ENHANCED POWDER PANELS

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INTRODUCTION

Ballistic threat-induced fires are a major contributor to aircraft vulnerability. This paper describes a recent investigation of new concepts for powder panels, an old alternative for discharging dry chemical agents to extinguish combat-induced fires in aircraft dry bays. Powder panels lining a dry bay can provide passive, lightweight, effective fire protection against ballistic impact by releasing powder into the fire zone to inert the space before the adjoining fuel spills into the space and is ignited by incendiaries.

The design and acceptability criteria for these devices are different from conventional fluid suppressant systems. Powder panels add weight based upon the surface area of the fuel wall/fire zone interface, as opposed to the volume of the fire zone, so the relative benefit of the panels is dependent upon the configuration of the particular bay. False discharges do not occur, but cleanup following a fire or inadvertent damage remains a concern.

Powder panels have seen limited use on helicopters and fixed-wing aircraft for many years. Yet, current powder panel designs are in essence very similar to those that have existed for decades. The recent production ban on halons due to ozone depletion concerns and technological advancements have renewed interest in powder panels.

The objective of this project is to identify concepts for powder panel enhancement (relative to current capability and halon 1301) and demonstrate proofs-of-concept. The basis for this advanced protection will be characterization of current powder panel technology and assessment of recently developed improvements in powder panel materials and construction. The expected outcome of this work will be enhanced powder panel concepts that are competitive with halon 1301 in critical parameters such as weight, volume occupied, fire extinguishing capability, etc. and, thus, are candidates for use in its place.

This work was performed under the Next Generation Fire Suppression Technology Program (NGP), funded by the Department of Defense's Strategic Environmental Research and Development Program (SERDP). This paper describes efforts during the first year of a two-year effort.

POWDER PANEL SURVEY

Efforts on this project began with a survey of powder panel applications in operational U.S. aircraft and investigations of previous powder panel testing. The purpose of the survey was to identify powder panel materials and designs that have been previously evaluated and those that have actually been integrated into aircraft designs. Using this information as a baseline, improvements in powder panel designs could be evaluated in this program.

Powder panels around aircraft fuel tanks were first developed and used by the Royal Aircraft Establishment in England [1]. They have also been examined widely for military combat land vehicles, such as tanks and armored personnel carriers [2-5], compared to aircraft applications. The survey included the collection of all available data, however, it focused on more recent test programs and on U.S. aircraft applications. In U.S. aircraft, the widest use of powder panels has been in helicopters. A number of test programs have been conducted to evaluate powder panel applications in helicopters. A significant effort was conducted, for example, to evaluate both parasitic (attached to existing structure) and structural (panels themselves function as structure) powder panels in Army AH-1S Cobra helicopters [6-9]. Although powder panels were never integrated into the AH-1S, they have found their way into the U.S. Marine Corps AH-1W Super Cobra [10] and are being evaluated for the AH-1Z and the RAH-66 Comanche helicopters. Testing was recently conducted at Boeing to evaluate powder panel applications in the AH-64 Apache. This evaluation examined the replacement of dry bay void space foam with powder panels along the fuel tank walls as well as other vulnerability reduction techniques. Perhaps the most notable recent integration of powder panels into an aircraft design is the use of these fire extinguishing devices in the V-22 Osprey tiltrotor aircraft’s sponsons and wing leading edges.

The survey included an examination of previous powder panel test programs relating to U.S. applications extending back to at least the late 1970’s [6]. Many of the test programs included evaluations of the fire extinguishing effectiveness of various powder panel designs and various dry powders contained within the panels [11-13]. Standard designs included the use of thin aluminum foil, Nomex, or composite panels sandwiching an aluminum or Nomex honeycomb core, which contained the fire extinguishing powder. Typical powders included aluminum oxide (Al_2O_3), Purple K, and Monnex, for example. Aluminum oxide has been extensively used in powder panel testing and is the only powder identified in U.S. aircraft applications, primarily due to its low corrosiveness compared to the other powders [3, 14]. A summary of some previously tested powder panel materials is included in Table 1.

