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Principles, Testing and In-Field Experience for the FIRE Panel Fuel Tank Protection Device

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ABSTRACT

A technology has been devised and recently deployed in highway vehicle transportation to protect vehicle fuel tanks from impact-induced fires. The technology is currently employed in the FIRE Panel product, which exhibits an improved design based upon powder panel technology used for decades to protect military aircraft from ballistic-induced fuel tank-fed fires. The device comprises a shallow shell, filled with a powder fire extinguishing agent, which is mounted on or near a fuel tank or other flammable fluid reservoir. In the event of an impact to the fuel tank or reservoir, such as due to a collision, which might rupture the tank and spill fuel to be ignited, the adjacent FIRE Panel also impacted shatters as designed, discharging a plume of extinguishing powder to inert the space around the leaking fuel tank or other reservoir, even if the vehicle travels some distance after impact. The simplicity and low cost of the device make it practical for most transportation applications. The science of inerting fuel vapor/air spaces with previously released dry chemical, and the notably low concentrations required for the application, as demonstrated by the Bureau of Mines in addition to military evaluations, will also be discussed. The pedigree of full-scale crash tests, using rocket sled facilities and actual gasoline and live ignition sources to provide a significant threat of fire, will be addressed. The various in-field applications of the device will also be discussed, including motorsports use in the Trans Am racing series, and most recently NASCAR, as used in actual competition. Military transportation applications now being evaluated for the product, including Tactical Wheeled Vehicle fuel tank protection, and their resultant test data will also be discussed. Highway vehicle applications, including its deployment by the thousands on Crown Victoria police cars, and real-world activations while in service will be reviewed.

INTRODUCTION

The propensity of fires in both public sector highway vehicle operations (as well as motorsports), and their subsequent impact to the public, was discussed in a prior paper[1] published by the author on this subject matter. It introduced the concept of "pre-inerting" potentially ignitable fuel spills by use of technology previously known as "powder panels" in the military, and subsequently incorporated into the commercially available FIRE Panel derivative. This technology will be briefly described in the following summary of the detailed narrative provided in the previous citation.

In the late 1970s, the British Ministry of Defence[2,3] 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[4]. It was found that panel thicknesses as small as 2.5 mm could protect aircraft fuel tanks from exploding ballistic projectiles[5]. Even more impressive performance was observed by the U.S. Army in their tests[6] 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 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 overdesign 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 the aforementioned paper[1].

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.

IGNITION THEORY PERTAINING TO POWDER INERTION AND POWDER PANEL FUNCTION

THEORY, EXPERIMENTAL AND "REAL-WORLD" OBSERVATIONS OF FUEL DISCHARGE CHARACTERISTICS IN COLLISIONS – To understand the underlying principles by which suspended powders/particulates in air can "inert" a local fuel/air region to prevent the onset and ignition and fire, a review and discussion of fundamental fuel fluid dynamic responses after realistic impact scenarios, and its influence on critical fuel ignition parameters, is essential. Severy[9] discusses, in his landmark study and experimental program of collision-induced vehicle fires, the presence of "crash-induced fuel sprays and mists", which are generated during impact and expected to subside within five seconds after the initiation of a collision, the period during which "dynamic" ignition sources such as exposed light filaments and metal-to-pavement sparking may be present. Elaborating further, he states "In the majority of collision-induced fires, a transient spurt of gasoline develops a vapor cloud in the vicinity of a transient ignition source, and this temporary burn provides a more sustained ignition source having a high probability of kindling vapor from any collision-generated leaks from the fuel tank, the filler, fuel lines, the evaporative control plumbing, or the carburetor". He also clarifies that "collision-induced spillages may involve liquid fuel splatter as well as fuel vapor clouds". In his vehicle collision experiments investigating the mechanics of fuel release, ignition and fire propagation (comprising 55 mph rear-end two-vehicle impacts)[10], he described the fuel release dynamics thusly: " When the rear-ended car had advanced about 2 ft., gasoline could be seen spurting forward from the rear wheel area. By the time the car had advanced 8 ft., gasoline had erupted forward to the front wheel area, and had extended out several feet on each side of the car." In these experiments, Severy placed an ignitor on the ground forward and to the side of the vehicle post-collision path, intending to forcibly ignite the "vapor cloud" preceding the gasoline release path to visibly highlight the invisible vapor cloud, and study its fire propagation effects (its characteristics or location were not intended to imply any simulation or recreation of ignition sources actually expected to be present on a vehicle, with the delayed ignition largely influenced by his placement of the device some distance down the post-collision coasting path of the impacted vehicle). He then described that "when the vehicle reached the 48-ft position, the fuel vapor cloud had passed over the igniter and general ignition from that point occurred. Thereafter, the burning rate of the fuel cloud progressed in an explosive-like manner and the runout of the vehicle continued as the fuel cloud flame front progressed, catching up with the vehicle as it slowed to a stop."

Arndt and Stevens[11] provide a similar discussion of the state of fuel release immediately after a collision. They state "the fuel form in a crash will affect ignition. Fuel in a crash takes the form of vapors (mist or droplets) and pools. Vapors are most likely to ignite and often play a large role in post-crash fires". They further characterize mists and sprays as follows: "Mists or droplets can take on properties of vapors and become a source of fuel in a post-crash fire. This is a function of the high surface area to volume dimensions. Mists or droplets form in different ways. A crushed fuel tank under high pressure causes a high fuel exit velocity resulting in shearing of the liquid into mists or droplets. Also, a liquid will shear into mist or droplets as it enters a moving airstream. Pools of some fluids are the least likely to ignite, requiring large inputs of heat energy to raise the temperature of the fluid for vaporization". They also clarify the importance of the interaction of the heat (ignition) source with the fuel vapor/mist cloud as follows: "The combustion of vehicle fluids is controlled by numerous variables in the post-crash environment, including but not limited to fluid flammability, fuel/air mixture ratio, and the presence, temperature, and location of a heat source within the fluid's vapor cloud".

