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13. ABSTRACT (Maximum 200 words)
This report documents work performed under the Next Generation Fire Suppression Technology Program to identify powder panel concepts for enhancing aircraft dry bay fire suppression performance relative to current capability and to demonstrate proofs of concept. Powder panels lining an aircraft dry bay can provide 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. Current powder panels, which are very similar to designs used for decades, have a limited range of performance and have not found wide acceptance. This program demonstrated the feasibility of enhanced powder panel concepts, showing new designs could afford the following benefits over current commercial powder panel designs: greater powder release into the dry bay, better dispersion of powder to prevent ignition off-shotline, longer powder suspension to prevent fire ignition for longer periods of time, and increased design flexibility that can be utilized to target weight, durability, and application-specific design goals. Enhanced powder panels were optimized to target likely aircraft production requirements and live fire tests demonstrated improved effectiveness over commercial powder panels at equal or lower weight and thickness.

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1. Introduction

Onboard fires represent a significant hazard to aircraft due to the large quantity of flammable fluids carried and the potential for a variety of ignition sources to be present. The combat environment for military aircraft or even a terrorist environment for civilian aircraft poses a significant fire hazard when a ballistic threat is introduced. These threats are designed to act as ignition sources upon penetration of onboard flammable fluid containers. As previous combat experience and vulnerability analyses have shown, fire is the most significant vulnerability faced by an aircraft subjected to ballistic threat impact.

Halon 1301, used for fire extinguishing and explosion suppression applications in fielded weapon systems, including aircraft, and mission-critical facilities, has been banned from national production due to its high ozone-depleting potential. Alternatives developed by industry have sizable weight and volume penalties, and their application to fielded current weapon systems could require expending large amounts of funding and time. Consequently, the DoD embarked on an aggressive new research and development program, the Next Generation Fire Suppression Technology Program (NGP). The NGP goal is to develop and demonstrate, by 2005, technology for economically feasible, environmentally acceptable and user-safe processes, techniques and fluids that meet the operational requirements currently satisfied by halon 1301 systems in aircraft. The NGP addresses the predominant fires occurring in aircraft dry bays and engine nacelles, focusing resources on identifying and examining promising chemicals and precepts for their effective dispersion and distribution in both current and planned platforms.

One area of focus for the NGP has been improved storage and delivery of fire extinguishing agents. Since the production of halon 1301 has been phased out, delivery systems that have used it for ballistic threat-induced fire protection in fire zones eventually will require some substitute technique. One technique for passively storing and delivering agent upon the impact of a ballistic projectile is the use of powder panels. Powder panels have most often been applied to the lining of aircraft dry bays to provide passive, lightweight, effective fire protection against ballistic impact. Projectile penetration of the dry bay and adjacent fuel tank releases agent from the powder panel into the fire zone to inert the space before the adjoining fuel spills into the space and is ignited by incendiaries. The recognition of ballistic threat-induced fires as a major contributor to aircraft vulnerability and a desire to avoid active halon fire extinguishing systems has led to a renewed interest in powder panels as a fire protection device.

Despite the potential for powder panels as an aircraft fire protection device, commercial powder panels are roughly the same design that has existed for decades, and their limited range of effectiveness has prevented further implementation in production aircraft. In 2001, the NGP embarked on an effort to use current technology and new ideas to examine the feasibility of enhanced powder panel designs and demonstrate proofs-of-concept. This report details a two-phase effort to accomplish this work (References 1, 2).

1.1 Powder Panel Background

Powder panels are passive fire protection devices for discharging dry chemical agents to prevent or extinguish combat-induced fires in military vehicles. They consist of two walls, an internal rib or core structure, and are internally loaded with a fire extinguishing agent, typically a dry chemical powder. Historically, commercial powder panels have consisted of thin walls of aluminum foil or composite sheets, with an aluminum or Nomex honeycomb core. Typical thicknesses for commercial powder panels have been reduced to just over 2.54 mm (0.1 in.). Powder panels are typically arranged along the walls of a void area in a military vehicle (called a dry bay in an aircraft) adjacent to or on the walls of a flammable fluid container (fuel tank, fuel line, hydraulic fluid reservoir, etc.). Figure 1-1 depicts the typical arrangements of powder panels. They are typically attached directly to the wall of the flammable fluid container by an epoxy adhesive. Testing has shown this arrangement to be more effective than mounting on the walls of the dry bay separated from the fluid container (Reference 3). Upon penetration by a ballistic projectile, powder panels release powder into the fire zone to inert the space before the adjoining fuel spills into the space and is ignited by incendiaries or other ignition sources.

