BALLISTIC EVALUATION OF FIRE PANEL FUEL TANK PROTECTION DEVICE FOR MILITARY VEHICLES - UPDATE

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INTRODUCTION

At last year's HOTWC meeting a paper was presented concerning several Commercial Off The Shelf (COTS) fire protection technologies whom might have some utility in military or other public sector applications, and some of which have a pedigree in prior military development as a type of "cross-pollination" of technology between the public and private sectors. One of the technologies described was the FIRE Panel fuel tank protection device, a commercial form of the powder panel concept also evaluated recently by the Next Generation Fire Suppression Technology Program (NGP). Amongst the current applications described at the time for the product, including the protection of police vehicle fuel tanks, was the imminent consideration by the U.S. Army of the device to protect the fuel tanks of their Tactical Wheeled Vehicles, which could also include utility and fuel truck vehicles, from ballistic impacts in combat, and the resultant fires that occur. This paper discusses the results of a series of ballistic tests performed over the past year by the U.S. Army in evaluating the technology for this application in a generic fuel tank configuration, with consideration of integration on specific platforms. Some plans for further evaluation and deployment are also discussed, as well as recent "real world" deployments of the FIRE Panel in actual police car collisions on the highway.

THE POWDER PANEL CONCEPT

In the late 1970s, the British Ministry of Defence [1, 2] devised a concept of preventing the occurrence of aircraft fires due to artillery shell impacts into fuel tanks adjacent to bays where the fuel could spill and ignite. This was accomplished by providing containers filled with liquid or powderized fire extinguishants in the shot lines of the projectile, which would thus rupture and disperse the extinguishant in the bay as when the fuel tank was also impacted. The discharged fuel spray and leak would then encounter the extinguishing medium as it interacted with incendiary particles and other ignition sources simultaneously, in effect "pre-inerting" the volume and preventing the ignition of the fuel. This concept was demonstrated in military trials with several derivatives and packaging embodiments, eventually evolving into a flat "powder panel" configuration, with an internal honeycomb core filled with powder extinguishant, as it became subject to investigation in the United States [3]. It was found that panel thicknesses as small as 2.5 mm could protect aircraft fuel tanks from exploding ballistic projectiles [4]. Even more impressive performance was observed by the U.S. Army in their tests [5] of powder panels placed on the interior wall of fuel cells adjacent to the crew areas of armored vehicles, when impacted by large shaped-charge ballistic rounds. It was found that panel thicknesses as small as 6 mm were adequate to prevent ballistically-initiated fuel fires in the crew area. Subsequently, the powder panel device was adopted for use on several military aircraft platforms, including the AH-1W Super Cobra, and the tilt-rotor V-22 Osprey aircraft now entering production. More platforms would have employed the device were it not for the reduced powder dispersion when impacted by small caliber bullets, due to the limited localized tearing of the ductile aluminum foil outer panel surfaces used when it was impacted over a small surface area, resulting in reduced powder discharge efficiency and the requirement to oversize the thickness of the panel to compensate. This increased over design resulted in system weights that were comparable to other options, such as conventional Halon extinguishing systems, in some applications. Additionally, the laborious process of hand fabricating the panels of this design, in a multi-step process of bonding a face sheet to the honeycomb, manually filling the cavities with powder, cleaning the honeycomb edge and bonding the outer face sheet, resulted in product costs that limited its utility to military systems. Many other references documenting the full breadth of military evaluations of the technology for a wide variety of applications are listed in a published Society of Automotive Engineers (SAE) paper [6] written by the author.