TABLE 1. EXAMPLES OF PREVIOUSLY TESTED POWDER PANEL MATERIALS

FRONT FACE	RIB STRUCTURE	BACK FACE	PANEL THICKNESS (mm)	POWDER
0.001" 8111-0 aluminum (Al) alloy foil, 0.004” Al, 0.020" 2024-T3 Al, 0.001” stainless steel, 0.20" titanium, 2-ply graphite-epoxy tape, 3-ply (0/90/0) graphite epoxy, 2-ply Kevlar-epoxy cloth, polyethylene, Pro-Seal coated ballistic nylon bags	2024-T2 Al honeycomb, fiberglass honeycomb, Al foil bags, Nomex honeycomb	0.001" 8111-0 alloy Al foil, 0.013” Al, 0.020" 2024-T3 Al, 0.16" 2024-T3 Al, 2-ply fiberglass/epoxy, 2-ply graphite-epoxy tape, 3-ply (0/90/0) graphite epoxy, 2-ply Kevlar-epoxy cloth, polyethylene, Pro-Seal coated nylon	1.27, 1.78, 2.29, 2.54, 3, 3.05, 6.4, 9.5, 12.7, 25.4	Monnex, KDKI, Al_2O_3, Al_2O_3+10% KI, Al_2O_3 with 1% silicon oxide, Purple K, potassium bicarbonate, 10% acetate in water

In addition to examining military-specific powder panel testing, an examination of recent powder panel work for non-ballistic applications was performed. Data were obtained for powder panel evaluations using a much wider variety of materials with potential for greater fire extinguishing effectiveness. Drawing upon data from the powder panel survey, a baseline set of materials and designs was established for examination in this project.

EXPERIMENTAL INVESTIGATIONS

An experimental test device (dry bay/fuel tank simulator) was designed and fabricated to enable a direct comparison of powder panel materials and designs, both existing and improved concepts. Through an impact dynamics study, various characteristics critical to the fire extinguishing effectiveness of powder panels can be examined. The test device shown in Figure 1 allows for the experimental screening of candidate powder panels by comparing these characteristics in a highly repeatable fashion. Among the characteristics that can be examined are panel fracture, including cracking and material removal, the amount of fire extinguishing powder released into the test article, the dispersion of this powder, and the time the powder remains suspended in the dry bay.

