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Mitigation of External Fuel Tank Damage from Overmatching Shaped Charge Threats

by Seth J Copeland, Michael Keele, and Seth Halsey

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Survice Engineering

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14. ABSTRACT

This study examined a) baseline damage to a metallic fuel tank when impacted by either a shaped charge jet or explosively formed penetrator threat and b) methods to mitigate the damage from a shaped charge threat, specifically addition of either an internal lining or external wrap, were evaluated.

15. SUBJECT TERMS

external fuel tank, ground vehicle, shaped charge jet, overmatching threat, survivability, EFP, explosively formed penetrator

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Summary

This study examined a) baseline damage to a metallic fuel tank when impacted by either a shaped charge jet or explosively formed penetrator (EFP) and b) methods to mitigate the damage from a shaped charge threat, specifically the addition of either an internal lining or external wrap. The 65-mm-diameter shaped charge warhead used in this study produces a jet consistent with the size of a typical rocket-propelled grenade. For experiments involving the 18- × 18-inch stainless steel tanks, a 135-mm-diameter EFP was used to evaluate the surrogate fuel tanks' survivability.

1. Introduction

Fuel tanks are fabricated from thin metal and can be perforated by battlefield threats. Current features to minimize damage from fragments and small-caliber bullet threats include overwraps and internal linings. When dealing with larger threats, such as shaped charge jets and explosively formed penetrators (EFPs), the aforementioned features become insufficient.

This current study focuses on fuel tank damage that results when the tanks are struck with shaped charge threats. There are two objectives: 1) to understand how significant fuel tank damage varies as a function of tank wall thickness and tank size and 2) to better understand how fuel tank features, such as external overwraps and internal linings, may limit the damage. This evaluation builds on work previously performed by Boyd et al.[1–6] and Payne.[7]

2. Experimental Setup and Results

2.1 Baseline Fuel Tank Experiments

To initiate the investigation into fuel tank survivability it was necessary to establish baseline damage and response to a fuel tank that is struck by an overmatching shaped charge. Variables included fuel tank wall thickness and material. A 65-mm-diameter copper shaped charge warhead was used for this part of the evaluation. A nominally 12-inch (305-mm)-diameter by 18-inch (457-mm)-long, cylindrically shaped fuel tank was used in which three wall thicknesses were evaluated, 1/32 inch (0.84 mm), 1/16 inch (1.6 mm), and 3/16 inch (4.8 mm). The tanks were filled with water to approximately 75% of their total volume representing a partially filled fuel tank. The two thinner tanks were cut, rolled, and welded using 304 stainless steel. The thickest fuel tank, 3/16 inch (4.8 mm), was produced from prerolled and welded A500 steel pipe in which A37 mild steel endcaps were cut and welded into place. Diagrams of the experimental setups are shown in Figs. 1 and 2. The fuel tank was positioned on top of a wooden v-block stand. Photographs of the setup are shown in Figs. 3 and 4. The shaped charge warhead is lined up to pass through a 1-inch (25.4-mm) through hole in the center of a 1-inch (25.4-mm)-thick rolled homogeneous armor steel plate welded onto the up-range side of the blast mitigation wall. This experimental setup was used to minimize the warhead debris field from traveling downrange and obscuring the view of the high-speed camera.