These performance and assembly cost issues were addressed in a new configuration [7] devised to improve powder discharge efficiency and ease of manufacture, with an intended focus on crash activation for ground vehicle protection. This configuration comprised a layout of horizontal channels, each independently filled with the dry chemical powder. The channels assure a proper distribution of powder when the panels are mounted vertically to prevent the effects of any settling, but the design also permits mass-production fabrication techniques such as extruding, vacuum forming or most preferably blow molding, which dramatically reduces the unit price in high-volume production. The polymers used to facilitate such production also exhibit an additional benefit of promoting a general “shattering” of the panel when impacted (versus localized tearing), thus promoting the complete or substantial discharge of the panel’s contents upon localized rupturing. When this behavior is coupled with the lengthwise channel design (versus individualized cellular compartments of previous designs), which further supports the emptying of the panel of powder contents at sites remote from the impact location, the capability to discharge most of the powder at high efficiency for a variety of impact scenarios is realized, resulting in a more efficient and lightweight design. The blend of polymers now in use have been specially selected to balance durability against normal incidental contacts, such as dropped tools and rocks thrown from the road at speed, yet facture reliably at energy levels associated with those anticipated to crush or rupture normally-designed fuel tank vessels.

Initial design prototypes of this advanced panel approach were used in competition on Sports Car Club of America (SCCA) Trans Am racing vehicles in 2001, without any negative operational difficulties reported. In the summer of 2002, the panel device, configured for and installed on a Ford Crown Victoria police interceptor (in addition to a fuel tank bladder) using actual gasoline, was tested in a crash test at the Goodrich Aerospace Hurricane Mesa rocket sled test facility. The high-speed (81.9 mph) rear-end impact of a 1970 Ford F-100 pickup truck into the protected vehicle demonstrated it’s powder dispersal capability under realistic crash conditions. This design is now offered commercially as the FIRE Panel product by FIRE Panel, LLC, for police vehicle fuel tanks, racing vehicles and other transportation applications.

The principle of flammable fuel/air mixture instantaneous inertion as exhibited with powder panel approaches such as the FIRE Panel exploits the potential of dispersing inert (or chemically active) heat sink particles into the ignitable mixture. Such an inertant, such as a fine powder mixed within the fuel and air, can inhibit the onset of ignition to prohibit conditions suitable for ignition until the application of ignition source and energy, fuel and air are no longer present in a combined fashion. Such an application provides several modes of inhibition to the ignition process:

(1) providing powder particles having higher thermal conductivity than the surrounding air, thereby extracting heat faster (and with less temperature buildup on the exterior of the particle to otherwise retard the rate of heat exchange) than as it propagates through the surrounding air,

(2) providing “inert” heat sinks that do not add reacting heat generation (as does fuel and air) to offset these losses,

(3) proving a more efficient heat extraction medium outside the immediate reaction zone to dissipate heat quicker than mere air, and with more thermal ballast, before heat can build up locally around the ignition source, and

(4) providing potentially other mechanisms of heat extraction, such as endothermic decomposition reactions, and possibly other chemical inhibitive effects on the combustion chain propagation process.

The Bureau of Mines [8] has been historically interested in the use of flame inhibiting powders to prevent the ignition and propagation of methane gas or coal dust fires/explosions throughout underground mine passages. They constructed an 8-liter flammability chamber to collect precise, controlled data on inerting concentrations of various powders required for stoichiometric fuel/air mixtures of methane or coal dust. Their experiments used a “high temperature, pyrotechnic match”, estimated to be of 35 J in energy level, and which released hot particles upon activation. The duration of burning appeared to last for almost one second. The “success” criteria in terms of preventing ignition and propagation was determined to be the minimization of pressure rise in the chamber due to the heated expanding gas created by ignition.