Other non-highway vehicle fuel reservoir impact scenarios also exhibit this general principle. The threat of fire in aircraft crash landings is most acute at, or soon after initial impact, when a fuel mist/vapor is released due to the impact energy applied to the wing fuel tanks and the fuel released, resulting in mechanical liquid shearing and airflow-induced generation of the mist. This vapor/mist can be easily ignited by instantaneous grinding metal sparks from the initial impact or sliding down the runway, ingestion into the engines, or wing landing light filaments, as has been evidenced in actual crash events. For this reason, substantial resources have been applied to date in the research and development of "anti-misting" fuels by the Federal Aviation Administration as a fire preventative and safety enhancement (and continues to be investigated by the National Aviation and Space Administration (NASA) as of this date). Even military system designers have frequently observed this principle of fuel mist/vapor generation, upon impact of a vehicle fuel tank by a ballistic projectile, in their many test programs. As an example, Finnerty[6] noted such a phenomena in his tests of armored vehicle crew compartment fuel tanks, when impacted by large-caliber shaped charge explosive rounds. He noted that ultra-fast response fire extinguishing systems were now being used by the Army to extinguish the "mist-fireball explosion". In this noted effort, Finnerty demonstrated the use of powder panels as a superior means of mitigating such a threat, without the generation of acid gases or other toxic by-products as is common with other extinguishants, and without requiring the use of intact electrical and detection systems during the violent encounter.

In general, upon severe impact, fuel reservoirs will collapse and reduce their internal volume, thereby increasing the pressure in the ullage (the vapor space above the liquid level), hence promoting the discharge of one or more pressurized jets through the damage holes. These jets will shear into small droplets while ejected through the air, also being influenced by fluid surface tension and Weber number considerations. The normally jagged, "petalled" damage orifices further function as nozzles to break up the ejected liquid stream, and atomize the liquid. In severe cases, some of these phenomena, including the formation of reflecting energy waves within the liquid fuel after impact, are referred to in general as a "hydraulic ram" condition.

Sprays and mists, which can also be referred to as an "aerosol" (defined in Webster's Ninth New Collegiate Dictionary as "a suspension of fine solid or liquid particles in gas"), are far more efficient generators of the fuel vapor necessary for ignition than simple leaks or pools. This is largely due to the generation of vapor controlled by the "vapor pressure" properties of the fuel, which is defined as the partial pressure (or relative volumetric concentration) of fuel vapor that will remain in equilibrium with the liquid state of the fuel at a given temperature. In other words, at a given temperature, a liquid has enough molecular energy to release a certain relative quantity of fuel as a vapor from its free liquid surface, until a sufficient quantity is released such that equivalent quantity enters the liquid from the vapor above (in an enclosed vessel), as equilibrium is established at the appropriate vapor pressure. As the liquid temperature is raised, the associated equilibrium vapor pressure also increases. If the vapor space is exposed to the environment, then vapor will continue to be generated and diffuse into the environment, until the larger local environment reaches that associated vapor pressure, or until the liquid completely. However, the rate at which this generation of vapor is accomplished is dictated by the free surface area of the liquid to the environment, for the vapor must emanate from that surface to enter the environment, and then diffuse locally based upon its vapor diffusion coefficients and other parameters. As a result, the rate at which fuel vapor can be generated and distributed throughout a volume of air (and possibly in contact with an ignition source) is a function of the surface area of the liquid fuel exposed to the air. A spray or mist of fuel has a much higher exposed surface area than a stream or pool, and is far more distributed throughout the air volume of interest, and therefore rapidly generates sufficient vapor (at least the "lean limit" of combustion) that is well mixed with air to facilitate ignition. The small liquid aerosol particles are also easier to heat quickly and vaporize further than are pools, and promote good mixing and combustion reactions at the onset of ignition to counteract heat losses due to fuel heating and vaporization.

As a result, the minimum ignition energies for pure fuel/air vapor mixtures are the smallest, as little as 0.2 to 0.3 millijoules for most hydrocarbons (and 0.28 millijoules for gasoline)[9]. Atomized sprays require little additional energy for ignition. Ballal (the author's dissertation advisor) and Lefebvre[12] developed a general model for the ignition characteristics of liquid sprays in air. In their derivation of governing physical formulas for these conditions, it was determined that the required "quench diameter" (discussed in the "Ignition Theory" section of this paper) was formed with a minimum input ignition energy, with the heat generated in the reacting mixture exceeding that lost by evaporating fuel droplets and other losses, with droplet diameters up to a threshold of 36 microns for kerosene, and 46 microns for iso-octane (a good surrogate for gasoline). Below this droplet size, ample excess heat energy is already generated in the reacting fuel and air to more than vaporize the fuel – in effect, a minimum ignition energy is reached at this level, comparable to vapor ignition, and further droplet size reductions do not reduce it further. It was also derived that the minimum ignition energy was proportional to the droplet diameter, raised to the 4.5 power. As a result, a droplet size double this minimum, at 92 microns, would theoretically require 6.3 millijoules.

In summary, it can be surmised that immediately or soon after the instant of impact, when fine mist aerosols of fuel are generated and dispersed for a limited time, is the most likely time period to observe the potential ignition of fuel released from a collision such as a rear impact, due to the widespread distribution or a readily ignitable fuel/ air mixture, and the very low ignition energies required while in that transient state.

GENERAL IGNITION THEORY OF IGNITABLE MIXTURES – The phenomena commonly known as "ignition" of flammable vapors, while exploited throughout society in any number of applications from automotive engines to gas furnace appliances, is still not fully characterized in the literature, and requires some degree of simplifying assumptions of the dynamic processes to mathematically model. This discussion will be an even more general simplification of the essential concepts, and in particular as they apply to the concept of powder particulate or other inhibitor "inerting". The reader is advised to consult further accepted graduate-level combustion engineering texts such as Kuo[13] (which discusses portions of the following summarization) for further details of this process, as well as numerous other sources in the open literature.