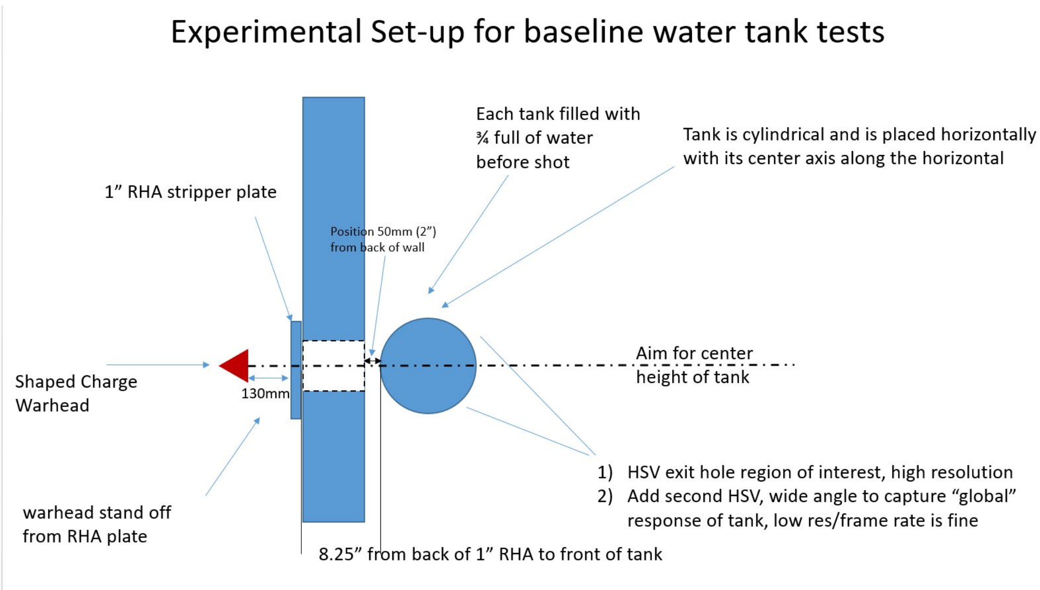

Fig. 1 Initial setup

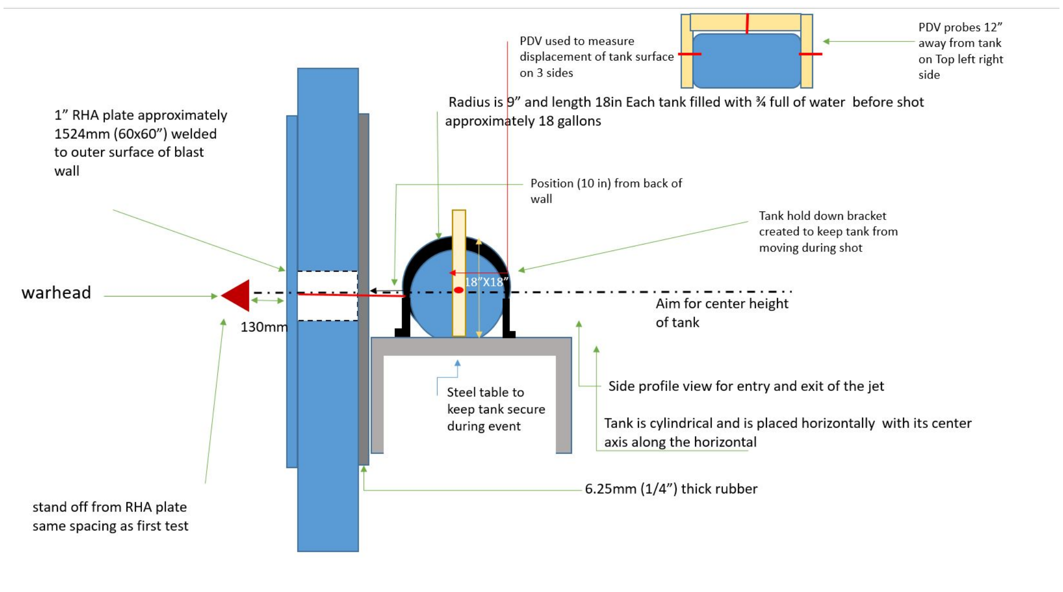

Fig. 2 Revised setup to minimize debris field

Fig. 3 Baseline experimental configuration (downrange)

Fig. 4 Baseline setup showing 65-mm shaped charge jet warhead up range of blast wall

Figures 5, 6, and 7 show high-speed video screen captures for the baseline 1/32-, 1/16-, and 3/16-inch-thick walled fuel tanks, respectively, at 1.5 ms after the shaped charge is detonated. A very distinct stream of fine particulate fluid can be seen engulfing the shaped charge jet as it travels downrange of the fuel tank. Figure 8 shows a photograph of the exit holes of each of the fuel tanks after the baseline experiments were competed. The thinnest wall tank, 1/32 inch, had a large exit hole measuring approximately 6 inches (152 mm) in diameter, which caused structural failure at the weld seams and along its horizontal length. The 1/16-inch-thick tank was bulged at the seams but did not have catastrophic structural failure; it had an exit-hole diameter of approximately 4 inches. Finally, the 3/16-inch-thick tank showed no signs of bulging and had the smallest exit hole, 1 inch in diameter. Due to the significant structural failure of the 1/32-inch-thick tank, it was not used for any follow-up experimentation.

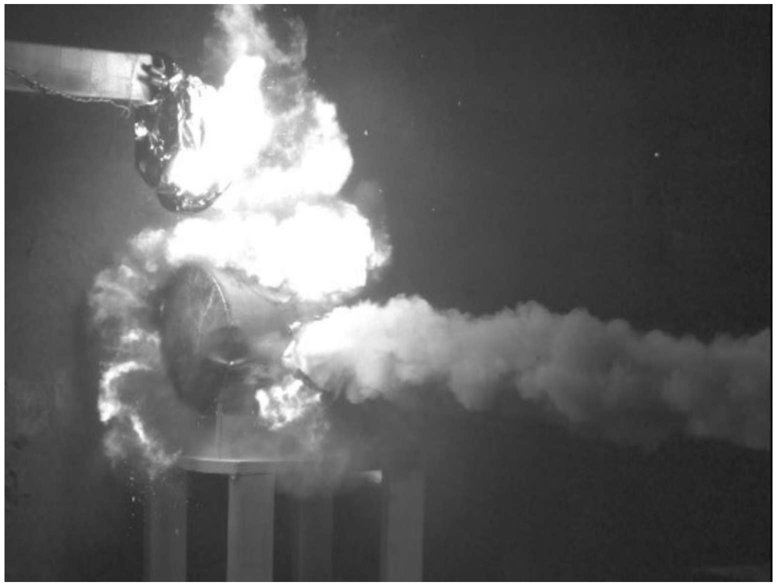

Fig. 5 High-speed video screen capture (rear view) of a shaped charge jet exiting the tank with 1/32-inch wall thickness (1.5 ms after detonation)