Using this test setup and criteria, data was collected on the threshold concentrations of various powders (expressed in g/m^3 of air) to prevent the ignition and flame propagation in stoichiometric methane/air mixtures. It was found that as little as 290 g/m^3 of monoammonium phosphate powder (commonly known as “ABC” powder in the industry, since it effectively fights both textile (Class A) and liquid/gas fuel (Class B) fires, and can be safely used on electrical equipment (Class C rating)) was sufficient to prevent sustained combustion, or “inert”, by their criteria. Comparatively, potassium bicarbonate, commonly known as Purple K, required 1,150 g/m^3, potassium bicarbonate and urea complex (commonly known as Monnex) 800 g/m^3, “rock dust” well over 1,000 g/m^3, and nitrogen 400 g/m^3. The authors of this research were not able to completely rationalize the significant performance enhancement of ABC Powder over Purple K, but they speculated that the lower volatilization temperature of ABC powder over Purple K, as well as some related chemical activity of the phosphate component, may explain its performance at lower pre-ignition temperatures, as opposed to the superior performance of Purple K when exposed to fully developed flames. Based upon this data, this author had recommended ABC powder for use in the powder panel devices for most automobile applications, when intended to be exposed to moderately energetic ignition sources of a very localized nature as expected in vehicle collisions. For other applications, such as military units designed to protect against more energetic pyrotechnic and explosive threats that deposit their excessive energy levels into the fuel before mitigation by the powders, other powders with higher performance levels in high-temperature environments, such as Monnex, are often selected for use.

The Bureau of Mines authors also performed additional experiments with Halon in stoichiometric mixtures of methane and air, to determine the influence of ignition energy strengths on required inerting concentrations. It was found that a spark source of several tenths of a joule was sufficiently inerted by a 4% concentration of Halon, whereas the pyrotechnic match of 35 J strength was shown to require an 8% concentration (requiring 500 g/m^3). Their analysis revealed that non-inerted methane/air mixtures resulted in flame temperatures of 2,200 K, near the adiabatic flame temperature for constant volume combustion. However, as a concentration of nitrogen is added at a level that previously provided successful inertion using the 35 J ignition source, a limit flame temperature of 1,500 K is reached (consistent with the published limit flame temperatures for the combustion of saturated hydrocarbons), below which combustion cannot be sustained. However, for 4% Halon, a flame temperature of 1,800 to 1,900 K was observed, well above this limit. The data can be extrapolated to show that the 1,500 K limit would be reached at a Halon concentration of 8%. Thus, it is shown that this level is a more meaningful inertion limit for flame propagation, and the 35 J ignition source is a more practical ignition source to test these limits. If the ignition source is raised to significantly higher levels, higher concentrations of inertant would be necessary as an additional heat sink to overcome the additional heat deposited by those sources. For these reasons, military designers significantly raise the inerting concentrations used in fuel tanks when exposed to larger, more energetic ballistic ignition sources, particularly when pyrotechnic, high explosive materials are added. The key observation from these findings is that when designing an inerting approach and resultant inerting concentration for a particular application, one must design and test against a sufficient ignition source to test the true bulk inertion limits, yet not oversize the energy level of such ignition sources to artificially raise the required concentration levels needed, while also replicating the physical scale of the real ignition source being simulated, the extent of exposure of the ignition discharge region to the environment, and other factors that influence the ignition process in reality.

ARMY EVALUATION OF FIRE PANELS FOR TACTICAL WHEELED VEHICLES

External fuel tanks on ground combat and tactical vehicles are vulnerable to ballistic attacks that can cause hazardous fires. The fires are due to the fact that the tanks are not protected and limited technologies exist to mitigate the resulting fire scenarios. A previous study by Boyd and Skaggs [9] demonstrated that filling fuel tanks with inerting materials did not reduce fire probabilities. However, this work did find that fuel tanks when subjected to certain ballistic threats almost always resulted in sustained fires. The sustained fire observation motivated a follow-up study by Skaggs, Canami and McCormick [10] which evaluated the effect of placing powder panel technologies on generic fuel tanks for reducing fire vulnerabilities from impacting ballistic threats.

EXPERIMENTAL APPROACH

Generic fuel tanks (55 gallon drums) made of polyethylene material were tested against an explosive, battlefield threat projected through the center width with powder panels placed on the tank along the shot line. Figure 1 presents a photograph of the experimental set-up which illustrates the shot line projecting through the middle of the tank, which is approximately 5.08 cm (2 in) below the top of the fuel level.