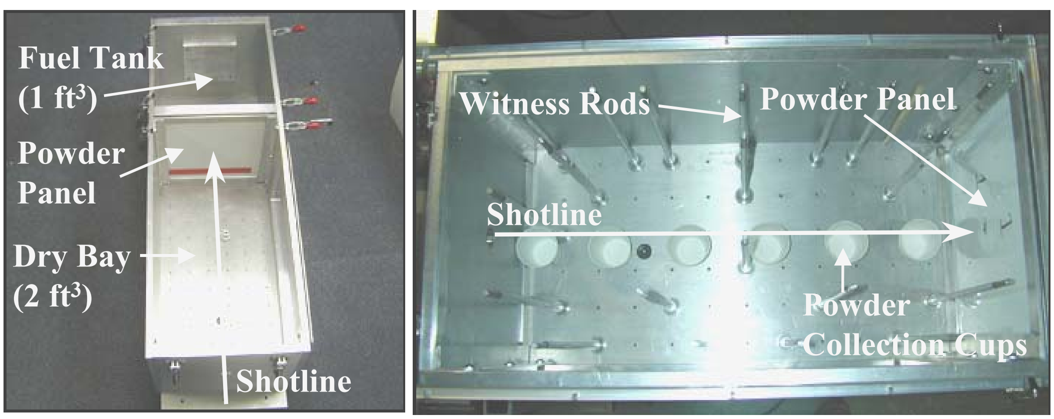

Figure 1. Experimental Test Device and Powder Collection Methods

The test device represents a 60.96 cm^3 (2 ft^3) aircraft dry bay and a 30.48 cm^3 (1 ft^3) fuel tank. The fuel tank is capable of holding fluid, and the dry bay is designed with Lexan windows to allow for visual observation of each test. Testing this first year did not involve fluid in the tank or airflow so the screening process would be simplified. Replaceable 7075-T6 aluminum panels of 2.032 cm (0.08 inch) thickness are inserted to represent the fuel tank wall adjacent to the dry bay. In most of the tests conducted thus far, powder panels have been secured directly in front of the fuel tank wall. This likely offers the worst-case scenario for evaluating the amount of powder released into the dry bay. The test device also allows for the installation of powder panels directly behind the dry bay wall where the projectile enters the test article.

The test device is designed to capture powder dispersion information so a direct comparison between candidate powder panels can be made. Figure 1 (right side) shows the powder collection methods used in the dry bay. Witness rods are located throughout the dry bay. Plastic tubes are slid over the rods to capture released powder during each test. The rods are placed in a pattern to ensure that the powder dispersion characteristics throughout the dry bay are understood. The plastic tubes are observed for qualitative signs of powder after each test. Powder collection cups are also located in the dry bay. These cups are located along the shotline, where the powder concentration is most important during a ballistic projectile impact. The path of the projectile incendiary or impact flash is the location where the mixture of flammable fluid and ignition source is most likely to result in fire initiation. The collection cups are examined and weighed after each test to determine the amount of powder collected. In addition to these collection methods, each panel is weighed before and after each test to determine the amount of powder released. Panel components are also individually weighed before each test. The removed area of the front face (dry bay side) of the powder panels is also determined. This area is typically a direct correlation with the amount of powder released into the dry bay and provides another measure to compare the panels. For comparison, the back face (fuel tank side) removed area of the powder panel is determined as well. Digital video was captured for each test to assist in determining the length of time powder was suspended in the dry bay.

So necessary experiments could be accomplished, an agreement was secured with the Air Force 46th Test Wing Aerospace Survivability and Safety Flight (46 OG/OGM/OL-AC) to make use of a light-gas gun to launch ball projectiles at velocities comparable to combat munitions. In testing conducted to date, 0.50 caliber hard steel ball projectiles have been fired at velocities greater than 670 meters/second (2,200 feet per second). The kinetic energy of these projectiles is roughly equivalent to a threat greater than a 7.62mm armor piercing incendiary (API), but somewhat less than a 12.7mm API projectile. A compressed helium-filled bottle rated at 20.684 MPa (3,000 psi) is being used to fire the projectiles in Range A of the Aerospace Vehicle Survivability Facility (AVSF) at Wright-Patterson Air Force Base, Ohio (Figure 2).