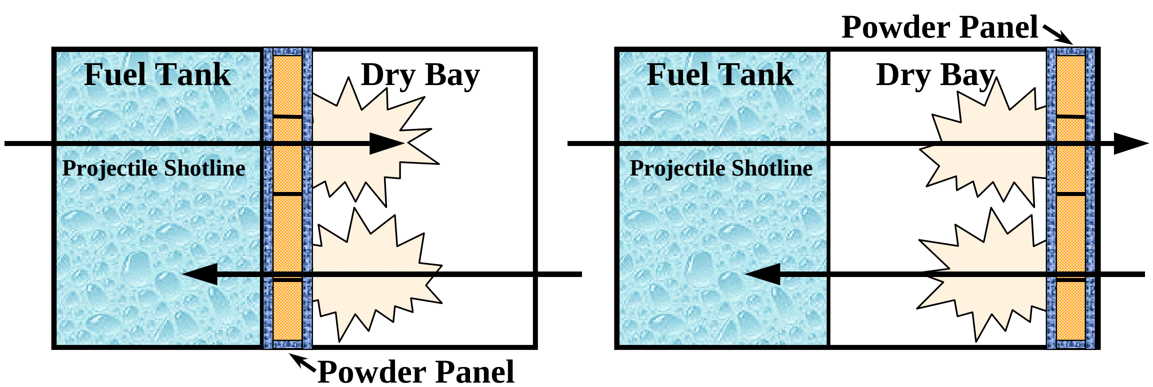

Figure 1-1. Typical Powder Panel Arrangements

The design and acceptability criteria for these devices are different from conventional active 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. Typical areal densities (weight/surface area) for commercial powder panels are on the order of 0.195 to 0.244 g/cm^2 (0.4 to 0.5 lb/ft.^{2}).

Powder panels are not a new concept for extinguishing ballistic threat-induced fires in aircraft, as discussed previously. They have in fact been around for many years. Despite testing which has demonstrated the effectiveness of these devices, powder panels have seen limited use in aircraft and armored ground vehicles. Powder panels around aircraft fuel tanks were first developed and used by the Royal Aircraft Establishment in England. Some U.S. helicopters and the V-22 aircraft have implemented powder panels in their vulnerability reduction designs.

Powder panels have also been widely examined for military combat land vehicles, such as tanks and armored personnel carriers, but have been applied in limited circumstances.

Several reasons exist for the limited use of powder panels. False discharges do not occur with these passive fire protection devices, but cleanup following a fire or inadvertent damage has been a concern. This concern, primarily in aircraft, stems from the possibility of corrosion by the contact of chemical powders with vehicle structure. As a result, current powder panels often use an inert fire extinguishing powder, such as aluminum oxide (Al_2O_3), to prevent reaction with the metal. In military ground vehicles, wide application of powder panels has been limited due to the potential ill, albeit limited, effects on crewmembers or obscuration of the crew compartment upon activation. Although non-toxic agents can be used, during the period of time the powder particles are suspended in crew areas, the crew may have difficulty breathing and operational effectiveness may be limited. Several other reasons cited for their limited use overall include concerns over durability, potential adverse effects on electromechanical components and optics, their ability to protect highly cluttered areas, airflow influences, a lack of protection from accidental fires, and difficulty in selling a low-tech approach.

Although powder panels have been examined for years, current commercial powder panel designs are in essence very similar to those that have existed for decades. However, a number of factors have renewed interest in powder panel technology. First, the banned production of halon 1301, due to its ozone depleting potential, has created a demand for new techniques to fill its role. Also, new materials, powders, and construction techniques have been developed, which may allow for improved powder panel performance (both system weight and fire extinguishing capability).

Since the production of halon 1301 has been phased out, systems that have used it for ballistic threat-induced fire protection in fire zones eventually will require some substitute technique. Powder panel technologies are viable alternatives for some of these applications. They don't require detectors, plumbing, wiring or bottles, and they are false-discharge resistant. Current designs have limitations, particularly limited powder dispersion ability, and problems providing protection against relatively small caliber threats. As a result, most don't compare favorably against halon 1301 in trade-off studies.

Improved powder panels could expand use of this fire protection technology for additional vulnerable fire zones on our critical weapons systems. New powder panel concepts with enhanced characteristics have been proposed recently. These include frangible materials to optimize dispersion, single-piece construction technology, modular designs, predosed sections, lighter weight materials, and lower cost materials. These enhanced powder panels could be used in applications as halon 1301 or other fire extinguishing system replacements, or they could replace existing powder panels with superior technology.