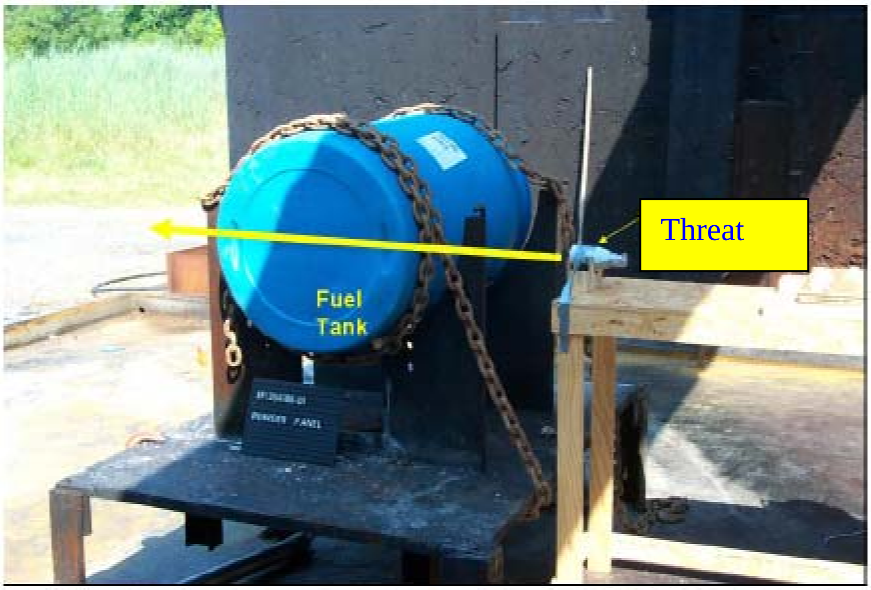

Figure 1. Experimental arrangement for baseline fire evaluation

Each fuel tank was filled to 47% of the total tank volume (26 gallon) with JP8 heated to 20 °F above the measured flash point (approximately 140 °F). The acquired data consisted of high and regular speed video coverage, infrared video coverage, and a submersible pressure transducer. The hydrodynamic ram pressures were measured using a sealed, piezoelectric pressure transducer that was submerged just off the centerline in the fuel tank, and rested at the bottom of the tank. Initial experiments evaluated a fuel tank subjected to the threat without any protection, followed by a parametric study of varying powder amounts in the panel applied to tank to determine fire out times vs. the amount of powder used for protection.

The powder panels were constructed using u-shaped saddles that were 0.5 in thick along the sides
but exhibited varying thicknesses (and resultant powder charge weights) at their base. Figures 2 and 3 show examples of the panels of varying powder charge.

Figure 2. Prototype powder panel (empty of powder)

Figure 3. Filled and installed powder panel and experimental arrangement

The powder used in the panels is a potassium bicarbonate-urea complex originally developed by ICI under the trade name MONNEX, and is intended for use in Class B and C fires.

RESULTS

Experiment 1

The first experiment was conducted with an unprotected fuel tank subjected to the ballistic threat. The interaction of the blast and penetrating force with the fuel tank created a sustained fire that covered the entire experimental site and required the on-site fire department to extinguish. Figure 4 presents a post-experiment photograph of the fuel tank which shows that it had practically melted due to the high intensity fire.

Figure 4. Post experiment photograph of unprotected fuel tank damage due to sustained fire

With the tank becoming completely destroyed, no damage hole measurements could be obtained, however prior experiments with other tanks yielded damage holes approximately 8 cm in diameter in the entry and exit sides. Hydrodynamic ram pressures reached a maximum value of 128.6 psi.

Experiment 2

The second experiment evaluated a 3 in thick (at the base) powder panel that contained 52.6 kg (116.5 lbs) of Monnex powder. No internal tank pressures were recorded due to gage malfunction. The interaction of threat with the tank ignited a flash fire that was extinguished by the powder panel in 143.5 ms, as observed with the high speed video camera. No video coverage was obtained from the infrared camera due to technical difficulties. It should be noted that the entire high speed video screen image at 7.5 ms was washed out, but a visual “hole” developed in the washed out area near the fuel tank and radially expanded until the fire was observed to be extinguished. The fire was primarily located on the threat entrance side of the fuel tank and at its maximum size covered the entire experimental site. The damage holes caused by the threat were measured at the entrance and exit points of the threat into the tank at 2.9 cm and 4.6 cm in diameter respectively. Figure 5 shows that after the experiment a substantial amount of powder had not been dispersed from the bottom as well as powder on the surrounding ground, both of which probably did not contribute to the fire suppression. It was also observed that fuel remained inside of the fuel tank.