What is commonly referred to as "ignition" is actually a "runaway", fast chemical oxidation reaction, which sustains itself and propagates throughout a flammable fuel/air mixture beyond its point of origin. The mixture typically requires a "jump-start" of energy to raise the temperature of the reactants to a level where the rate of heat release exceeds the rate of heat loss to the environment, hence leading to "runaway" ignition and flame propagation. This rate of heat release is a function of the fuel/air combustion reaction rate, which can be expressed as a relationship obeying Arrhenius' Law:

$$k = A \exp(-E_a/RT) \qquad (1)$$

where k is the reaction rate constant, E_a is the activation energy for the reaction, R is the universal gas constant, and T is the temperature of the reactants. As is apparent, the reaction rate (and hence, the rate of chemical heat release) is exponentially related to the temperature of the reactants. The reactants must be raised to a temperature sufficient to support a reaction rate of a time scale typically associated with flame propagation, particularly when the surrounding reactants are only present for a transient period of time. Under the conditions of interest, heat losses can be attributed to heat conduction and convection to the outer mixture (not yet sufficiently reacting), and thermal radiation to some degree (although the reactants within the ignition region may reclaim some of this energy). In addition to the heat required to raise the reactants to the temperature required for sufficient reaction rates, additional heat is necessary to vaporize liquid droplets if present to produce sufficient vapors.

Therefore, an artificial "ignition source" must add sufficient additional heat to raise the reactants' temperature to a sufficient level to maintain high reaction rates and heat release, and to compensate for losses to the environment (and through physical components of the ignition source itself), and change of phase of the fuel, if necessary. At this point, the total quantity of heat released is a function of the volume of mixture producing the reaction heat. The heat losses, however, are for the most part a function of the two-dimensional boundary surface between the reacting region and the as yet non-reacting region (with such surface boundaries conceptualized as spherical surfaces in unconstrained free volume reactions), and the difference in temperature between the reacting and non-reacting zones. The critical point to note with the artificial "ignition source" is not only that it raises the reactants in immediate proximity to a sufficiently high level to maintain adequate reaction rates, but it also "pre-heats" adjacent regions, or initiates their own heat-releasing reactions to a greater degree. More importantly, if a larger volume of reactants is sufficiently heated for it to generate a net positive heat release rate, then as this radius of reacting volume grows, the ratio of volume (which controls the heat release rate) to outer boundary surface area (which controls the rate of heat loss) grows (as does the ratio of the cubed value of the radius to its square), which "tips" the scales more in favor of net heat generation.

At some critical dimension of the "ignition kernel" as it grows as more heat is released and due to continued heat donation from the "ignition source", the "quench diameter" limit is reached, and a total net positive heat release rate for the entire ignition kernel is achieved (commonly known as the event called "ignition"). If the ignition source supplies an insufficient quantity of heat to reach this state, or not over a sufficiently long or short period of time, then the heat losses will overcome and quench the incipient ignition. The minimum ignition energy is directly proportional to the volume inscribed within the quench diameter, and hence proportional to the cube of the diameter itself. The previously cited model of Lefebvre and Ballal[12] derived an expression for the "quench diameter" as follows:

$$d_q = D\, [\, (\rho_{fuel})/(\rho_{air}\, \phi\, \ln(1 + B))\,]^{0.5} \qquad (2)$$

where d_q is the quench diameter, D is the fuel droplet diameter, ρ_{fuel} is the density of the fuel, ρ_{air} is the density of the air, ϕ is the equivalence ratio, and B is the mass transfer number, expressed as the ratio of heat available for evaporation, divided by the heat required for evaporation (and a function of the fuel itself). The critical "ignition" energy level necessary to obtain reactions to the threshold of the "quench diameter" is then sufficient to "pre-heat" the adjacent reactant mixtures with insufficient heat losses to offset heat generations, with resultant "runaway" conditions leading to flame propagation throughout the mixture. The flame may sweep through and consume all the available reactants, or reach an equilibrium state whereby sufficient heat is available from the flame to continue to supply a sufficient supply of fuel vapor from a liquid source, such as an extended spray or pool fire.

For stagnant (non-flowing) mixtures, a total quantity of heat required from the ignition source is usually relevant, normally expressed in Joules (J); for fast moving flows, the rate of heat addition (in watts (W = J/s)) is normally more pertinent, to rapidly heat the mixture before it is swept away (as is common in jet engine combustors and similar applications). The time scales associated with post-collision fuel and air flow rates are likely somewhere between these two extremes, therefore consideration of both total heat release and heat release rate of ignition sources is merited. If sprays or mists have droplet sizes less than 10 microns, or are raised to elevated temperatures, then minimum ignition energies of such mixtures will be comparable to that of pure gaseous mixtures[14].

This ignition phenomena becomes even more complex when considering the addition of dispersed inert heat sinks to 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 suitable application of ignition source and energy, fuel and air are no longer present in a suitably 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[15] 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 have documented that ignitions of such vapors or dusts have been typically caused by frictional heating of cutting bits, or electric or electrostatic spark, some of which could originate from mine-operating vehicles or equipment, and which is relevant to those ignition sources present on automobiles. Their historical approach was to dust the mine walls with "rock dust", or calcium carbonate, such that when it is normally "kicked" up and suspended in air, along with the coal dust mixed with it and/or methane released in the air, it can inert the air space to prevent establishment of a flame and propagation. However, they had found that very large quantities of such rock dust were needed to effectively inert (and were normally less than adequate for methane explosions); hence the interest in devising other solutions using other powders that were more efficient in inerting. 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. Being a comparable hydrocarbon with similar published minimum ignition energies (and inerting concentrations for inertants like nitrogen) to gasoline vapors, this data provides good correlation to required inerting concentrations for worst-case stoichiometric gasoline vapor/air mixtures, without the need for additional heat to vaporize liquids or sprays which would reduce the required inerting levels – hence, a good "worst case" (but rare) scenario for the automotive application.

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 know 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 ha recommended ABC powder for use in the powder panel devices for most automotive 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.

A final point should be made about the mechanical dispersibility of the powders in such a post-collision discharge event, which is critical to the effectiveness of the system as a whole, in addition to its performance in relative concentrations in laboratory scale data. Finnerty, in addition to many other investigators who have tested powder panel derivatives in full scale tests, noted that in impacts, "when a fuel mist is released at the jet-exit hole, the mist travels along the jet path, as expected. The powder from the damaged powder pack also travels along the jet path (Zabel et al, 1988). The powder is thus preferentially transported to the place where it is needed, the location of the fuel mist. Thus, even if, on the average, there is an insufficient powder release to render the entire compartment nonflammable, there is locally a high powder concentration where there is a high fuel-mist concentration". This phenomenon may be explained by further consideration of the "aerosol" definition previously cited. Note that the definition includes both liquid and solid particles. It has been noted that fuel mists emanating from collisions may be in the tens of microns in particle size, being the most likely (along with the adjacent vapor) to ignite first when encountering an ignition source, by requiring the least quantity of ignition energy. The specific gravity of gasoline is on the order of 0.8. It is interesting to note that ABC dry chemical is reported to have a specific gravity of 0.85, and is used with a particle size distribution in the preponderance of tens of microns. Therefore, having similar size, mass and density to the fuel mist droplets released, and released from the same point of origin at the fuel tank, it would be expected that the powder particles would follow the fuel mist and vapor cloud released after an impact.