1.2 Fire Ignition and Powder Panel Effectiveness

Powder panels work through the release of fire extinguishing powder into the mixing zone of a flammable fluid and an ignition source to essentially inert the zone or prevent a fire from igniting. To assist in the discussion of powder panels and their effectiveness, it is helpful to discuss fire ignition, as it relates to an onboard aircraft fire due to ballistic projectile penetration.

For any fire to initiate, the interaction of a flammable fluid, oxidant, and ignition source is required (Reference 4). However, the simple mixing of these three ingredients does not ensure fluid ignition or the initiation of a sustained fire. Fire initiation by a ballistic threat is a complex phenomenon involving a process that sequentially brings together the three ingredients at the right time, in sufficient and proportional quantities, and with the needed intensity. The process begins when the ballistic threat penetrates the vehicle, functions its incendiary, and traverses the vehicle penetrating the fluid container, thereby releasing fluid into the open volume of the vehicle. This open volume is referred to as a dry bay in aircraft. While each threat type is inherently different, the result is the same, i.e., deposition of thermal energy into a volume of air in front of the impact hole and the raising of the temperature of this volume. If the threat impacts a flammable fluid container within the vehicle and releases fluid, the fluid will be injected into the dry bay some distance by the threat/container impact and the container pressure. As the fluid is injected into the dry bay, it atomizes (i.e., breaks up into droplets). As the droplets penetrate into the heated air, they begin to vaporize, and the fluid vapor mixes with the surrounding air and produces a flammable fluid/air mixture. As the fluid/air mixture is heated, a chemical reaction will commence.

As the reaction proceeds, heat is lost to the surrounding air by conduction. If the rate of heat produced by the reaction exceeds the rate of heat lost by conduction, the chemical reaction will accelerate until all the oxygen (for fuel rich conditions) within this volume is consumed, a flash is seen more or less simultaneously throughout this volume, and ignition has occurred. If the rate of heat lost exceeds the rate of heat produced, then the temperature of the volume will begin to decrease, and the rate of reaction will decline as well. Eventually the reaction will cease and ignition will not occur. As such, ignition is simply a reaction that proceeds to consume the available flammable fluid/air mixture contained within the volume encompassed by the ignition source, resulting in a flame visible within this volume. If after ignition occurs, sufficient oxygen and the flammable fluid source are available, a sustained fire may result that could lead to a loss of the aircraft.

Fire extinguishing powder introduced into this volume immediately upon impact by the ballistic projectile has the potential to reduce the probability of a fire ignition. The powder must render the fuel/air mixture nonflammable so the chemical reaction does not continue. The powder can do this in two ways. According to Reference 5 (and further citations in this reference), it is widely believed that fire extinguishing powders can function as both energy-absorbing materials and as solid surfaces on which free radicals can be destroyed. Heat may be absorbed by the heat capacity of the solid, the heat of fusion at the melting point, the heat capacity of the liquid, heat of dissociation from breaking of chemical bonds, and heat of vaporization. These all contribute to the total energy absorbing capability (endothermicity) of the fire extinguishing powder (Reference 6).

From a chemical aspect, it has been found that there is a catalytic path for destruction of free radicals in certain fire extinguishing powders, for example, H, O, and OH, by utilizing the potassium in potassium salts (References 7, 8). Potassium salts have been shown to be more effective than sodium salts, and iodide anions are more effective than chloride anions. Any powder that has a chemical fire extinguishing capability will also have the heat-absorbing (endothermic) capability (Reference 9).

Testing has shown that smaller and more numerous powder particles, through the increased surface area available, are more effective at reducing the chance of fire ignition than fewer, but larger particles (Reference 10). Reference 6 has shown that less weight of salt per unit volume of fuel-air mixture is required for extinguishment, if the salt is finely divided. Large particles may actually pass through the flame zone before they can reach flame temperature, and thus not absorb as much heat as an equivalent mass of finer particles. In other words, the time required for small particles to become effective is less than that for large particles. Thus, micrometer-sized solids are more efficient as fire extinguishing powders than are larger particles. Large surface areas are important in both the heat absorption and the chemical interference mechanisms.

The effectiveness of the powder panel can, therefore, be enhanced through the proper use of a fire extinguishing powder (type and particle size), and by maximizing the amount of powder released into the mixing zone consisting of the flammable fluid and the ignition source. The objective of the enhanced powder panels is to appropriately select a powder and maximize the amount of powder released into the mixing zone.

2. Task Objectives

The objective of this project was 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 consisted of characterization of current powder panel technology and assessment of recently developed improvements in powder panel materials and construction. The expected outcome of this work was 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.