Fig. 6 High-speed video screen capture (rear view) of a shaped charge jet exiting the tank with 1/16-inch wall thickness (1.5 ms after detonation)

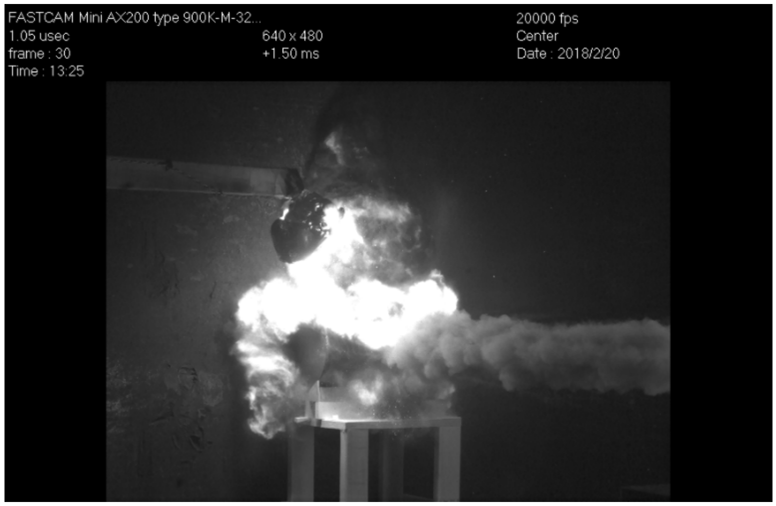

Fig. 7 High-speed video screen capture (rear view) of a shaped charge jet exiting the tank with 3/16-inch wall thickness (1.5 ms after detonation)

Fig. 8 Exit holes of 1/32-, 1/16-, and 3/16-inch-thick steel fuel tanks

2.2 Inner-Liner Fuel Tank Experiments

The next series of experiments was conducted to evaluate whether an inner fuel tank liner could minimize the rate of fluid loss and possibly clog the entry and exit holes shortly after the shaped charge jet perforates the fuel tank. The approach relies on the abrupt internal overpressure from the hydraulic ram to rapidly "pump" or "push" the liner material through the same hole that is created by the shaped charge jet. To be effective, the rate at which the liner backfills the entry and exit hole would need to be commensurate with the rate at which the fluid is escaping from the fuel tank.

These inner-liner experiments used the same setup as shown in Fig. 2. The fuel liner experiments used the 3/16-inch-thick walled tank. The fuel tank was filled 75% full of water to simulate a partially filled tank exactly like the baseline experiment. Rubber and Kevlar felt liners were evaluated in these experiments.

The first experiment was prepared with two layers of 1/4-inch (6.4-mm)-thick rubber placed inside the tank and held against its inner walls with expanded metal wire mesh. These experiments used the 3/16-inch-thick walled fuel tanks; the results from this experiment are shown in Figs. 9–11. The rate of fluid loss observed by the high-speed video, albeit qualitative, was reduced at comparable time steps. Though it is difficult to see in the postevent photo, the rubber inner liner had a significantly smaller hole size in comparison with that of the hole in the metal fuel tank. When comparing the fuel tank's damage to that of the 3/16-inch-thick walled baseline fuel tank the hole size was drastically decreased as well. The rubber did not, however, clog the entry or exit hole of the metal fuel tank as was the expectation. The next inner-liner experiment used Kevlar felt (Figs. 12–14). No distinct differences were observed between the Kevlar felt liner and the rubber liner experiments; the performance of either the rubber or Kevlar was such that they did not clog the holes.

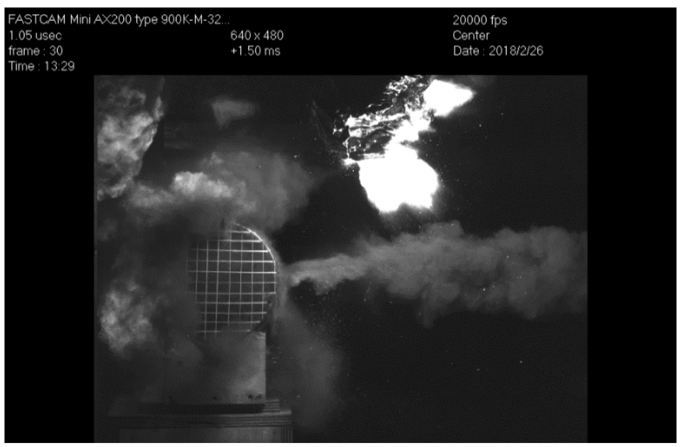

Fig. 9 High-speed video screen capture (side view) of shaped charge jet exiting 3/16-inch-thick fuel tank with double wrap of 1/4-inch inner rubber liner 1.5 ms after detonation

