Ballistic Testing of Pressurized Hydrogen Storage Cylinders

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Abstract: *Hydrogen fuel cells have potential as future power sources for military vehicles and power generation systems. Hydrogen storage as a compressed gas presents several safety concerns in military applications. In order to optimize future design and integration work, these risks need to be investigated and understood. This work investigates the behavior of a pressurized hydrogen storage cylinder when penetrated by a ballistic threat, perhaps the greatest safety concern in a military application.*

Keywords: fuel cells; fuel processing and storage; hydrogen storage; hydrogen safety; ballistic test

Introduction

The United States Army Tank Automotive Research, Development and Engineering Center (TARDEC) has been investigating hydrogen fuel cells for primary and auxiliary power sources in ground vehicles. Specifically, polymer electrolyte membrane (PEM) fuel cells have been under study, as they operate cooler, quieter and more efficiently than gasoline or diesel burning engines. PEM fuel cells require ultra-high purity (99.999% or greater) hydrogen in order to operate, as any impurities can damage the catalyst inside. In order to supply this hydrogen to the fuel cell, hydrogen is stored on the vehicle in storage cylinders and compressed to either 5,000 pounds per square inch (psi) or 10,000 psi depending on the application. This high pressure method of storing hydrogen is a safety issue that warrants thorough testing.

Currently there are two tank designs (types) used for storing hydrogen, depending on the pressure. Cylinders that store hydrogen at 5,000 psi are typically Type III tanks, while those that store it at 10,000 psi are Type IV. Type III tanks are composed of an aluminum liner wrapped with carbon fiber and resin; Type IV tanks contain a composite liner also wrapped in carbon fiber and resin. The cylinders tested demonstrate pressurized storage and can be used to answer several frequently asked questions regarding the safety of pressurized hydrogen storage.

As part of the manufacturing and certification process, cylinder builders are required to subject the storage tanks to several abusive tests but some possible military applications can be more abusive than the tests required for certification. Several investigations have been conducted to investigate the safety of hydrogen cylinders for commercial and civilian use [1-4], yet none have investigated cylinders pressurized with hydrogen exposed to incendiary rounds or rocket propelled grenades. In order to test the safety of hydrogen storage cylinders in a military application, several different types and makes of cylinder were subjected to live fire testing. The purpose of this testing was to discover any safety issues that result from a tank being punctured by several types of ballistic rounds and a rocket propelled grenade (RPG) while pressurized with hydrogen gas.

Test Conditions

In order to perform testing in a safe and controlled manner, a surface danger zone (SDZ) of 100 yards was established to prevent any possible injury [5]. Only remotely controlled equipment (cameras) were permitted inside the SDZ while the range was hot. To capture data, a high speed camera and several real time cameras were placed in doghouses around the range, focused on the cylinder and impact zone. A thermal camera was placed downrange in order to monitor possible thermal events, such as a flame due to hydrogen's nature to burn in the ultraviolet spectrum causing difficult visualization in daylight [6].

During ballistic testing, the launcher was placed just outside the SDZ, allowing the launcher to be reloaded in case of a miss or unconfirmed hit on the pressurized cylinder. Some of the cylinders had electronic pressure release devices that could not be opened on the test site. As such, the range was only declared safe after penetration and venting of the cylinder's contents was confirmed via video review. A static RPG was used to simulate an RPG strike directly on a cylinder. The RPG was placed within a few inches of the cylinder, armed, and then remotely detonated. Table 1 presents the type of cylinder, pressure, and round fired for each test.