3. Technical Problems

In order to become a viable concept for combat fire protection in aircraft, two major technical problems for powder panels needed to be addressed. These two major problems, performance and practicality, are intertwined. Previous powder panel testing evaluated a number of different powder panel designs and materials and showed limited ranges of effectiveness. One consistent factor in many of these designs was the use of a honeycomb structural material as the rib or core material. Honeycomb provides several positive attributes to powder panels. First, it adds structural integrity to the panel, as honeycomb has proven to be as a structural design technique in aircraft construction. Honeycomb also allows for even distribution of the fire extinguishing powder throughout the panel, minimizing concerns over powder settling. It also can be constructed of very lightweight materials such as Nomex or aramid fibers. The limiting factor for honeycomb has been its performance. Only cells in the direct path of projectile penetration, and perhaps those just around the penetration area, are torn and allow powder to escape.

Different faces for the powder panel have been tested, focusing on materials such as aluminum foil and several different composites. Many of these efforts have focused on durability in the aircraft environment. However, performance, as quantified through surface area removal or fracturing, has been limited. This is true despite techniques to enhance opening of the powder panel walls such as weak or selective bonding of the panels to the core, particularly for the front or open face to the fire zone. Very thin sheets or films have also been tried to promote surface removal and allow powder to escape.

Consequently, this project needed to demonstrate the feasibility of completely re-designing a powder panel so that it could release a more effective amount of powder. However, production and qualification requirements levied on fire protection methods, such as powder panels, might show these designs to be impractical for aircraft applications. Therefore, additional work was required to optimize these panels for attaining potential design requirements. For example, with aircraft weight restrictions being very demanding, powder panel weight needs to be minimized before it can even be considered competitive as a fire protection solution for a particular aircraft application. This goal involves proper material selection and powder panel thickness determinations. Another key aircraft requirement is durability in the aircraft's harsh operating environment. This includes an ability to survive under extreme (both hot and cold) temperature, vibration, g-loading, and exposure to a variety of chemicals (jet fuel, hydraulic fluid, etc.). These environmental restrictions further reduce the set of materials and design concepts that can be used. Other production requirements may be related to such items as maintainability and reliability. Thus, the problem becomes one of developing a powder panel that is competitive with other fire extinguishing technologies by releasing sufficient powder when penetrated by a ballistic projectile to prevent fire ignition, while still remaining acceptable under tightly controlled aircraft environment requirements.

4. General Methodology

NGP research into enhanced powder panels was organized into two phases. In the first phase, background information was gathered on the state-of-the art of current powder panels, initial concepts for enhanced powder panels were examined, and the feasibility of improved powder panel features was demonstrated. In Phase II, the examination was widened to study if enhanced powder panels were not only feasible, but could become practical, while maintaining improved performance. Optimized powder panels were examined for their potential to meet production requirements and their benefits were examined against other fire protection alternatives. The program concluded with final live fire demonstration tests of the optimized powder panels.

4.1 Powder Panel and Application 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, it was then possible to explore potential improvements in powder panel designs.

Powder panels around aircraft fuel tanks were first developed and used by the Royal Aircraft Establishment in England (Reference 11). They have also been examined widely for military combat land vehicles, such as tanks and armored personnel carriers (References 12, 13, 14, 15), compared to aircraft applications. The powder panel survey conducted in this program included the collection of all available data; however, it focused on more recent test programs and on testing related to U.S. aircraft applications.

An example of the integration of powder panels into a U.S. aircraft design is the use of these fire extinguishing devices in the V-22 Osprey. However, 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 (References 11, 16, 17, 18). Although powder panels were never integrated into the AH-1S, they did find their way into the Navy UH-1Y Huey and AH-1W Super Cobra (Reference 19). AH-1W and UH-1N legacy aircraft are being upgraded to the AH-1Z Super Cobra, which uses powder panels for dry bay protection. Testing was recently conducted at Boeing to evaluate powder panel applications in the AH-64 Apache. This evaluation examined the use of powder panels along various fuel tank walls. Powder panels have also been evaluated recently for the RAH-66 Comanche helicopter.

The powder panel application survey indicated no U.S. fixed wing aircraft currently employ powder panels. A number of reasons have been offered for the lack of implementation of powder panels in fixed wing aircraft. Among these reasons are that powder panels do not assist with accidental fires; low-tech approaches are difficult to sell; and there are concerns over accidental leakage that could lead to corrosion, durability, volume-filling capability with clutter involved, and detrimental airflow influences.