After some time, these droplets will vaporize, and some powder will settle that is not further entrained by air currents, but of the immediate time scales observed just after a collision, when encountering transient ignition sources and still in a highly-ignitable mist/vapor cloud, this coincident entrainment is to be expected, and in fact, is observed in actual tests. Reviews of collision events have noted fuel spray discharges toward the front wheels shortly after rear impacts, and conical emanations from the rear of the vehicle (with the vapor clouds noted in Severy's tests) as well as extending forward until the vehicle moves significantly, in the same manner as has been observed in powder dispersals in actual FIRE Panel crash tests. Previous experiments at Ohio State University, observed by the author and others, have shown that such powder clouds necessary to prevent the ignition of sustained spark ignitors exposed to gasoline pools are visibly so faint to be described as "wisps" or "light smoke", barely discernable by the naked eye. Thus, although localized powder concentration measurements are difficult to measure in a large scale, outdoor crash test environment, visible evidence of a powder plume (of any notable opacity, as seen on photo or film coverage) at any point is typically indicative, based upon prior controlled experiments, of a more than adequate plume concentration to prevent ignition. It should be noted, for reasons previously discussed, that the mist/vapor cloud produced just after impact is the most hazardous condition that must be addressed, due to its ease of ignition, and for which the FIRE Panel product is expressed designed.

SUITABLE IGNITION ENERGY LEVELS FOR ON-BOARD VEHICLES AND "REAL-WORLD CRASH EVENTS - As stated previously, ignition sources selected to evaluate fire prevention devices in actual vehicle crash tests must be sufficiently energetic and robust to ignite sprays and mixtures, be of comparable energy levels to that of ignition sources actually found on vehicles, and have configurations, in terms of their interaction with fuel and air mixtures (and powders or other inertants), in the same manner as would be encountered in actual collision events. Severy[9] prepared a table of ranked relative hazards of various automotive ignition sources, based upon his review of many real-world documented crash events. He first labeled "lamp filaments" as an "extreme hazard", if contacting liquid fuel or vapor, presumably due to the high temperatures of the filaments (and duration, which is reported to be sustainable up to seven seconds). "Metal-to-pavement sparking" was also labeled a "severe hazard". The "storage battery" was also labeled a "severe hazard" for some impact scenarios, if the battery was disrupted and had significant electrical discharge. "Electrical wiring" was also noted as a "severe hazard" where a short creates heating or sparking. The exhaust system was not seen (as with other investigators) as being a likely means of igniting gasoline, but it can serve to vaporize fuel to be ignited elsewhere.

Severy reported to have conducted tests dragging metal on pavement at speeds as low as 8 km/h (5 mph), and generated red to orange sparks, which steel exhibits at 800 C (1470 F). Higher speeds produce white sparks, which steel exhibits at 1200 C (2190 F), certainly hot enough to ignite gasoline if a spray or vapor is immersed in the shower of sparks. Crash tests by Fiat showed that such sparks can ignite fuel. Severy noted that the highest temperature ignition sources on vehicles are lamp filaments at 1400 C (2550 F).

Arndt and Stevens[11] conducted a series of experiments to assess the ability of various types of ignition sources, as represented by simulated surrogates, to ignite various automotive fluids. They used an operating catalytic converter, which when naturally heated by its operating engine could produce component temperatures from 204 C (400 F) to 649 C (1200 F). Each of the fluids was sprayed on the catalytic converter as it was operated at various temperatures. Alternative ignition sources were used in addition to the converter surface – applied metal friction sparks, generated by a grinding disk applied to a block of mild steel and thrown a distance of five feet to the surface, and a single model rocket motor ignitor (not to be confused with an actual rocket motor) was energized at a distance of one inch from the surface. Both were applied one second after fuel was applied, to give time for fuel vapor to form. The friction sparks were observed to be yellow to orange as they left the disk, cooling in the air until they contacted the catalytic converter surface, then becoming orange to red upon impact. This implies that the temperature of the friction sparks was likely in the range of 500 C to 900 C (932 F to 1652 F) at the time they impacted the surface. The rocket motor ignitor was used to simulate the effect of an external ignition source that has more energy than friction sparks (e.g. light bulb filaments, electrical shorts, etc.). The rocket ignitor manufacturers claimed that the ignitor would develop a temperature of approximately 649 C (1200 F). The key bridge wire component of the ignitor was of the nichrome family. The energy generated by the ignitor as estimated to be 25 J during the first second it was energized. A flat steel plate was used to create surface temperatures below 204 C (400 F), down to 38 C (100 F), being heated by the sun or a small amount of burning fuel below it to reach the precise temperature. In their results, it was found that neither 91, 89 nor 87 octane gasoline was possible to ignite with the catalytic converter alone, in a range of temperatures from 649 C (1200 F) to 204 C (400 F). However, it was observed that the sparking source ignited all gasoline grades with only the steel surface, heated to a nominal 38 C (100 F), which would be a common pavement temperature for a wide array of environmental temperatures. The same scenario was true with use of the rocket motor ignitor, with all grades ignited at 38 C (100 F), with the exception of 87 grade gasoline, which ignited at 52 C (125 F). These results suggest that both grinding metal sparks and energy sources in the range of tens of joules are effective and reasonable surrogate simulators of ignition sources present on vehicles, and can actually ignite gasoline when exposed to real world conditions.