Table 1: Initial cylinder and test conditions

Manufacturer	Type	Pressure (psig)	Round Type
Quantum	IV	0 (empty)	7.62 M80 Ball
Worthington	III	3,500	7.62 AP
Quantum	IV	3,200	7.62 API
Luxfur	IV	3,100	7.62 AP
Worthington	III	3,200	7.62 AP
Quantum	IV	3,000	RPG

Results

After several practice shots to sight in the launcher, an empty Quantum tank was used as a control for the test. Two (2) 7.62 ball rounds and one 7.62 armor piercing (AP) round were fired at the cylinder in order to determine if the round could penetrate a tank. The results of these shots were inconclusive. The rounds all clearly struck the cylinder, yet an entry was not clear. Several attempts to probe the entry holes could not determine if the round had completely penetrated the wall of the cylinder. It was thought that the composite liner inside the cylinder had swollen around the entry hole, prohibiting a probe to go through the wall. Though penetration was unable to be determined, the test was continued as several cylinders were equipped with electronic pressure releases that could not be safely depressurized in the field. 7.62 AP rounds were chosen as the default round to increase the probability of penetration. After the test concluded, the control cylinder was cut open to determine if the rounds had penetrated since the entry holes could not be probed in the field. Upon opening the cylinder, a single round was found inside, the armor piercing

Figure 1: Control cylinder after three initial test shots. The arrows indicate where the rounds hit the cylinder.

round. The entry hole had not swollen, the carbon fiber wrapping of the tank layered back on top of itself making it difficult to probe through. The inside of the cylinder was inspected and no other entry holes were found where the two other rounds had hit the outside of the cylinder. The liner did become slightly delaminated from the wrapping due to the impact even though the cylinder was not pressurized.

The first test with a pressurized cylinder involved a Type III tank that was penetrated with the AP round. The tank began to vent instantly and the round visibly bounced around inside the cylinder, ricocheting off of the aluminum liner leaving marks on the outer composite wrap where it dented the liner. The round did not exit the cylinder. The liner remained intact except for a few broken fibers at the entry hole. There was no fire observable or detected. The temperature of tank changed drastically as the gas escaped from the entry hole, as was expected. The tank took approximately 5 minutes to vent its contents to the atmosphere.

The second test of a pressurized cylinder was a Type IV tank penetrated by an armor piercing incendiary (API) round. The

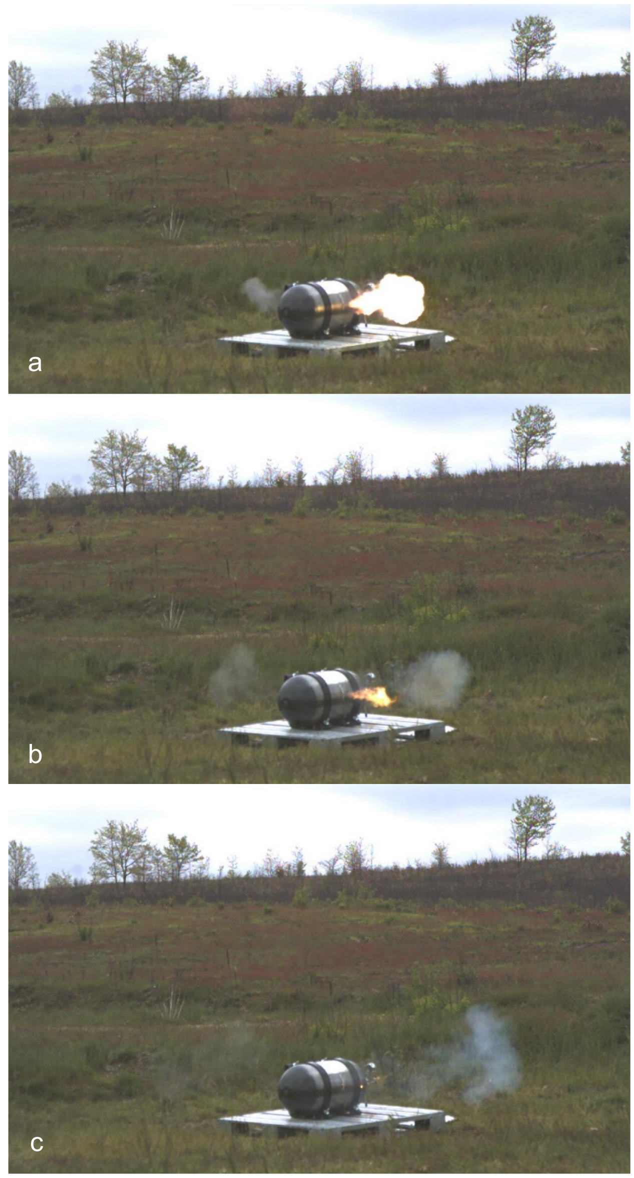

Figure 2: 7.62 API test after impact: (a) the initial flame jet after penetration along with visible exit plume, (b) flame jet sustained briefly while particulates burn off and transitions to a near-invisible hydrogen flame, (c) small flame from a residual particle passing through the near-invisible hydrogen flame.