Fig. 10 Entry hole of 3/16-inch-thick fuel tank with double wrap of 1/4-inch inner rubber liner

Fig. 11 Exit hole of 3/16-inch-thick fuel tank with double wrap of 1/4-inch inner rubber liner

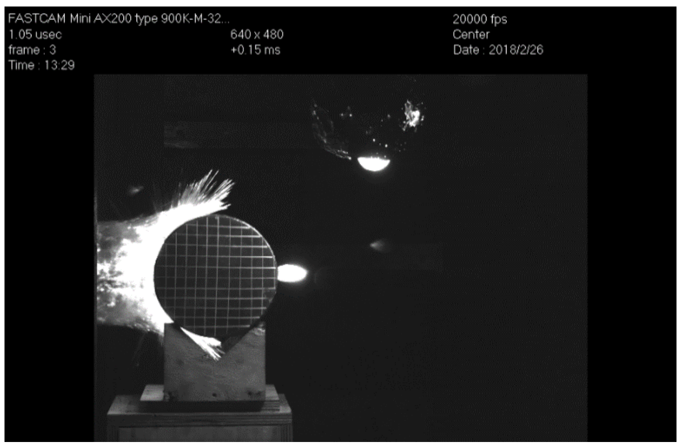

Fig. 12 High-speed video screen capture (side view) of shaped charge jet exiting 3/16-inch-thick fuel tank with double wrap of 1/2-inch inner Kevlar felt liner 0.15 ms after detonation

Fig. 13 Entry hole of 3/16-inch-thick fuel tank with double wrap of 1/2-inch inner Kevlar felt liner

Fig. 14 Exit hole of 3/16-inch-thick fuel tank with double wrap of 1/2-inch inner Kevlar felt liner

To better understand the inner-liner interaction with the fluid in the tank undergoing hydraulic ram, a 3/16-inch-thick fuel tank was fabricated with polycarbonate endcaps, which enabled viewing the shaped charge jet as it passed through the fuel tank. The endcaps were clamped tightly to both sides of the cylindrical tank using threaded rod. Two of these fuel tanks were evaluated. The first polycarbonate endcap experiment used the baseline configuration (no inner or outer wraps) and the second experiment used a Kevlar inner liner. The results are shown in Figs. 15–20. This alternative viewing method failed to yield higher-quality information due to the rapid creation of microbubbles in the fluid. The bubbles formed upon wave reflection with the inner wall or liner of the fuel tank. The creation of these bubbles immediately hampered the view port on the endcaps of the tanks. This obscured any further viewing of the high-speed camera shortly after the shaped charge jet passed though the fuel tank.

Fig. 15 High-speed video screen capture (side view) of shaped charge jet at exit of a 3/16-inch-thick tank with 1/2-inch polycarbonate (transparent) endcaps 0.233 ms after detonation

Fig. 16 Postevent photo of 3/16-inch-thick tank with 1/2-inch polycarbonate endcaps

Fig. 17 Partial build view of 3/16-inch fuel tank with Kevlar inner liner and 1/2-inch polycarbonate endcaps

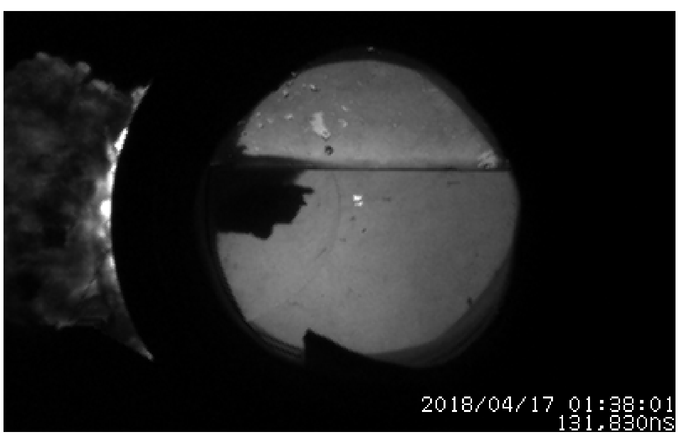

Fig. 18 High-speed video screen capture (side view) of a shaped charge jet just entering a 3/16-inch-thick tank with Kevlar inner liner and 1/2-inch polycarbonate endcaps, at 0.132 ms after detonation