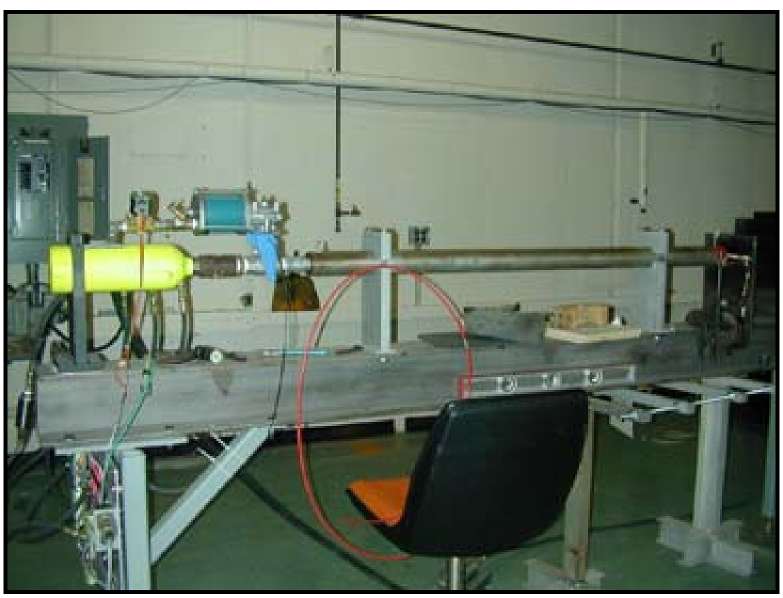

Figure 2. AVSF Range A Light-Gas Gun

Testing during the first year involved only one dry chemical fire extinguishing agent. The powder selected was $KHCO_3$ (Purple K) due to its non-toxic nature, visibility for post-test inspection, and fire extinguishing effectiveness. Corrosion from long-term exposure was not a concern in these tests.

A total of 32 powder panel tests were conducted during the first phase of this program. These tests included components similar to those examined in previously tested powder panel programs to provide some baseline data. Among the materials tested were thin aluminum (0.4064 mm thick) and aluminum foil panels. Also examined were 3.175 mm (0.125 inch) and 6.35 mm (0.25 inch) thicknesses of 5052 aluminum honeycomb, acting as the rib structure for various panels. A Nomex (aramid fiber paper) honeycomb core of 9.525 mm (0.375 inch) thickness was also tested.

The majority of tests conducted thus far, however, have featured unique materials and designs not evaluated in previous powder panel ballistic testing. For the front panel face (dry bay side), materials that exhibit brittle properties upon impact, but durability in handling, were of utmost interest. In early testing, the emphasis has been on the use of thermoplastic polymer materials, particularly for the panel front face. Plastics have also been tested for the back face (fuel tank wall side) and in various configurations for the internal rib structure of the panel. The goal has been to find a front face material and powder panel design that results in significant material loss and powder release into the dry bay during the ballistic impact event. Front face materials evaluated have included a polycarbonate (Lexan), polystyrene, polypropylene, and polymethyl methacrylate (acrylic-Plexiglass). Although other thermoplastics may show similar or better properties, the materials tested thus far are cost-effective and easily obtainable in off-the-shelf forms. Some off-the-shelf forms of some of these materials were panels used in overhead fluorescent light fixtures. These panels come in a variety of designs that may enhance or degrade their brittle nature. Both acrylic and polystyrene lighting panels in a variety of faceted designs were tested. The use of intentional surface scoring of flat acrylic panels was also examined using a couple of different scoring patterns. The intent was to determine if surface scoring could be used to enhance the fracture characteristics of the material.

Thermoset polymers were also evaluated for the front face. Tested materials included two polyester resins, an epoxy resin, and a thin epoxy primer. The thin epoxy primer tested was only 0.0762 mm (0.003 inch) thick. It is available commercially as a spray and requires a careful procedure for forming it and bonding it to the rib structure. The other thermoset materials are readily available in commercial form, requiring the mixing of a two-part liquid resin.

Thermoplastic materials have also been examined for the back panel. The impetus for experimenting with the back panel is to determine if the fracture characteristics of the back panel influence the front panel in any way. For the test device configuration examined, there was no need for powder to be released into the fuel tank; rather it is intuitively more desirable to inhibit the back panel hole size to reduce flammable fluid leakage. As mentioned earlier, testing thus far has not involved the use of fluids in the fuel tank.

A number of materials and designs have been examined for the powder panel internal rib structure. The rib structure adds rigidity and strength to the panel, prevents settling of the powder, and must allow for easy release of as much powder as possible. Some of the panels examined thus far were single piece extruded materials that had front and back walls and internal channels. These panel designs were composed of polycarbonate and polypropylene. They were filled with powder in their production form, and the ends were sealed for testing. As mentioned, honeycomb materials were also examined. One honeycomb material evaluated was 3.175 mm (0.125 inch) thick, composed of polycarbonate material, and featured a circular cell structure. The honeycomb materials maximized the amount of bonding area to the front panel, which typically inhibited front face cracking.