RECENT CRASH, FIRE AND OTHER TESTING OF POWDER PANEL DEVICE

TRUCK SIDE IMPACT TESTS BY AUTO SAFETY RESEARCH INSTITUTE – The Auto Safety Research Institute has been conducting a program to explore technology options or redesigns to address a perceived propensity of impact-induced fires on older model General Motors pickup trucks, which feature “side saddle” fuel tanks mounted on the exterior of the frame rails. Amongst the options considered included center mounted and bed mounted fuel tanks, and racing-type fuel cells and bladders, to name a few. Their crash tests to evaluate the merits of these alternatives included side impact tests, centered at the interface of the truck cab and bed, impacted at a 60 degree angle by a late model Caprice sedan. The FIRE Panel company was invited to fabricate a prototype of their product for the rectangular metal casing being evaluated in their next crash test series[18] at the Transportation Research Center (TRC) at East Liberty, Ohio. This casing enclosed a racing-type flexible bladder planned for evaluation in the program. Since the facility was not configured to handle a large spill of actual gasoline, a non-flammable Stoddard fluid was used as a surrogate. As such, the powder panel was evaluated with respect to its ability to generate a plume of powder suitable to engulf the fuel tank region after impact, including as the vehicle moves post-collision, for this type of collision scenario. The presence of the powder would be indicative of its ability to mitigate fire in that region. The panels were fabricated to fit the exterior of the metal casing, on the bottom and four sides, with a series of five individual flat, fluted panels at a final weight of approximately nine pounds. The Caprice vehicle impacted the 1985-87 General Motors pickup at 80 km/h (50 mph) at a 60 degree angle, centered on the cab/bed interface as described, and almost directly in line with the fuel tank and panel mounted just behind the bed fender skin. Upon impact, the powder from the shattering panels engulfed the undercarriage of the truck (and the hood of the Caprice), even as it was propelled forty feet or more, until the truck rolled over one quarter turn on its side. The report author stated that the powder engulfed the vehicles until they came to a stop, and continued to reside for several seconds afterwards. As such, the device performed as designed by creating a cloud of inerting powder to prevent any fuel tank-related fires, if any had been possible in this scenario. A photograph of the impact event can be seen in Figure 1, with the light-colored powder emerging from the panel. Figure 2 is a photo some time after the conclusion of the test. The rectangular fuel cell can be seen on the ground between the vehicles, along with panel powder residue.

Fig.1. Powder discharge in truck crash test.

Fig.2. Truck and Caprice after impact.

CROWN VICTORIA CRASH TESTS WITH IGNITION SOURCES (NOVEMBER 2003) – After the July 2002 testing of the powder panels on a Crown Victoria police interceptor, and after the product had entered the market and had been fielded on several thousand police vehicles for some time, several potential users had asked questions about potential scenarios related to test validation that they would prefer were addressed, prior to use of the device. These questions generally comprised:

(1) how would the panel function in preventing fire if a bladder were not present?

(2) Can the FIRE Panel prevent fires if notable fuel spillage is certain, as well as realistic but sufficiently robust ignition sources?

(3) How can one verify that a fire would have occurred if protection had not been applied?

(4) Would the powder plume look the same if the vehicles were operated on pavement, as opposed to dirt in the configuration of the test facility previously?

(5) How would the device perform in an approximate 125 km/h (75 mph) 50% offset impact from a Ford Taurus, as Ford and the City of Dallas have done?

The FIRE Panel company determined that additional full scale crash tests would be useful to address these questions, to further confirm the performance capabilities of the device. Two additional Crown Victoria police interceptors and two Ford Taurus' were procured, and high-speed rocket sled-driven crash tests were scheduled to be performed in November 2003 at the Goodrich Aerospace rocket sled track facility at Hurricane Mesa, Utah. A concrete pad, 30.5 m (100 ft) long by 10.7 m (35 ft) wide was prepared at the impact site to assure that the vehicles, after collision, would move in a manner similar to vehicles on actual roadways, and to further affirm that any plumes seen under the vehicle are due to powder discharge, and not dirt under the vehicle. Two tests were planned – a baseline test with no protection, and a test under identical conditions with a panel installed on the fuel tank. The first baseline test comprised the impact of a 1993 Ford Taurus into a 1998 Ford Crown Victoria police interceptor, and the second protected test involved a 1994 Ford Taurus impacting a 1999 Ford Crown Victoria police interceptor. For both Taurus "bullet" vehicles, the headlights were on to provide their filaments as potential ignition sources. The Ford Crown Victoria police interceptors (CVPIs) were filled with 18.05 gallons of gasoline, at 95% of their capacity. The headlights and flashers of the CVPIs were also on to assure additional ignition sources, as well as having the engine running at the time of impact and at least 10 minutes before, to assure that the engine and all exhaust components were at normal operating temperatures before impact (to further assist with ignition), and with its transmission in "Park". The vehicles were positioned such that the Taurus "bullet" vehicle would impact the CVPI with a 50% offset, on the driver's side of the rear bumper. This arrangement was consistent with other parties that have performed similar CVPI crash tests, and replicates a scenario where a highway patrolman has pulled over to a road shoulder, and a vehicle loses control, crosses the shoulder's edge and impacts the CVPI, as has been commonly seen in actual events and fire incidents. Figure 3 is a picture of one of the "bullet" Taurus vehicles on the rocket sled, Figure 4 is a closeup of the powder panel designed for the CVPI fuel tank application, Figure 5 is a photo of the panel installed on the front face of the fuel tank, and Figure 6 is a photo of a technician installing the panel, using the special Dual-Lock tape that facilitates removal, with installation taking about twenty minutes.

Fig.3. Taurus "bullet" vehicle on rocket sled.

Fig.4. Panel design for CVPI fuel tank.

Fig.5. Panel mounted on CVPI fuel tank.

Fig.6. Technician installing panel on CVPI.