round penetrated both walls of the cylinder, clearly entering and exiting. The entry hole immediately began to vent, the venting hydrogen mixed with the air, and the incendiary nature of the round ignited the escaping gas mixture. The gas venting from the exit hole did not ignite. The flame was visible after it ignited due to the particulates in the air around the penetration and then quickly became invisible after the particulates burned off. The sustained flame was detectible on the thermal camera and as some residual carbon fiber exited the tank, as seen in Figure 2c. The escaping gas continued to burn for 20 minutes after the initial penetration until all of the hydrogen had been consumed. The flame jet never grew larger than shown in Figure 2b, shrinking gradually as the hydrogen concentration decreased.

The third cylinder tested was also a Type IV tank from a different manufacturer. A 7.62 AP round was fired at it and it penetrated both walls of the cylinder, clearly entering and exiting. The round first penetrated the steel mounting strap used to hold the cylinder to the pallet before passing through the cylinder wall and through the other side. The exit hole had several strands of frayed carbon fiber wrapping surrounding it, along with bubbles trapped in the surface resin layer due to the venting hydrogen. The tank vented completely in about 5 minutes with no indication of ignition.

The final cylinder tested with a 7.62 AP round was a Type III tank from the same manufacturer as the first test. The tank was penetrated through one of the straps holding it to the pallet and out through the opposing wall. The tank vented completely in about 5 minutes without any ignition of the hydrogen.

The static RPG was fired at a Type IV cylinder. The RPG detonation caused a large jet of liquid metal to be shot through the cylinder. This jet can be seen in Figure 3a. After the RPG was fired, a large cloud of debris and flame enveloped the test site. After the debris began to clear, the burning hydrogen could be observed. A tail of flame was observed coming from the exit hole formed by the RPG. After the hydrogen had completely evacuated the cylinder,

Figure 3: RPG impact: (a) the initial detonation of the RPG with initial jet, (b) flame tail sustained briefly after RPG penetration.