Several rib designs were conceived to enhance powder release and yet prevent the settling of powder that might reduce its effectiveness to impacts in certain areas. One design included sections of hollow acrylic tubing aligned horizontally and spaced at vertical distances of one inch or less (Figure 3). Both the tubes and the spaces between the tubes were filled with powder to ensure total coverage to threat impact. This rib design provided significant panel stiffness due to the amount of bonding surface area and seemed to provide leverage for sections of the front face to flex and break out. Another design concept was to use strips of solid plastic oriented horizontally in a fashion similar to the tubes. In these trials, the width of the solid strips was minimized since powder would not be present in these locations during a projectile impact. Tests were conducted with the number of these ribs minimized, the spacing maximized, and the overall panel thickness minimized. These panels were relatively stiff due to the strength of the panel face-to-rib bonds, but allowed for significant flexing of the front face due to the rib spacing. A corrugated aluminum of approximately 1.5875 mm (0.0625) inch peak-to-peak height was also examined in some tests. This design, the acrylic tube design, and variations of the horizontal plastic strip design allowed for filling of the powder panel after the panel was nearly assembled. Only the one edge had to be sealed after filling. This design variation may offer some improvement for assembly as well as performance.

Figure 3. Rib Design Featuring Hollow Acrylic Tube Channels (Post-Test)

EXPERIMENTAL SCREENING RESULTS

Table 2 describes some of the panels tested in the first year. This table lists some of the more novel and effective designs as well as some designs that feature more baseline design concepts and less effective performance. Table 2 indicates the weight of each 1 foot square section, a design feature that will be optimized in the second year of testing. Total panel weights tested thus far have ranged from 428.2 grams (0.944 pounds) to 1,403.0 grams (3.093 pounds). Most of the weight difference is due to varying thicknesses of the panels, with the weight of the powder contributing significantly because of increased panel internal volume. Although not listed here, weights have also been tabulated for individual powder panel components.

TABLE 2. COMPARISON OF EFFECTIVE (TOP HALF) AND INEFFECTIVE (LOWER HALF) POWDER PANEL DESIGNS

Test No.	Material Description	Thickness (mm)	Panel Weight (g)	Powder Loss (g)	% Powder Loss	Front Face Area Removed (cm^2)
8	0.08" clear acrylic faces, 0.375" acrylic tube ribs	13.5	1402	48	5.6	31.6
9	0.07" cracked ice acrylic front, 0.06" white styrene back, two white styrene ribs (0.12" thick) at 4" and 8"	6.9	769	23	5.0	17.7
12	0.08” (2" x 2" scored) clear acrylic, 0.08" clear acrylic back, 0.125" polycarbonate honeycomb rib	7.6	579	9	4.6	22.6
21	0.07" acrylic prismatic front, 0.06" white styrene back, two white styrene ribs (0.12" thick) at 4" an 8"	7.8	552	30	12.8	20.3
23	0.07" styrene prismatic front, 0.06" white styrene back, two white styrene ribs (0.12" thick) at 4" and 8"	6.5	517	28.4	12.8	25.6
27	0.098" polyester resin front, 0.06" white styrene back, two white styrene ribs (0.12" thick) at 4" and 8"	7.1	620	8.2	4.0	25.4
28	0.098" polyester resin front, 0.06" white styrene back, two white styrene ribs (0.12" thick) at 4" and 8"	7.4	876	83.3	18.7	80.6
1	0.016" Al front, polyethylene corrugated rib, 0.01" Al foil back	6.0	630	0.6	0.17	1.3
2	0.01" Al foil front, polyethylene corrugated rib, 0.016" Al back	5.9	594	0.04	0.01	1.3
13	0.06" white styrene faces, 0.375" aramid rib	13.5	1128	1.5	0.2	1.3
14	0.07" cracked ice acrylic front, 0.08" clear acrylic back, 0.25" Al honeycomb rib	10.5	832	1	0.23	1.3
15	0.06" white styrene faces, 0.25" Al honeycomb rib	10.2	764	1	0.25	1.3
16	0.08" clear acrylic faces, 0.25" Al honeycomb rib	10.8	942	3	0.65	1.6
18	0.08” (2" x 2" scored) clear acrylic front, 0.08" clear acrylic back, 0.125" Al honeycomb rib	7.2	638	2	0.82	9.5