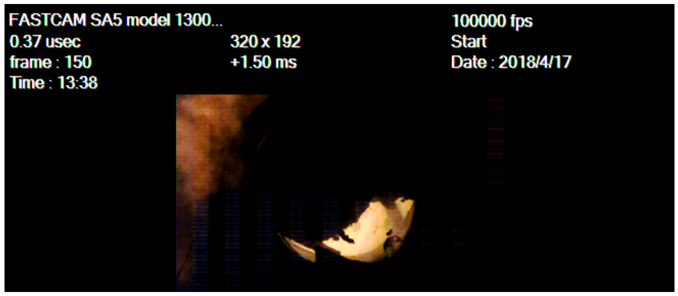

Fig. 19 High-speed video screen capture (side view) of a shaped charge jet after exiting a 3/16-inch-thick tank with Kevlar inner liner and 1/2-inch polycarbonate endcaps, at 1.5 ms after detonation

Fig. 20 Postevent photo of 3/16-inch-thick tank with Kevlar inner liner and 1/2–inch polycarbonate endcaps

2.3 Overwrap Fuel Tank Experiments

The purpose of the next series of experiments was to evaluate if an overwrap on the fuel tank could reduce the damage and possibly minimize the rate of fluid loss when overmatched by a shaped charge jet. In this case, the 1/16-inch-thick steel fuel tank was used. Recall that when the baseline 1/16-inch-thick tank was evaluated, bulging was observed from overpressure, but no catastrophic structural failure occurred. Moreover, the hole was noticeably larger than that seen in the baseline 3/16-inch-thick steel fuel tank. The rationale for using the thinner tank for these overwrap evaluations was so any improvements made to the tanks could be more easily observed.

As with the previous experiments a Kevlar composite and rubber were evaluated for effectiveness as overwrap protection. A single outer wrap of 1/2-inch-thick rubber, as well as both a 20- and 40-layer overwrap of Kevlar, was evaluated. Each of the Kevlar layers was approximately 1/16-inch thick, making the total outer wrap between 1.25 and 2.5 inches (31.8 and 63.5 mm) in total thickness. The rubber overwrap experiment (Figs. 21–26) showed that the damage caused to the 1/16 inch-thick walled tank was decreased when compared to the baseline 1/16 inch-thick walled fuel tank. The postexperimental comparison between the baseline and rubber overwrap are shown in Figs. 8 and 26. The postexperimental analysis showed that the peeling back of the tanks' edges was decreased by the protective outer layering of the wrap. It was speculated that the rubber overwrap may have been responsible for protecting edges from ripping wider during the hydraulic-ram response due to its ability to knock down debris and absorb shock from the tank.

Fig. 21 1/16-inch-thick steel tank with 1/2-inch rubber overwrap (pre-event) on the experimental stand

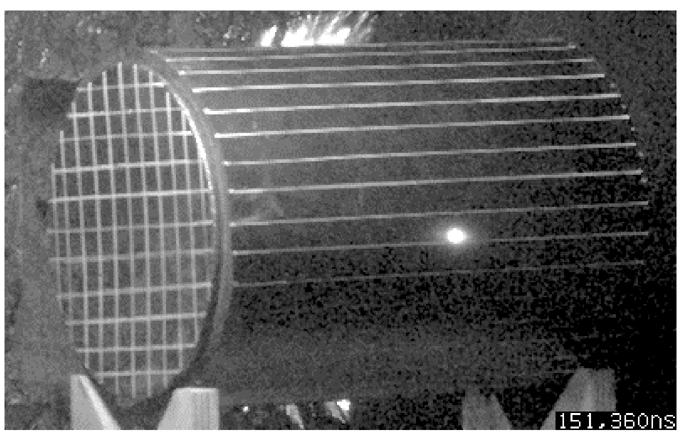

Fig. 22 1/16-inch-thick steel tank with 1/2-inch rubber outer wrap, 0.151 ms after shaped charge detonation

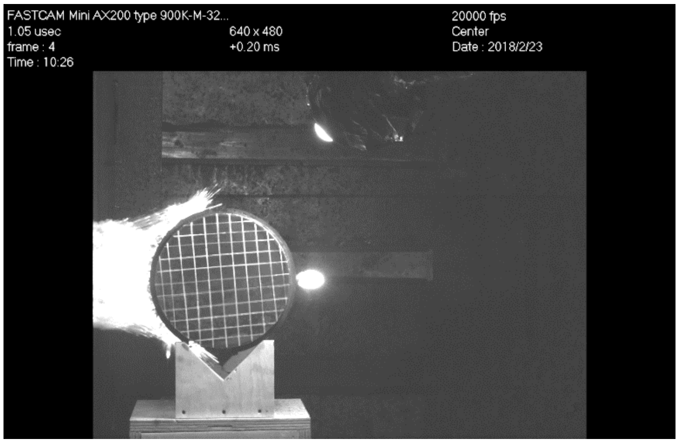

Fig. 23 1/16-inch-thick steel tank with 1/2-inch rubber outer wrap, 0.200 ms after shaped charge detonation