To best assure that significant fuel would be released and contact ignition sources, two modifications were made to the CVPIs used in test. First, a multi-pointed metal prong device was attached to the axle, facing the fuel tank, to assure that adequate puncture of the tank would occur when it was forced into the rear axle, and distributed along the fuel tank. None of the rubber shields Ford has recently added were incorporated in the layout as well, so as not to impede any potential for release of fuel. Secondly, two artificial ignition sources were added to the CVPIs tested, in the vicinity of the fuel tank. A nichrome wire device was devised, which when heated by a 12V source produced a surface temperature of over 1200 F. This device is actually recommended by its manufacturer to ignite liquid and gaseous fuels (although not normally in crash tests), and it was intended to simulate lamp filaments and shorting electrical wires, and is similar in energy to the rocket motor ignitor used by Arndt and Stevens, shown to reliably ignite fuel sprays. In fact, this device was calculated to have a output rate of heating of 32.3 watts (and a temperature of over 667.0 C (1200 F)), or 32.3 Joules per second, versus 25 J for the device used by Arndt and Stevens, and 35 J for the pyrotechnic match used by the Bureau of Mines in their powder inertion tests. It was mounted under the axle to protect it, but in the path of fuel discharge from the fuel tank (and was monitored by a thermocouple to assure that it functioned properly up to the point of impact). The second device was a grinder power tool in contact with a steel angle piece, creating a shower of sparks very similar to Arndt and Stevens' device, to represent dragging metal. It was mounted just forward of the axle, to send the shower of sparks under the fuel tank from front to back. These sources were thought to represent highly likely and realistic ignition sources for rear impact, using the best surrogates of equivalent ignition energy available. Figure 7 is a photo of the fuel tank puncture device added, Figure 8 is a photo of the nichrome wire heat source added to the vehicle, and Figure 9 is a photo of the spark generator mounted on the vehicle.

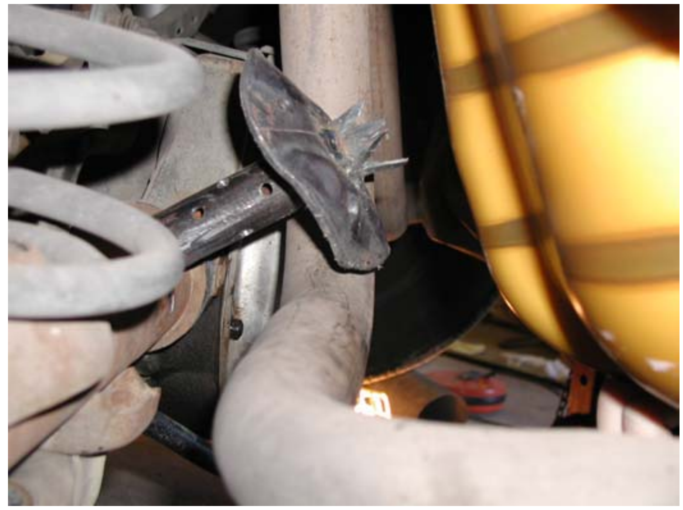

Fig.7. Fuel tank puncture device in place.

Fig.8. Ni-chrome wire filament/wire ignition source

Fig.9. Spark generating assembly with grinding wheel mounted on the CVPI.

The first crash test was an unprotected baseline conducted to observe if the test arrangement would result in a fire. The Taurus was propelled and impacted the CVPI at a speed of 133.2 km/h (79.9 mph), with a wind speed of 4.5 knots. Almost upon impact, the CVPI erupted into flames. As can be observed in the full speed and slow motion video, the target CVPI catches fire, and a fireball was visible as the force of the impact caused the CVPI to be propelled down the track. As the CVPI moved down the track it rotated clock wise due to the 50% offset hit (relative to the direction of travel) and came to a stop approximately 26.4 m (86.58 ft) down track and approximately 8.05 m (26.42 ft) to the passenger side of the centerline. All during this transit time from impact to rest some 86 feet down the track, the CVPI was consumed in flames. The flames continued when the vehicle came to rest. Post crash inspection revealed that the fuel tank was punctured in several locations and fuel flowed freely from the punctures. The normal crash-related ignition sources and the supplemental ignition sources were easily able to ignite the leaking fuel, causing a severe fire condition. The leaking fuel left a “trail” from impact to rest. The trail was being consumed by the flames as the target CVPI traveled to a rest.

A second test was performed with a 1999 CVPI. It was prepared in an identical fashion to the first test except that FIRE Panel engineers installed a standard FIRE Panel, taken from inventory, to the axle side of the fuel tank. The panel was identical to the units currently being sold to law enforcement agencies. The panel contained approximately six pounds of “ABC” fire extinguishing dry powder. The fire suppressing powder used in the pPanel contains a higher concentration of the mono ammonium phosphate ingredient than is found in normal fire extinguishers, thereby enhancing its effectiveness. The panel was secured to the fuel tank of the target CVPI by the same means used in normal installations, using the Dual Lock fastening materials, taking less than 20 minutes. The bullet Taurus impacted the second CVPI at 79.6 mph, with a recorded wind speed of 3.0 knots. Almost immediately after impact, a powder cloud could be seen under both vehicles. This cloud of fire suppressing powder grew in intensity, as noted by the richness of the color of the cloud, and enveloped both vehicles. After impact, the CVPI traveled 28.5 m (93.5 ft) down the track and approximately 8.0 m (26.25 ft) to the passenger side of the centerline. As in the first test, the CVPI rotated almost 360 degrees before coming to a stop. As the CVPI traveled down the track, at certain periods it appeared relatively engulfed by the cloud of fire suppressing powder expelled from the panel. The powder cloud was observed to linger around the CVPI after it had come to a stop for some time, with no fire present. After the vehicle came to a rest, fuel could be seen leaking from the fuel tank. Post crash, FIRE Panel engineers present captured a small amount of the leaking fuel and ignited it to demonstrate that the fuel could have been ignited, were it not for the inerting process of the fire suppressing powders. The tests thus demonstrated the capability of realistic artificial ignition sources to ignite fuels discharged from fuel tanks damaged in actual crash tests, and for the powder panel device to mitigate the ignition of fuel discharged in actual crash events when exposed to such ignition sources. Figure 10 is a photo of the burning CVPI immediately after the baseline crash test, and Figure 11 is a photo of the vehicle after the fire was extinguished. Figure 12 is a photo of the second crash test, with the panel deploying and powder cloud just after impact. Figure 13 is a photo of this vehicle right after impact.

Fig.10. CVPI burning immediately after impact in baseline test.

Fig. 11. CVPI in baseline test some time after coming to rest.

Fig. 12. Panel deployment and powder plume around CVPI in second test (just after impact).

Fig. 13. CVPI after impact (with panel installed).