Table 2 also provides an estimation of the powder lost in each test. The estimate of the powder loss is determined by comparing the panel weight before and after each test and weighing/estimating panel material lost. In cases where the panel was not effective at dispersing the powder, the hole on both faces of the panel may have been virtually the same size as the projectile (approximately 12.7 mm diameter). In other cases, a significant amount of the front face material may have been lost (Figure 4). Obviously, in these cases, a significant amount of powder was also released from the panel. The amount of powder released during testing has varied from a fraction of a gram in some of the more standard designs to over 100 grams.

Figure 4. Test Example of Significant Panel Fracture and Material Loss

A review of the test data indicated a wide disparity in the reaction of the panels. In some tests, the powder loss was negligible, i.e., no powder was detected on the witness rods and no powder deposited in the cups. In these ineffective powder panel tests, more powder is actually observed exiting the back of the panel, along with the projectile, versus entering the dry bay. In other tests (Figure 5), the cloud of powder in the dry bay engulfed the entire dry bay and remained for a matter of minutes. Many tests resulted in some minute residue in the cups that was more likely spall from the powder panel front face and/or ribs, rather than the powder. In tests of effective powder panel concepts, powder was observed on all the witness rods and measurable powder weights were observed in all six cups. The amount of powder deposited in the collection cups has varied during testing from no trace to over seven grams by weight. Typically, 0.05 grams or less was captured in any single cup, with the highest concentration of the powder being closest to the powder panel, as expected. Twenty different witness rods were placed throughout the dry bay and visible powder was noticed in more effective tests on all of the witness rods. To further verify the dispersion of the powder, several panels were tested with dry bay clutter and powder was still observed on all witness rods, even those in isolated areas.