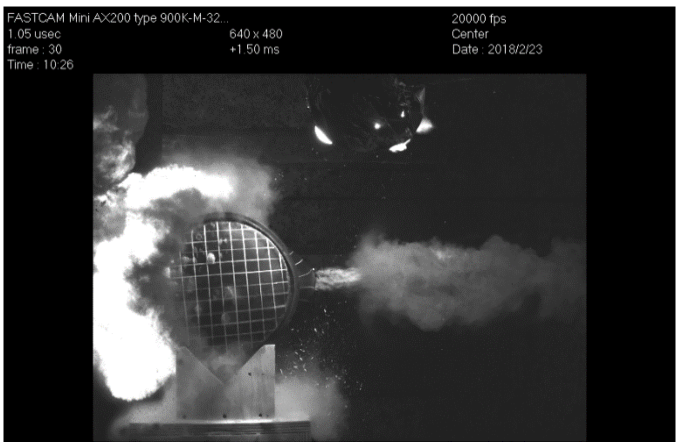

Fig. 24 1/16-inch-thick steel tank with 1/2-inch rubber outer wrap, 1.5 ms after shaped charge detonation

Fig. 25 Postevent photo of 1/16-inch-thick steel tank with 1/2-inch rubber outer wrap (removed), entry hole

Fig. 26 Postevent photo of 1/16-inch-thick steel tank with 1/2-inch rubber outer wrap (removed), exit hole

Two final overwrap comparison experiments were performed with approximately the 1.25-inch (20-ply) equivalent thickness of Kevlar and 2.5-inch (40-ply) equivalent thicknesses of Kevlar weave. Photos of the 1/16-inch-thick tank with the Kevlar weave wrap can be seen in Fig. 27. For the overview and results see Figs. 27–32. Information gathered from these two experiments suggested the multilayering of Kevlar wound tightly on the tank's surface increased the effective hoop strength of the tanks, thereby changing the force distribution on the tank's surface during the event. This can be seen specifically in Fig. 32 where the exit hole is decreased over that of the baseline but the endcaps have failed. This variation in additional protection both helped decrease hole size and also effectively made the Kevlar-overwrap experimental tanks fail due to the introduction of a weak point in the tank's configuration. Both of the Kevlar overwrap experiments show similar damage and performance. Postevent findings suggest there is little to no difference in fuel tank hole size performance between Kevlar overwraps and rubber overwraps. However, the drawback of additional hoop strength generated by the Kevlar overwraps, causing the tanks to fail at the weld seams, negates the beneficial effects of the reduced hole sizes for Kevlar.

Fig. 27 1/16-inch-thick steel tank with 20-layer Kevlar overwrap (pre-event) on the experimental stand

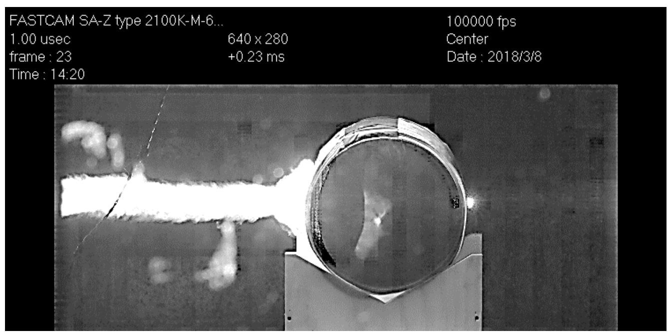

Fig. 28 Shaped charge jet pass through of 1/16-inch steel tank with 20-layer Kevlar overwrap 0.230 ms after detonation

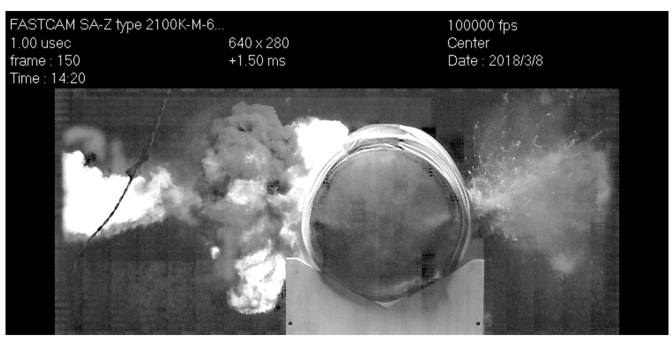

Fig. 29 1/16-inch-steel tank with 20 layers of Kevlar wrap 1.5 ms after shaped charge jet detonation (closeup view)

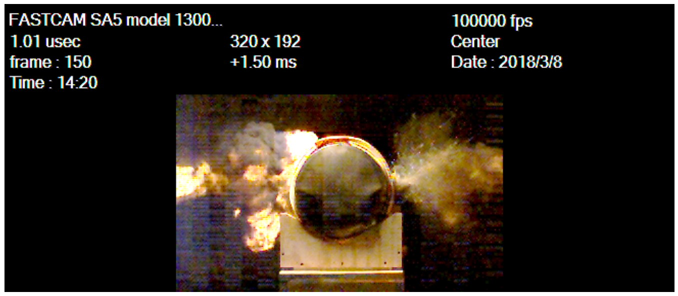

Fig. 30 1/16-inch steel tank with 20 layers of Kevlar overwrap 1.5 ms after shaped charge jet detonation