Figure 5. Post experiment photograph of 3 in. thick powder panel

Experiment 3

The third experiment evaluated a 2 in. thick powder panel that contained 40.05 kg (88.3 lbs) of Monnex powder. The interaction of the ballistic threat with the tank ignited a flash fire that was extinguished by the powder panel in 178 ms. However, the fire out time observed by the visible camera was obscured by the powder and soot from the fire suppression process. Observations from the infrared video indicated a fire out time of 1.206 s. It should be noted that the entire high speed video screen was washed out at 1 ms, and the fire appeared to reflash until it extinguished. Both the visible and infrared video showed the fire pushing away from the fuel tank over some time until extinguishment. The fire was primarily located on the entrance side of the fuel tank, and its maximum size was approximately 121.92 cm (48 in) in width and 139.7 cm (55 in) tall. The damage hole diameters caused by the threat were measured at the impact entrance and exit points of 12.76 cm and 4.39 cm respectively. Figure 6 shows that after the experiment some powder had not been dispersed from the bottom of the panel, as well as the existence of powder on the surrounding ground, which also probably did not contribute to the fire suppression.

Figure 6. Post experiment photograph of 2 in. thick powder panel

Experiment 4

The fourth experiment evaluated a 1.5 in thick (at the base) powder panel that contained 34.15 kg (75.3 lbs) of Monnex powder. The interaction of the threat with the tank ignited a flash fire that was observed on the high speed video to be extinguished by the powder panel in 40 ms, although the infrared video indicated a fire out time of 1.758 s. It should be noted that the entire high speed video screen was washed out at 1 ms, and the fire appeared to reflash several times at 3.5 ms and 13 ms after the threat was initiated. The fire ball was primarily located on the threat side of the fuel tank and at its maximum size was approximately 236.0 cm (93 in) width and 139.7 cm (55 in) tall. The damage hole diameter caused by the threat was measured at the entrance and exit of the threat into the tank at 2.9 cm and 1.9 cm respectively, while the maximum hydrodynamic ram pressure was 17.19 psi. Figure 7 shows the powder panel breaking apart primarily along the bottom area, as well as excess powder observed on the ground. The panel break up does not appear to be as severe as the panels in experiments 2 and 3.

Figure 7. Post experiment photograph of 1.5 in. powder panel

Experiment 5

The fifth experiment evaluated a 1 in. thick powder panel that contained 24.35 kg (53.7 lbs) of Monnex powder. The high speed video indicated that the developed flash fire was extinguished by the powder panel in 57.5 ms, although the infrared video indicated a fire out time of 2.862 s. It should be noted that the entire high speed video screen was washed out at when the threat was initiated, with the fire covering all of the experimental site within the camera field of view. The damage hole diameters caused by the threat were measured at the entrance and exit of the tank at 4.84 cm and 2.1 cm respectively. Figure 8 shows that the bottom of the powder panel appears to have completely shattered with no remaining powder (this was the first panel that demonstrated a full bottom break up). Again excess powder is observed on the ground.

Figure 8. Post experiment photograph of 1 in. thick powder panel

Experiment 6

The eighth experiment evaluated a 0.5 in. thick panel that contained 15.87 kg (35 lbs) of Black Widow powder. The Black Widow powder is a proprietary blend of fire suppressant powder. It should be noted that high speed video was not obtained due to a camera trigger malfunction. Infrared video coverage demonstrated that an initial fire occurred for 206 ms that appeared to dissipate, but then reappeared and grew toward the tank until the fire was completely out at 1.37 s. The damage hole diameters caused by threat were measured at the entrance and exit of the tank at 4.86 cm and 1.76 cm respectively. Figure 9 shows that the bottom of the powder panel appeared to have completely shattered with little remaining powder (the black coloring on the tank is attributed to the Black Widow powder color). This was the second panel that demonstrated a full bottom break up, however the excess powder seen on the ground in previous experiments was not as prevalent.