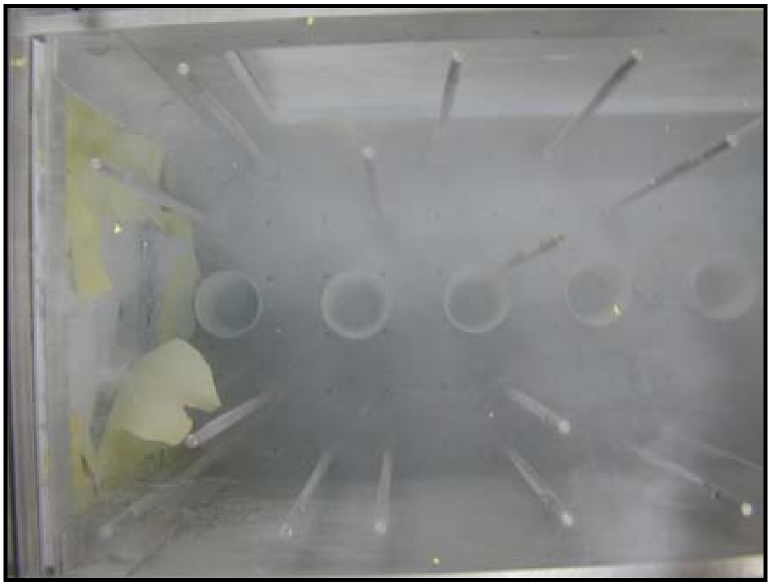

Figure 5. Test Example of Effective Powder Release and Dispersion

CONCLUSIONS

The outcome of the non-fire screening tests was gratifying. The most promising of the new powder panel designs examined in this project offer the potential to be competitive with halon 1301 in a wider variety of dry bay designs. In one of these cases (epoxy primer front face), nearly 50% of the front face area was removed, almost 60% of the powder was released, and the powder remained suspended throughout the dry bay for over four minutes. This was true despite the fact that this was one of the thinnest panels tested. This compares with testing of other powder panel designs integrated into operational aircraft, where the powder dispersed only along the shotline, dissipated in tenths of a second, and the amount of dispersed powder was limited to the region of projectile penetration [15]. Figures 6 and 7 show major performance benefits achievable with the enhanced design concepts listed in Table 2 by test number. Figure 6 demonstrates that more promising powder panel designs could increase powder release 5 to 10 times over more standard powder panel designs. Likewise, testing of these enhanced designs resulted in 15 to 20 times greater front panel face area removal compared to more standard designs (Figure 7).

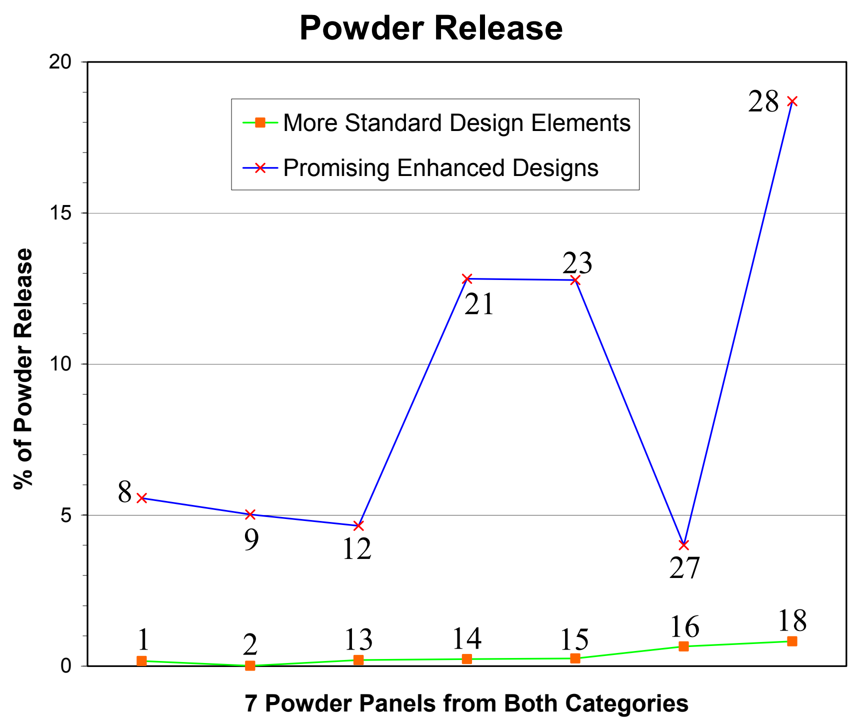

Figure 6. Effect on Suppressant Delivery of Standard Design Features and Enhanced Designs, Showing 5x to 10x Greater Powder Release in the Latter