Fig. 31 1/16-inch steel tank with 20 layers of Kevlar wrap (removed), entrance hole

Fig. 32 1/16-inch steel tank with 20 layers of Kevlar wrap (removed), exit hole

The last overwrap concept evaluated used a pressurized hose loaded with powder to simulate a fire retardant as an overwrap. The fiber-reinforced rubber hose was approximately 45 ft (13.7 m) long with a 3/4-inch (19.1-mm) outer diameter and a 1/2-inch (12.7-mm) inner diameter. It was wrapped around the outside of the 1/16-inch-thick cylindrical-shaped tank in a single layer, close packed as shown in

Fig. 33. The hose was partially filled with simulated fire-suppressive powder and firmly wrapped around the tank prior to being placed on the v-block experimental stand. It was then pressurized to 100 pounds per square inch. The objective of this experiment was to observe the rate at which the powder was extinguished from the hose in comparison to the exit rate of fluid during the event of the shaped charge jet passing through the tank. The results from high-speed video screen captures (Figs. 34 and 35) show the powder was exhausted local to the shaped charge jet impact site at a rate commensurate with the fuel flow.

Fig. 33 Concept view stainless steel tank

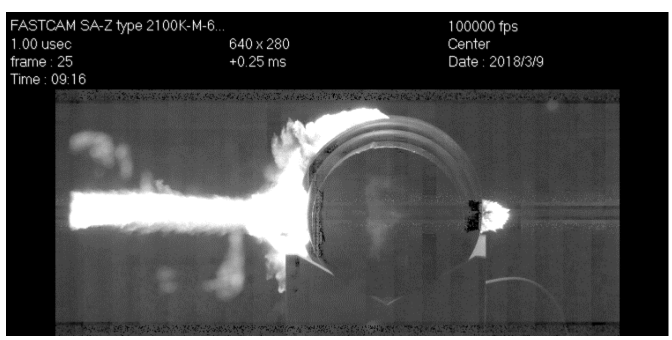

Fig. 34 1/16-inch-thick walled tank 3/4-inch outer diameter pressurized rubber hose wrap at 0.25 ms after shaped charge jet detonation

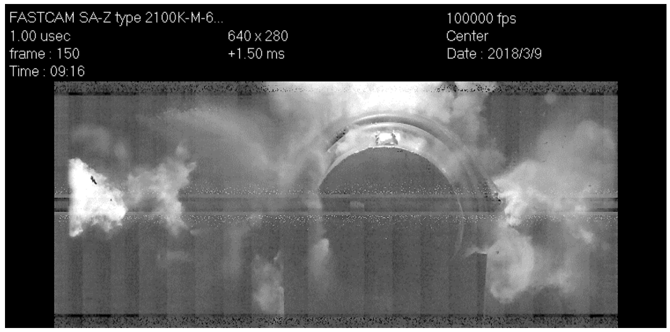

Fig. 35 1/16-inch-thick walled tank 3/4-inch outer diameter pressurized rubber hose wrap at 1.5 ms after shaped charge detonation

2.4 EFP Fuel Tank Experiments

Three experiments were performed using EFPs as ballistic threats. For these engagements, a 135-mm-diameter EFP lab device that forms a train of copper particles was chosen. An 18-inch-diameter by 18-inch-long tank made of 3/16-inch-thick 304 stainless steel was used as the experimental vessel as shown in Fig. 36. The engagement path across the transverse axis of the tank, the experimental setup, and configurations remained the same as previously used for the shaped charge jet engagements. To create a baseline, the tank was shot by the EFP with the tank void of any liquid. An unfilled tank was used because there would be a better chance of tank survival without hydraulic ram effects. The results showed that the tank took severe damage even without the hydraulic ram. The hole size was approximately 5–6.5 inches (127–165 mm) in diameter with multiple perforations around its edges due to fragments from the EFP as shown in Figs. 37 and 38. The next experiment was identical except the tank was filled to 75% of its internal volume with water (Figs. 39 and 40). The engagement with the EFP resulted in the endcaps being blown off by the hydraulic ram, which also introduced ripping along the outer surface of the tank resulting in failure across its axis.