Figure 9. Post experiment photograph of 0.5 in. powder panel filled with Black Widow

SUMMARY

Table 1 presents a summary table of the experimental results.

Table 1. Summary Of Army Fuel Tank Ballistic Protection Data

Exp #	Target	Measured Panel Weight, lbs	Empty Panel Weight	Powder Load, lbs	Front Side Damage Hole, cm	Back Side Damage Hole, cm	IR Fire Duration Time, s	Vis Fire Duration Time, s	Peak HDRAM Pressure, psi
0	Empty Drum	NA	NA	NA	8.825	7.709	NA	NA	NA
1	55 gallon polyethylene Fuel Drum	NA	NA	NA	NA	NA	INF	INF	128.6
2	3" thick powder panel	152.5	36	116.5	2.905	4.64		0.1435	NA
3	2" thick powder panel	121.5	33.2	88.3	12.76	4.39	1.206	0.178	NA
4	1.5" thick powder panel	107	31.7	75.3	2.898	1.882	1.758	0.04	17.19
5	1" thick powder panel	84	30.3	53.7	4.84	2.1	2.862	0.0575	NA
8	0.5" thick BW powder panel	64	29	35	4.86	1.76	1.37	NA	23.58

Figure 10 presents an empirical relationship between the amounts of fire suppression powder applied vs. the fire out time observed from the described experiments.

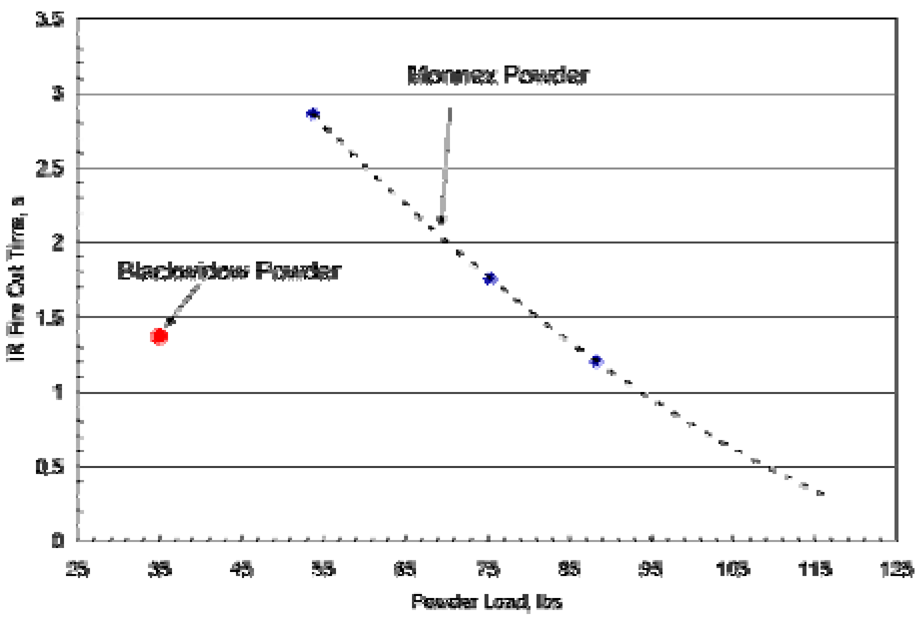

Figure 10. Relationship between observed fire out time vs. amount of powder inside of powder panels

As anticipated, the more Monnex powder within a panel, the quicker the fire out time, but in general the fire out times are short enough that crew members should not be subjected to hazardous fires when suppressed by the powder panels. As powder amounts decreased in the experiments, the more fire re-flashes were observed. However, the optimal panel design and Monnex powder load for actual applications can still be further optimized. In addition, the Monnex powder panels appear to protect the plastic fuel tank and reduce damage hole sizes relative to the unprotected fuel tank evaluated as a baseline condition. The Black Widow-filled powder panel was much more effective with a mass efficiency of 58.5 % relative to the Monnex powder-filled panels.