ARMY TESTS OF PANEL FOR TACTICAL WHEELED VEHICLES –

In 2004 the U.S. Army Research Laboratory began an effort to explore various protection schemes to protect military Tactical Wheeled Vehicles (TWVs) from severe secondary fuel tank fires resulting from impacts by current battlefield ballistic munitions. The powder panel technology, as with any other protection scheme for large, pyrotechnic blast-derived fire threats, is intended not to stop the pyrotechnic blast that occurs instantly from the explosive material inside it, but it is envisioned to use the impact to dispel a blanketing cloud of powder to prevent the ignition of the fuel discharged after impact, to prevent a large pool fire that further endangers occupants. An embodiment for this extreme powder panel application has been configured and evaluated in full-scale live fire tests, initially using fuel tank surrogates, and panel prototypes to accommodate this tank size. The powder capacities of these derivatives are far higher than those powder panel versions now used on street and racing vehicles today, due to the nature of this threat. Figures 14 and 15 are photos of the handcrafted prototype powder panel shells that were fabricated and evaluated in the surrogate tank tests.

Fig. 14. Tactical Wheeled Vehicle (TMV) panel prototype for surrogate tank testing (side view)

Fig. 15. TWV panel prototype (end view).

The U.S. Army initial evaluations of the protection of fuel tanks on military vehicles from ballistic threats comprised the use of generic fuel tanks (55 gallon drums) made of polyethylene material, and subject to a horizontal ballistic threat projected through the center of the side of the tank, with the powder panels placed in a cradle, holding and surrounding the tank (including along the shot line). Figure 16 presents a photograph of the experimental set-up, which illustrates a ballistic threat projecting through the middle of the tank, which is approximately 5.08 cm (2 in) below the top of the fuel level. 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. Initial experiments evaluated a fuel tank subjected to the ballistic threat without any protection (baseline), followed by a parametric study of varying powder amounts enclosed in the panel to determine fire out times vs. amount of powder used for protection. The powder panels were constructed for this series using U-shaped saddles that are 0.5 in thick along the sides but grow to varying thicknesses in the bottom, to vary the capacity of powder in the panel to determine the minimum quantities required.

The baseline experiment, using an unprotected fuel tank subjected to a ballistic threat, created a sustained fire that covered the entire experimental site and required the on-site fire department to extinguish. Figure 17 presents a post-experiment photograph of the fuel tank, which shows that it had practically melted due to the high intensity fire. Hydrodynamic ram pressures reached a maximum value of 128.6 psi. The next five experiments were of an identical configuration, except that panels of various base cavity thicknesses from 3.0 to 0.5 inches (corresponding to total powder contents weights from 52.6 kg to 15.87 kg) were evaluated in each event, to determine the minimal quantities (if any) of powder necessary to prevent a sustained, catastrophic fire.

Figure 18 is a photograph of a powder panel-protected fuel tank after ballistic impact. In this photograph, the intact nature of the fuel tank structure, and the shattering and powder dispersing nature of the powder panel can be clearly seen. It was found that in these events, the interaction of the ballistic threat with the tank ignited a flash fire that was extinguished by the panel in milliseconds, as observed with the high speed video camera. It should be noted in these tests that the entire high speed video screen would "wash out" in a few milliseconds (due to the impact flash and blast), but a visual "hole" would develop in the area near the fuel tank, and radially expand until the fire 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 in the fractions of a second before powder discharge and quenching. The damage holes caused by the threat, measured at the entrance and exit of the tank at the site of ballistic impact, were on the order of 3 cm and 4.5 cm respectively. All five versions of the powder panel, including the smaller version only 1.27 cm thick, were sufficient to prevent the establishment of a sustained fire (no effort was made to further reduce the powder capacity of the panels). The U.S. Army determined that the "fire out" times (on the order of a second or less thermally, and usually not visibly observed) are short enough that crew members should not be subjected to hazardous fires when suppressed by the panels. They also observed that the panels appeared to protect the plastic fuel tank and reduce damage hole sizes relative to the unprotected fuel tank evaluated as a baseline condition. Based on these successful results, the U.S. Army plans to demonstrate the powder panel technology on an actual military vehicle in a full-up live fire test, to consider its implementation in the battlefield, and a specially-made powder panel configuration to accommodate the unique features of the actual vehicle fuel tank in question is being fabricated, at the date of this writing.

Fig. 16. Experimental arrangement for baseline fire evaluation.

Fig. 17. Post experiment photograph of unprotected fuel tank damage due to sustained fire.

Fig. 18. Intact fuel tank and shattered powder panel after successful fire protection test.

OTHER EVALUATIONS OF FIRE PANEL FOR MOTORSPORTS, OTHER APPLICATIONS – In mid-2003, The National Association of Stock Car Auto Racing (NASCAR) performed their own in-house evaluation and testing of the powder panel technology as a supplement to the fuel cell and other fuel containment designs of their Nextel Cup racing cars. A specially designed panel configuration was proposed, flat in shape but with an arrangement of individual cells that permitted filling of multiple cells in channel arrangements, yet offered flexibility in trimming the panels in set dimensional increments to accommodate a wide range of fuel cell dimensions (and for use on bus tanks and other flat surface applications as well). The panels were sized to fit on the top surface of a Nextel Cup-sized fuel cell, with a thickness and powder load to result in a panel weighing less than one pound per square foot. The smaller powder load, under weight constraints similar to aerospace applications, results in a reduced period of extended powder discharge and distance. However, it does provide an ample supply of powder at the moment of impact, the time understood to most need additional help in preventing a flash fireball, as a supplemental level of protection to the existing vehicle technology and design. Although their evaluations are unpublished, their deliberation led to their approval of the device for use in Nextel Cup competition. Figure 19 is a photo of the flat, cellular panel design now being used in motorsports.

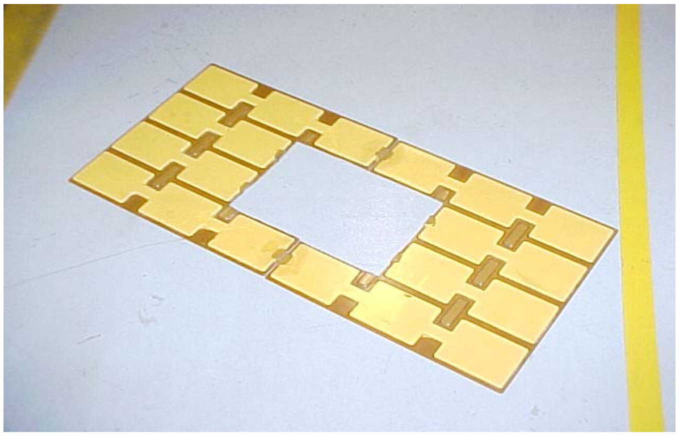

Fig. 19. Photo of the flat racing powder panel design.