Despite the resistance to implementing powder panels, the success of Phase I evaluations of enhanced powder panel designs sparked interest by several aircraft programs. The potential for increasing effectiveness without negatively impacting weight and other concerns has generated renewed interest. Among the programs inquiring about enhanced powder panel development are the F-35 Joint Strike Fighter, CH-53E Super Sea Stallion, RAH-66 Comanche, and the V-22 Osprey. In the midst of these discussions, Skyward entered into proprietary rights agreements with Bell Helicopter Textron, Inc./The Boeing Company and Sikorsky Aircraft Corporation/The Boeing Company to discuss the possibility of integrating enhanced powder panels into aircraft such as the V-22 and RAH-66, for example. These proprietary rights agreements allowed for the free exchange of design details and production or qualification requirements that may be levied on newly developed panels.

The survey conducted in this NGP project included an examination of previous powder panel test programs relating to U.S. applications extending back to at least the late 1970's (Reference 16). 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 (References 3, 20, 21). 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 ($KHCO_3$), and Monnex ($KC_2N_2H_3O_3$) for example. Al_2O_3 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 (References 13, 5). A summary of some previously tested powder panel materials is included in Table 4-1.

Table 4-1. Examples Of Previously Tested Powder Panel Materials

FRONT FACE	RIB STRUCTURE	BACK FACE	PANEL THICKNESS (mm)	POWDER
• 0.0254 mm (0.001") 8111-0 aluminum (Al) alloy foil • 0.102 mm (0.004") Al • 0.508 mm (0.020") 2024-T3 Al • 0.0254 mm (0.001") stainless steel • 5.08 mm (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 • 0.330 mm (0.013") Al • 0.508 mm (0.020") 2024-T3 Al • 4.06 mm (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 • 3.0 • 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

The literature review revealed some unique powder panel designs and configurations evaluated in previous testing (Reference 22, 23), but also more common powder panel materials and designs. Very thin aluminum or aluminum foil and composite materials have most often been evaluated for the front face or the face toward an open dry bay. Similar materials have been evaluated for the back face or the face attached to or directly adjacent to the flammable fluid container. As Table 4-1 indicates and the literature search showed, the most common rib structural design by far evaluated in previous powder panel testing has been honeycomb. The honeycomb has been composed of various materials, but it has most often been evaluated to enable even distribution of powder and for structural rigidity of the panel.

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. A limited license agreement was established with Horizons Unlimited to examine some recent powder panel design concepts and allow for evaluation of a patented design concept. Drawing upon data from the powder panel survey and this agreement, a baseline set of materials and designs was established for examination in the first phase of this project.

The second phase of the NGP project involved an expanded survey and investigation that included the identification of aircraft using active halon systems for fire protection, particularly in areas where powder panels could be used. This research was to be used for later comparisons of potential powder panel fire protection systems with current halon systems (Section 4.5). The expanded survey also included the identification of design issues for integrating enhanced powder panels into production aircraft and the identification of any necessary qualification testing required before implementation.

The examination of aircraft fire protection systems in the expanded survey revealed halon systems are infrequently used in dry bay areas (Reference 24). Conversely, powder panels have been demonstrated to be effective almost exclusively in these areas. Active halon fire extinguishing systems are prevalent in engine nacelles or auxiliary power unit compartments for fire protection (e.g., A-10, B-2, C-12, C-130, F-14, F-22, P-3 and many other aircraft) or for inerting in fuel tank ullage areas to protect against ullage explosion (e.g., A-6, F-16, and F-117). Powder panels have typically been evaluated in aircraft dry bay areas and have only been integrated into production aircraft in these areas (e.g., V-22 and AH-1W). Therefore, as a part of the cost-benefit or return-on-investment analysis discussed in Section 4.5, a direct comparison of an existing halon fire extinguishing system with an enhanced powder panel system proved to be difficult.

There are only a few potential examples of halon fire protection systems that could provide direct comparisons for a dry bay area. Most of these examples, however, do not offer likely replacement possibilities and are not applicable across a wide range of aircraft. For example, the C-5 aircraft has a center wing leading edge dry bay, which is protected by a halon fire extinguishing system. However, this system was incorporated to protect against overheat or safety-related fires from hydraulic components, not ballistic impact. It is located above the fuselage and would be difficult to hit for most reasonable combat scenarios. Replacement with a passive powder panel fire protection system may not prove practical in this case. As in this example, some of the current halon systems are focused on protecting flammable fluid lines or electronics, which has not been a focus for integrated powder panels, thus far. The C-5 has two other dry bay-type areas with halon protection, focusing on electronics protection, not flammable fluid container protection. The B-1 also has an overwing fairing protection system, meant for protection of a hydraulic line and fuel line. It is not an ideal area for comparison with powder panels, either, for the same reasons discussed for the C-5 aircraft. Data were gathered during this survey for other aircraft areas that provide a more practical application for enhanced powder panels.