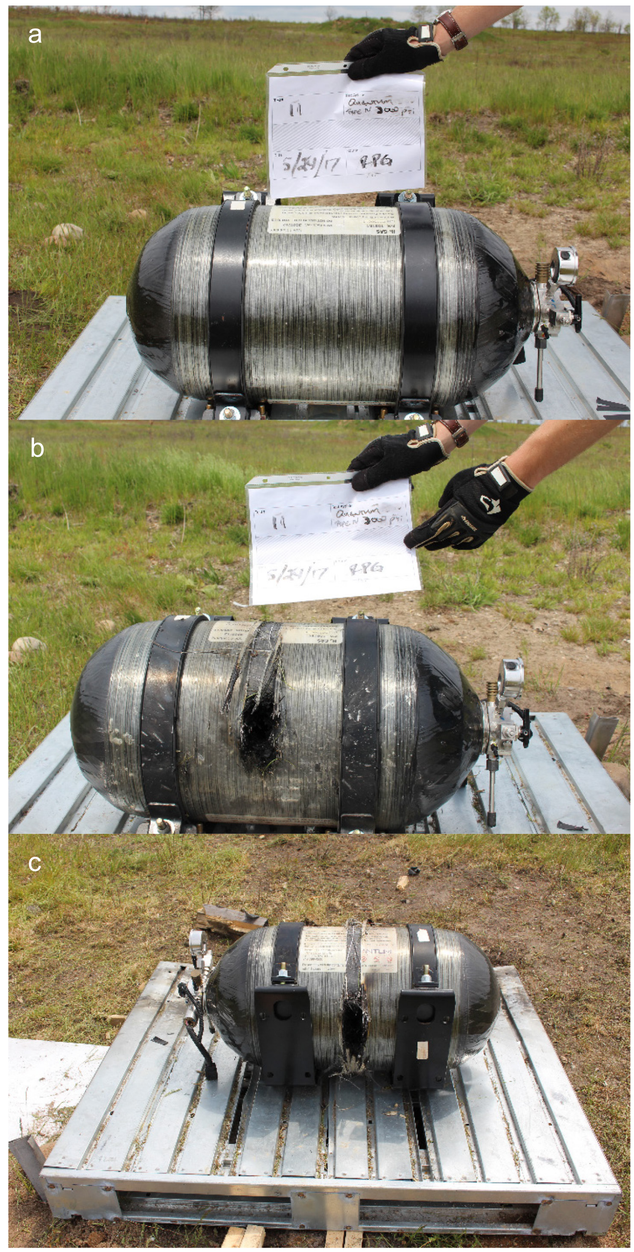

Figure 4: Cylinder before and after RPG test: (a) cylinder before test, (b) cylinder with entry hole from RPG, (c) exit hole from RPG.

which took around one minute, the cylinder was observed to be intact. Figure 4 shows large entrance and exit holes and a strip of the outer layer of carbon fiber wrap on the top side of the cylinder was missing in between the holes. The cylinder did not rupture or burst in a destructive manner, even with the close proximity of the explosive.

Conclusions

In the ballistic live fire test, hydrogen storage tanks pressurized with hydrogen were exposed to three common types of 7.62 rounds, M80 ball, armor piercing, and armor piercing incendiary. It was found that M80 ball rounds may not penetrate Type IV tanks. Only the armor piercing round penetrated the cylinder. When penetrated by AP rounds, the cylinder will vent quickly without producing a flame. The cylinder will not catastrophically fail when pierced by a round, retaining its structural integrity and venting its contents safely. A recommended best practice for future fuel cell vehicle design is to add a vertical vent path around the hydrogen storage cylinders to the roof of the vehicle in order to allow hydrogen to escape quickly in the event of a hit, reducing the chance for hydrogen to accumulate to flammable and explosive concentrations in air [7].

Perhaps the largest threat to hydrogen storage cylinders are armor piercing incendiary rounds. When penetrated with an API round, the gas escaping from the entrance hole could possibly ignite and burn for 20 to 30 minutes. Due to hydrogen's nature to burn in the ultraviolet, a flame is invisible to the naked eye in daylight and faint in dark conditions making it difficult to identify. A thermal or ultraviolet camera is required to determine if there is a flame present. In order to reduce the chance of a complete vehicle fire, it is recommended to surround the cylinders in nonflammable material and a vertical vent, as mentioned previously. While this is a dangerous case, the buoyant nature of hydrogen causes it to travel away from the cylinder and upwards when penetrated [7]. This behavior reduces the risk of a total vehicle fire when compared to liquid fuels, which can pool below the vehicle, spread to other extremely flammable components (such as tires), and result in the entire vehicle becoming engulfed in flames [8]. Hydrogen flames radiate little heat, reducing the chance that nearby material will be ignited by the flame unless in extremely close proximity.

When struck by a rocket propelled grenade, a Type IV hydrogen storage cylinder will be penetrated through both walls and vent quickly with a short burn off period. The tank will not catastrophically burst and produce limited shrapnel, mostly carbon fiber and resin strands with relatively little mass and no sharp edges. Limited resources and uncertain availability of range personnel only allowed for one shot with an RPG to take place. Without a control to compare against, any claims of increased or decreased impact due to the presence of hydrogen is subjective at best. With that in mind, engineers familiar with RPG testing claimed that the impact of the RPG on the hydrogen cylinder was close to that of an impact with an inert target, signifying that hydrogen may not contribute significantly to the explosive force of the impact. Further testing is required to validate this claim.

Understanding the risks involved with hydrogen storage will allow for systems to be intelligently designed, mitigating most risks. While hydrogen presents several concerning properties, the risks associated with storing it are not entirely dissimilar to liquid fuels that are currently used. Storing the hydrogen at pressure will not cause any more significant safety issues than liquid fuel in the event of a ballistic penetration or explosion due to the inherently safe design of the storage systems.

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