Based upon these successful results, the U.S. Army contracted FIRE Panel, LLC to build prototype FIRE Panels with designs tailored for several specific vehicle platform fuel tanks, for further ballistic testing and vehicle field trials, with potential consideration of deployment pending successful results. These additional ballistic tests are scheduled to occur in the summer of 2005.

OTHER MILITARY VEHICLE TESTS OF THE FIRE PANEL DEVICE

In April of 2005 another military ground vehicle supplier requested prototype FIRE Panels for consideration to protect their platform of interest. In this case, they desired to protect occupants in a small confined crew compartment, adjacent to an exterior vehicle fuel tank, which was deemed vulnerable to impact by medium caliber armor piercing rounds, which could disperse and ignite flammable fuel vapors in the crew area. A small, flat panel, containing only approximately two pounds of Monnex powder, was designed, assembled and shipped for mounting on the interior wall of the fuel tank, next to the crew compartment, for their ballistic tests. A simple patch of hook and loop tape was used to mount the panel to the tank. Subsequent ballistic tests showed the successful prevention of fires due to such impacts, and future tests are anticipated with even more weight-optimized versions. Details of the experiments and designs may be documented at a later date, pending approval of the release of such information.

"REAL WORLD" DEPLOYMENT OF A FIRE PANEL ON A POLICE VEHICLE

Since the summer of 2003, by far the most prolific use of powder panels commercially has been in the retrofit onto Crown Victoria police interceptors, installed by the police departments (state police agencies and local municipalities) that have purchased them. To date, approximately 10,000 police vehicle powder panels have been purchased and installed for police duty.

On May 31, 2004, in Johnston County, North Carolina, it was reported [11] that a roadside North Carolina State Trooper police vehicle was struck in the rear at high speed by another vehicle, and the equipped powder panel deployed just as observed in crash tests, discharging an enveloping powder cloud, with no resulting fire. The event was captured on another police vehicle in-car camera videotape, with selected images captured from the video shown in the following figures. Two North Carolina state troopers pulled over a minivan on the highway roadside, with the second police car (whose dash camera image is seen) behind the first as backup. Figure 11 is the last pre-impact frame of video, showing the troopers by the minivan, just before impact by a pickup truck, glancing the rearward police car and hitting the rear of the forward police car at very high speed in an approximate 50% offset, just like the crash tests performed earlier by the FIRE Panel company.

Fig. 11. Police cars on roadside before impact

Figure 12 shows the truck impacting the forward police vehicle at high speed, with a large plume of powder from the rear of the forward police car, emanating from the installed powder panel onboard (which are outfitted on all North Carolina State Police Crown Victoria cars).

Fig. 12. Police car, truck immediately after impact

In Figure 13, the large plume can still be seen remaining as the vehicles come to a stop. In Figure 14, on the on-screen timer reveals that fifteen seconds later, a powder plume still resides around the rear of the police car, with no fire observed. The officers were not seriously injured, although a police dog in the impacted vehicle later ran away from the vehicle, recovered a day later, shaken but unharmed. Later in the summer of 2004, a New York state police car outfitted with a powder panel was impacted similarly, with no fire although fuel leakage was observed.

Fig. 13. Powder plume resides after vehicles stop

Fig. 14. Powder remains near tank after 15 seconds.

SUMMARY

The powder panel technology concept, currently embodied in the FIRE Panel product, continues to advance in new application areas and evolved embodiments. Some of the most challenging applications are in the field of military vehicles, and recent ballistic tests by the military have shown its merits in battlefield protection. These developments are complimented by "real world" highway deployment and activation events that demonstrate its immediate benefit to the public.

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