Discussions were held during the course of the NGP survey with various aircraft manufacturers to examine production design requirements or issues, and to provide data to them, which could allow for the consideration of enhanced powder panels in design trade studies. Discussions were held with Bell Helicopter - Textron, Inc., The Boeing Company, Sikorsky Aircraft Corporation, and Lockheed Martin Corporation. Specific aircraft discussed were the V-22, RAH-66, and F-35. As discussed previously, proprietary rights agreements were established with Bell/Boeing and Sikorsky/Boeing, and an existing agreement was in place between Skyward, Ltd. and Lockheed Martin. The proprietary agreements allowed for the free exchange of design details and production or qualification requirements that may be levied on newly developed panels.

Specific production aircraft requirements were considered proprietary in most cases, but general design requirements were not and are notable. Among the key design criteria often mentioned in the discussions were powder panel thickness, areal density (weight per unit area), and temperature environment. As with any other aircraft component, particularly a forward-fit component, size and weight are big factors. The powder panel must not interfere with existing equipment and cannot create a significant weight penalty. Since design values associated with specific military aircraft are part of the technical specifications for the respective aircraft, these values will not be discussed herein.

However, these values along with current commercial powder panel thicknesses and weights were used as design goals for the Phase II optimization effort. Commercial powder panels used for testing were composed of a thickness over 0.254 cm (0.1 in.). The core was composed of a honeycomb design and the face sheets were constructed of a composite material. These panels had an areal density of around 0.2 g/cm^2 (0.4 lbs/ft.^{2}). In repeated conversations with aircraft manufacturers, the temperature range most often quoted as a potential extreme requirement for powder panels was from -40°C to 104°C (-40°F to 220°F). In many aircraft areas, continuous service temperature would not reach these extremes, but for purposes of the optimization design effort, these temperatures were considered important.

The aircraft prime contractors were also asked if enhanced powder panels would have to undergo any qualification tests such as thermal cycling, impact resistance, vibration or other durability testing, chemical resistance examinations, and moisture absorption evaluations, for example. Based upon their responses, data suggest that commercially available powder panels may have used individual material data to support such qualification, but the assembled powder panels did not appear to be subjected to many of these tests for production qualification. This is not to imply that future powder panel applications may be relieved of such requirements. Some limited production design criteria were considered for the fully assembled enhanced powder panel, such as panel thickness, areal density (weight per unit area), and temperature environment, as mentioned above. However, resources in this program did not permit a full examination of many of these other potential production requirements.

4.2 Impact Dynamics Experiments

Phase I experimental testing with enhanced powder panels began in the fall of 2001. 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 were examined. The test device shown in Figure 4-1 allowed for the experimental screening of candidate powder panels by comparing these characteristics in a highly repeatable fashion. Among the characteristics examined were panel impact dynamics, 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 remained suspended in the dry bay.