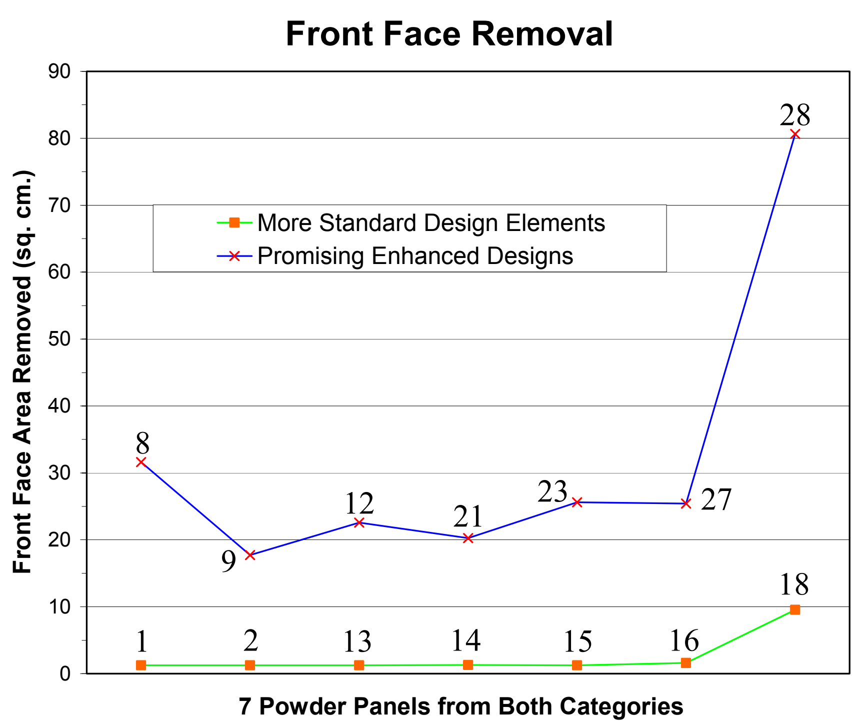

Figure 7. Effect on Powder Panel Fracture Area of Standard Design Features and Enhanced Designs, Showing 15x to 20x More Front Face Area Removed in the Latter

Early observations indicate, as predicted, that the front face material properties are of utmost importance. More brittle materials outperformed ductile materials (that resist fracturing) by releasing more powder into the dry bay. The projectile seemed to melt its way through polycarbonate and polypropylene materials, and even some polystyrene materials, resulting in little or no powder released into the dry bay. Acrylic front face panels and faceted acrylic and styrene materials reacted in a much more brittle nature, resulting in lost material or cracking that more effectively released powder into the dry bay. One acrylic panel with a prismatic square pattern actually did not perform very well. It is probable that the pattern on the panel actually inhibited crack growth. Mixed results were found during testing of scored acrylic panels. Some cracking seemed to follow scoring lines in the vicinity of the impact that may have contributed to more material loss. However, comparisons between two-inch and four-inch scoring patterns showed that cracks emanating from the hole area, created directly by the projectile impact, were actually prevented from growing longer, i.e., scoring lines acted as crack stoppers. With additional experimentation, though, it appears crack growth optimization techniques could be used to enhance performance.

A strong synergism was found between the rib structure and the front face. Increasing the bond area between the face and ribs inhibited powder dispersion. Results indicated that standard honeycomb ribs resisted greater front face cracking because of the increased number of bond sites. Experiments bonding honeycomb materials to the front face in selected areas, such as the panel perimeter, proved effective for polycarbonate honeycomb, but not for the aluminum honeycomb. Further study is required to determine if this was due to the more brittle properties of the polycarbonate or to weaker/fewer bonding sites to the front face panel. Design concepts using channels or horizontal ribs proved to be associated with the most effective powder panels, particularly when a more frangible front face was used. Channel designs allowed more powder to be released from the impact location than more segmented or cellular designs. Tradeoffs will be necessary between rib spacing and powder loading, as sufficient powder must be available at all potential impact sites. Three-piece powder panel designs outperformed easy-to-assemble double-wall extrusion designs, as built-in rib channels inhibited cracking.

Variation in the powder panel back face had much less effect on powder panel performance than the front face or rib design. Although sufficient data have not yet been produced to prove the hypothesis, it is postulated that a smaller hole in the back face may actually mitigate the chance of a dry bay fire by reducing fuel leakage and confining it to an area along which most of the powder is released. One finding has been that the front face of the powder panel can be designed to fracture and release large amounts of powder, while minimizing the damage to the panel back face. Testing thus far has not involved a fluid-filled tank, thereby eliminating hydrodynamic ram pressures on the fuel tank wall and reducing the chance of damage to the back face. Polystyrene was used as the material for many of the panel back faces tested thus far. In most of these cases, the damage sustained by the back face has been a hole just larger than the diameter of the 12.7 mm diameter ball projectile.

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