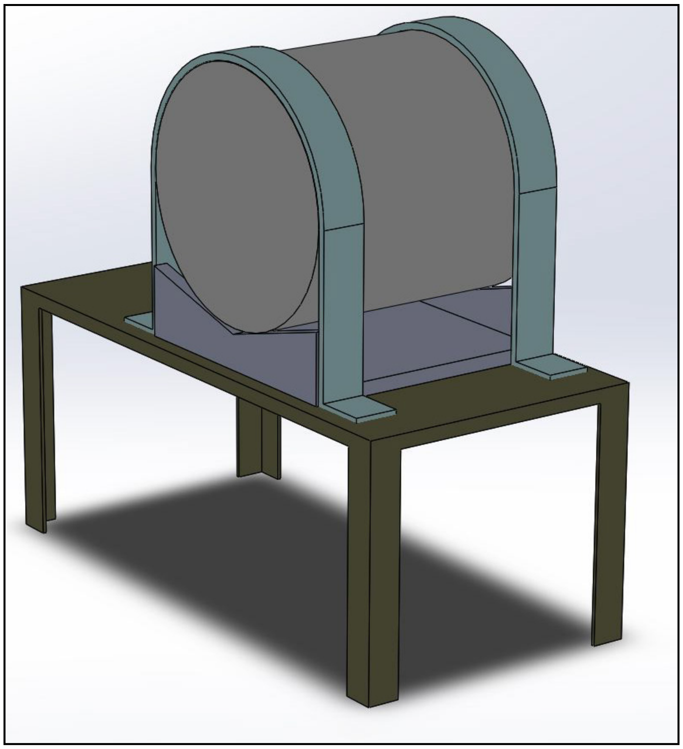

Fig. 36 EFP experimental stand and tank configuration

Fig. 37 EFP engagement postevent damage of a 3/16-inch stainless steel tank, exit hole

Fig. 38 EFP engagement postevent damage of a 3/16-inch stainless steel walled tank, entrance hole

Fig. 39 EFP engagement postevent debris of a 75% filled 3/16-inch-thick stainless steel tank (note remains and the exit-hole location)

Fig. 40 EFP engagement postevent damage of the tank bindings with debris for the 75% fill 3/16-inch-thick stainless steel tank

The final experiments performed in this series deviated from the previous experiments by investigating the effects of a double walled tank. The same threat and experimental setup were used except a double walled 3/16-inch tank with a 1-inch air gap and polycarbonate endcaps were used in place of the single walled 3/16-inch stainless steel tank (Fig. 41) in an effort to determine if the double walled air gap could help mitigate the forces acting on the tank as the EFP particles pass through. The results from this engagement indicated that the air-gap standoff was insufficient to withstand the energy of the EFP and the resultant hydraulic ram forces enacted upon the tank's structure (Figs. 42 and 43).

Fig. 41 **Pre-event, 75% filled 3/16-inch stainless steel double walled tank with polycarbonate endcaps for EFP engagement experiment**

Fig. 42 **Postevent, 75% filled double walled 3/16-inch stainless steel tank EFP engagement, EFP particle entry location**

Fig. 43 Postevent, 75% filled double walled 3/16-inch stainless steel tank EFP engagement tank debris

3. Conclusions

Multiple wall thicknesses were assessed for perforation of 12-inch-diameter by 18-inch-long cylindrical fuel tanks by a 65-mm-diameter copper shaped charge warhead. The 1/32-inch-thick steel tank failed structurally at the welds. The structure of the 1/16-inch-thick steel tank bulged, but the welds did not fail and the nominal entry and exit hole diameters were 4 inches. The thickest steel tank had a 3/16-inch wall, which showed very little signs of structural bulging and had a nominal entry and exit hole diameter of 1 inch. Hole diameter directly relates to the fuel tank's thickness and fill volume.

When inner liners of rubber or Kevlar were added to the baseline 3/16-inch-thick steel fuel tank, the smaller holes in the liner material lead to a lower rate of fuel/water loss, as observed on high-speed video. However, the configurations that used inner liners did not achieve the desired result of completely clogging the entry and exit holes of the fuel tank. More design considerations and subsequent experimentation is needed.

When outer wraps of rubber or Kevlar fabric were added to the 1/16-inch-thick steel fuel tank, the size of the entry hole, exit hole, and fluid loss (as observed on high-speed video) was lessened. The amounts of debris from the threat that perforated the outer tank's surface were reduced, allowing for improved postshot tank condition. New diagnostics are being considered to quantify rate of fluid loss.

A fuel tank wrapped with a pressurized hose loaded with powder to simulate a fire retardant was evaluated. The high-speed video showed that the powder was exhausted local to the shaped charge jet's impact site and at high rates relative to the event occurrence. This approach of using a continuous hose to provide outer wrap structural reinforcement/protection against fragments as well as fire suppression at the damaged area showed promise. When the tank was struck by the shaped charge jet, this protection method exhausted its contents at a relevant time rate to that of the shaped charge jet passing through the tank. It also provided additional outer protection to the tank by knocking down small debris.

When exposed to an overmatching threat such as a 135-mm-diameter EFP, there is catastrophic damage to the fuel tank. It appears a major redesign would be required to improve the fuel tank's survivability. Otherwise, a mechanism for jettisoning a fuel tank immediately after an EFP engagement could be used as an alternative way to maximize the distance between the subsequent pool fire and the vehicle.

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