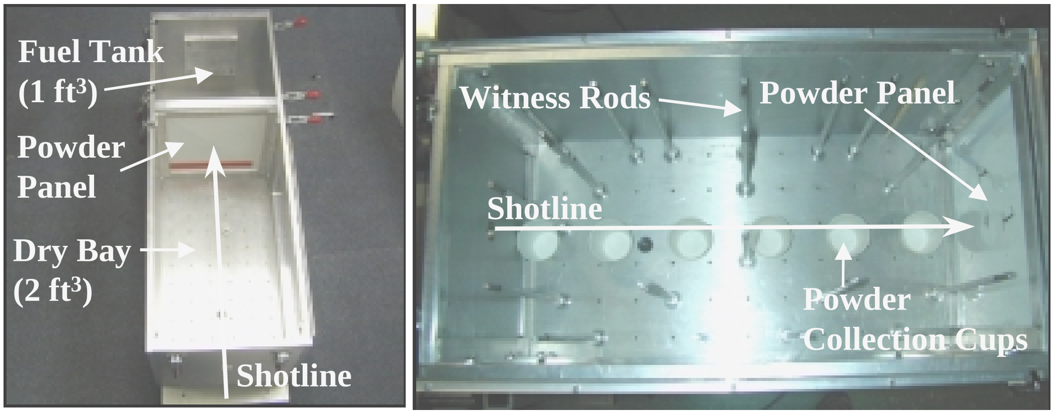

Figure 4-1. Experimental Test Device and Powder Collection Methods

The test device simulates a 0.057 m^3 (2 $ft.^3$) aircraft dry bay and a 0.028 m^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 in the first phase did not involve fluid in the tank, or airflow, so the screening process would be simplified. Replaceable 7075-T6 aluminum panels of 2.032 mm (0.08 in.) thickness were inserted to represent the fuel tank wall adjacent to the dry bay. In most of the tests, powder panels were secured directly in front of the fuel tank wall. This offered the worst-case scenario, without fluid in the tank, for evaluating the amount of powder released into the dry bay. The test device also allowed for the installation of powder panels directly behind the dry bay wall where the projectile enters the test article.

The test device was designed to capture powder dispersion information so a direct comparison between candidate powder panels could be made. Figure 4-2 (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 qualitatively examined for 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 were examined and weighed after each test to determine the amount of powder collected. In addition to these collection methods, each panel was weighed before and after each test to determine the amount of powder released. Panel components were also individually weighed to assist in determining the mass of powder loaded into each panel. The removed area of the front face (dry bay side) of the powder panel was also determined. This area was typically a direct correlation with the amount of powder released into the dry bay and provided another measure to compare the panels. The back face (fuel tank side) removed area of the powder panel was also determined for comparison with the front face and to examine the influence of one upon the other. Digital video was captured for each test to assist in determining characteristics related to powder suspension and dispersion.

Experimental testing was conducted at the Air Force 46th Test Wing Aerospace Survivability and Safety Flight's Aerospace Vehicle Survivability Facility (AVSF) at Wright-Patterson Air Force Base (WPAFB), Ohio (Figure 4-2). The Aerospace Survivability and Safety Flight (46 OG/OGM/OL-AC) was the managing laboratory for this NGP work. In Range A of this facility, a light-gas gun (compressed helium-filled bottle rated at 20.68 MPa (3,000 psi)) was used to launch 0.50 caliber hard steel ball projectiles at velocities of approximately 671 meters/second (2,200 feet per second). The kinetic energy of these projectiles was roughly equivalent to a threat greater than a 7.62mm armor piercing incendiary (API), but just less than a 12.7mm API projectile.

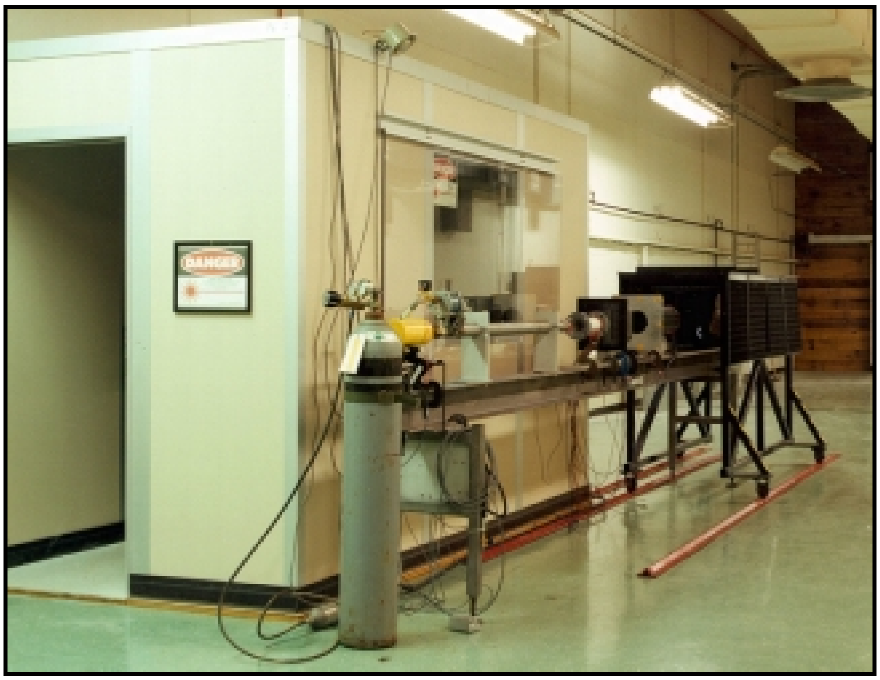

Figure 4-2. AVSF Range A Light-Gas Gun

Testing during Phase I involved only one dry chemical fire extinguishing agent. The powder selected was Purple K ($KHCO_3$) 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.

