduction over the previous best design, and would confine the warhead less. Unfortunately a violent deflagration was observed. Both halves of the warhead, as well as the PIMS, were recovered ~100 yards away. The PIMS still fractured longitudinally through the impact point. This concluded the test series; all results are listed in Table 1.

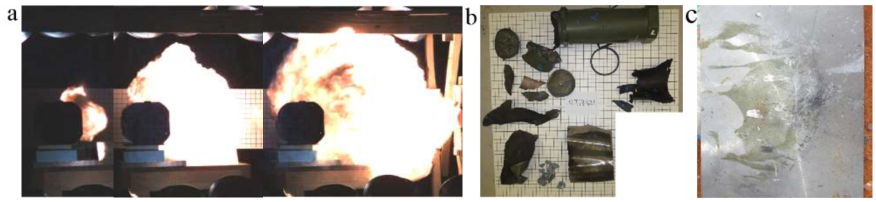

Figure 16. 0.125” Hardened Steel Warhead PIMS (RT18621) (a) HSV at 311 μs, 895 μs, 1206 μs from impact; (b) Recovered debris; (c) Witness plate gouging

Table 1: Summary of Results

Serial No.	Container PIMS Material	Container PIMS Thickness (in)	Warhead PIMS Material	Warhead PIMS Thickness (in)	PIMS Weight per Length (lb/in)	Velocity (fps)	BOP at 10ft Peak 1 (psi)	BOP at 10 ft Peak 2 (psi)	Witness Gouge	Type
RT18591	Steel	0.125	---	---	0.729	8391	3.9	3	Y	III
RT18592	---	---	---	---	---	8253	---	1.9 at 20ft	Y	III
RT18593	Steel	0.1875	---	---	1.072	8345	1.75	---	N	V
RT18594	---	---	Steel	0.1875	0.959	8219	2.3	1.35	Y	IV
RT18595	6061 Al	0.25	---	---	0.490	8273	2.8	1.75	Y	IV
RT18597	Hardened Steel	0.1875	---	---	1.074	8287	2.2	---	N	V
RT18598	Steel	0.125	7075 Aluminum	0.125	0.956	8275	1.75	---	N	V
RT18599	6061 Aluminum	0.125	7075 Aluminum	0.25	0.716	8416	2.25	---	N	V
RT18620	6061 Aluminum	0.125	6061 Aluminum	0.25	0.700	8511	1.5	---	N	V
RT18621	---	---	Hardened Steel	0.125	0.628	8463	2.9	2	Y	IV

7. Summary and Conclusions

Several FI mitigation schemes for a 120 mm warhead were modeled and tested. Steel and aluminum PIMS were chosen based on past experience and engineering judgment. High rate continuum modeling was utilized to qualitatively identify designs which produced minimal damage to the warhead body. This provided an upper bound on the required protection, as the ballistic limit of the warhead body has been suggested as an approximate threshold for violent sub-detonative response. A variety of warhead and container PIMS were fabricated from steel at two different hardnesses as well as two grades of aluminum. A viable solution was found very early on in the test series, allowing for progressive reduction in PIMS weight over the remaining tests while maintaining a Type V reaction. It was observed that a steel PIMS of a given thickness was significantly more effective when applied to the container rather than to the warhead support. It also appeared that impacts sufficient to perforate the warhead body always resulted in ignition of the explosive charge and violent deflagration shortly thereafter, and that the transition from violent to almost no reaction occurred over a very narrow range of mechanical insults. This observation might be used to further optimize the design computationally. Overall, an aluminum spaced plate design with a 0.25” warhead PIMS inside a 0.125” container PIMS was identified to fully mitigate FI with the least amount of weight per unit length. This is a ~35% improvement over the thinnest steel PIMS found to work, which might be expected since the aluminum design better utilizes the available space in the container. The steel hardness or aluminum grade did not appear to have an appreciable effect on test outcomes. Future work will cover integration of these designs into the packaging for production purposes, as well as attempts to further reduce the weight using different materials.

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