In another unpublished test, the FIRE Panel company was asked to provide a prototype hood liner version of their powder panel technology for use in an actual front end impact test on a pickup truck. The prototype was mounted under the hood, in a recessed area normally filled with the hood liner, with approximately 2.72 kg (6.0 lbm.) of ABC dry chemical powder. The design was also augmented with two automatic dry chemical fire extinguishers that fired 4.54 kg (10.0 lbm.) of ABC dry chemical in the lower regions of the engine bay. The pickup truck was propelled, in a 50 degree offset arrangement, into a fixed barrier at 83.3 km/h (50.0 mph). Additionally, a fuel fire was pre-set in the engine compartment, and allowed to grow, up to the moment of impact. At the point of impact, the hood buckled as designed, breaking the powder panel and sending a cloud of powder in the engine compartment, supplemented by the other extinguishers. As the truck tipped in the air (raising the rear section) due to the impact, the fire spread underneath the chassis, but the powder followed the fuel and fire path and extinguished the fire, by the time the vehicle rested again on all four wheels. Figure 20 is a photo of the prototype powder panel hood liner unit tested.

Fig. 20. Prototype powder panel hood liner unit, mounted in the truck hood.

RECENT APPLICATIONS AND FIELD EXPERIENCE WITH POWDER PANELS IN MOTORSPORTS AND VARIOUS FORMS OF TRANSPORTATION

POLICE VEHICLES AND OTHER STREET APPLICATIONS – 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, over 5,000 police vehicle powder panels have been purchased and installed for police duty. Some heating issues with newer model police vehicles and their current exhaust pipe placement relative to the fuel tank has resulted in the inclusion of exhaust pipe heat shields included with every police panel kit purchased. The panels are mounted while the vehicle is on the garage lift, by cleaning the tank region where the panel is mounted, applying the special Dual Lock tape to the proper sites, and pressing the panel in place, with the entire process taking a few minutes. The police vehicle does not have to be taken out of service during the installation process, and no special tools are needed.

On May 31, 2004, in Johnston County, North Carolina, it was reported[19] 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 21 is the last 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 by the FIRE Panel company. Figure 22 shows

Fig. 21. Police cars on roadside before impact.

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). In Figure 23, the large plume can still be seen remaining as the vehicles come to a stop. In Figure 24, 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. 22. Police car, truck immediately after impact.

Fig. 23. Powder plume resides after vehicles stop.

Fig. 24. Powder remains near tank after 15 seconds.

Additionally, models of the Bentley automobiles imported by Von Genaddi Coach Builders, and modified in a manner such as their "Shooting Brake" model, have now been outfitted with powder panels on their custom fuel tanks as standard equipment. Figure 18 is a photo of such a powder panel-equipped Bentley "Shooting Brake" model.

Fig. 25. Bentley model equipped with panel.

MOTORSPORTS COMPETITION EXPERIENCE WITH POWDER PANELS –

After approval of the powder panel for Nextel Cup competition, the PPI Motorsports Nextel Cup team agreed to employ the device in competition, as a means of gathering a mutual experience of "lessons learned" in terms of the proper use of the product for this application, and began use of the device in service in NASCAR Nextel Cup competition in the latter part of the 2003 season. It was initially mutually agreed to move the panel placement from the top of the fuel cell to the aft vertical trunk "crush panel". In this location, the panel has a better potential for a "direct hit" if the vehicle is rear-ended or backs into the track wall, and then is forced into a rollbar loop protecting the fuel cell, thereby shattering the panel and directing the discharge of powder over the top of the fuel cell. A series of two individual panels was devised, to be mounted on both sides of the crush panel, using the cellular panel design. Some actual racing rear-end crash events have occurred with the car that have resulted in the discharge of powder (but no fuel leakage or fire observed). Adjustments have been made to the mounting approach, such as adjusting the amount of tape used to affix the panel and where it is placed, to balance an ease of removal if necessary by crew members, yet be sufficiently durable in the event of normal wear and tear of racing activities, and retain its mounting position until it shatters during activation. In 2004, the American Speed Association (ASA) has reviewed the device, and officially "recommended" it for use for its competitors for its national touring series. For their application, four smaller panel pieces, mounted on the exterior of the fuel cell on the back two corners, was deemed most suitable for their application. Figure 19 is a photo of the flat powder panel design, installed in its normal position for Nextel Cup competition.

Fig. 26. Racing powder panel in Nextel Cup car.

CONCLUSION

The powder panel concept, now evolved into the FIRE Panel technology, has advanced in its design, embodiments and range of applications over the last few years. It is underpinned by many years of development, full-scale testing and actual use by the British and U.S. military, as well as sound, cutting edge combustion and fire safety science, employing this knowledge using principles not normally exploited. Its unique answer and method of addressing the challenge of vehicle post-collision fires (including motorsports) has clearly illustrated the imperative of clearly understanding the details and subtleties of the automotive post-crash fire threat, including a competency in understanding the fuel release dynamics and ignition exposure phenomena, and the proper means of replicating these critical parameters in full-scale evaluations of such unique technologies. The panel device has been tested and demonstrated in several ambitious, large scale crash test and fire programs, both conducted by FIRE Panel staff and by independent specialist organizations, and has consistently shown its ability to discharge and disperse inerting powder, and prevent the ignition of realistically discharged fuel, in these crash test events. Although the police car versions of the device have seen considerable proliferation and field service use in the last year and a half, including reports of actual real-world crash deployments, it is being used in other applications as well, including high-end specialty vehicles, as well as motorsports. In fact, the motorsports applications have led to new panel designs and placement techniques, and recent experiences in Nextel Cup competition have further refined this approach. New motorsports applications are planned for the latter half of 2004 and 2005, as well as novel military applications. Additional independent testing for a variety of crash scenarios is encouraged to further document its effectiveness.

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