4.3 Live Fire Proof-Of-Concept Demonstrations

During the summer of 2002, following Phase I experimental testing, Skyward, Ltd. was afforded the opportunity to participate in several live fire demonstration tests of enhanced powder panels. These proof-of-concept tests were conducted in two different test series simulating aircraft dry bays and involving the potential ignition of a fuel fire. These tests provided Skyward with an opportunity to select some of the more effective enhanced powder panel design features identified in Phase I, perform some quick optimization, add some unique design features not previously evaluated, and perform live fire testing, all in advance of the initiation of Phase II. The promising results of these demonstration tests provided a leap forward for the initiation of Phase II.

4.3.1 JTCG/AS Demonstration Testing

The ability of enhanced powder panels to prevent fire ignition was first demonstrated in a Joint Technical Coordinating Group on Aircraft Survivability (JTCG/AS), since renamed Joint Aircraft Survivability Program Office (JASPO) test program examining reactive powder panel concepts, which is a method of using a reactive energetic backing with any powder panel design to enhance powder delivery effectiveness (Reference 25). These tests were conducted at the Naval Air Warfare Center-Weapons Division Weapons Survivability Laboratory in China Lake, California. Four tests of enhanced powder panels without reactive backing were conducted. These tests involved the firing of 12.7mm API projectiles into a dry bay/fuel tank simulator containing JP-8 fuel. Projectiles were fired at approximately 757 m/s (2,500 ft./s) at a 0° obliquity angle into the dry bay, impacting an aluminum striker plate, which was separated from the powder panel/fuel tank by approximately 0.305 m (1 ft.). The projectiles functioned upon impact of the striker plate and then continued through the powder panel, penetrating the fuel tank and releasing JP-8 fuel. A 0.46 m wide x 0.61 m high x 1.22 m long (1.5 ft. x. 2 ft. x 4 ft.) dry bay (right side of Figure 4-3) was connected to a 1.22 m x 1.22 m x 1.22 m (2 ft. x 2 ft. x 2 ft.) fuel tank (left side of Figure 4-3). A 3.175 mm (0.125 in.) 2024-T3 simulated fuel tank bulkhead was positioned on the front or initial impact side of the fuel tank. The powder panel was attached to this removable bulkhead panel with a 2-part epoxy adhesive. Tests were also conducted with commercial powder panels in this test series to provide a basis of comparison with the enhanced powder panel tests, as well as to tests with no protection.

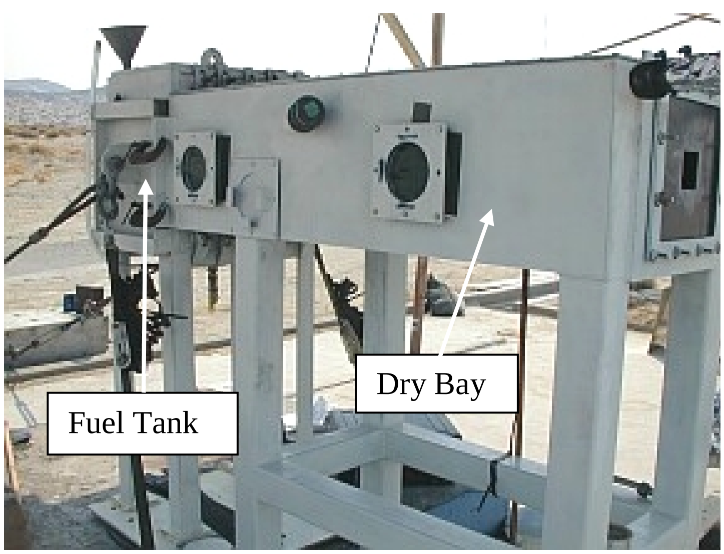

Figure 4-3. JTCG/AS Test Article Setup

4.3.2 FAA Demonstration Testing

A second demonstration test series of an enhanced powder panel was conducted in a Federal Aviation Administration (FAA) program (Reference 26). This test series was also conducted at China Lake, just after the JTCG/AS series. This test examined the feasibility of powder panels in preventing fuselage fires in commercial aircraft caused by the release and impact of an uncontained engine rotor blade with flammable fluid lines. Figure 4-4 shows a schematic of the test article. A simulated rotor blade was fired through the lower bay and into the luggage compartment and an ignitor initiated a fire in the presence of leaking fuel as the rotor blade penetrated the lower bay. An enhanced powder panel successfully prevented a fire from igniting in one of the tests. A second test was invalidated due to problems with the timing sequence, but unrelated to the powder panel. Two commercial powder panel tests were also conducted during this test series to evaluate their effectiveness and allow comparison of the results with those of the enhanced powder panel test.

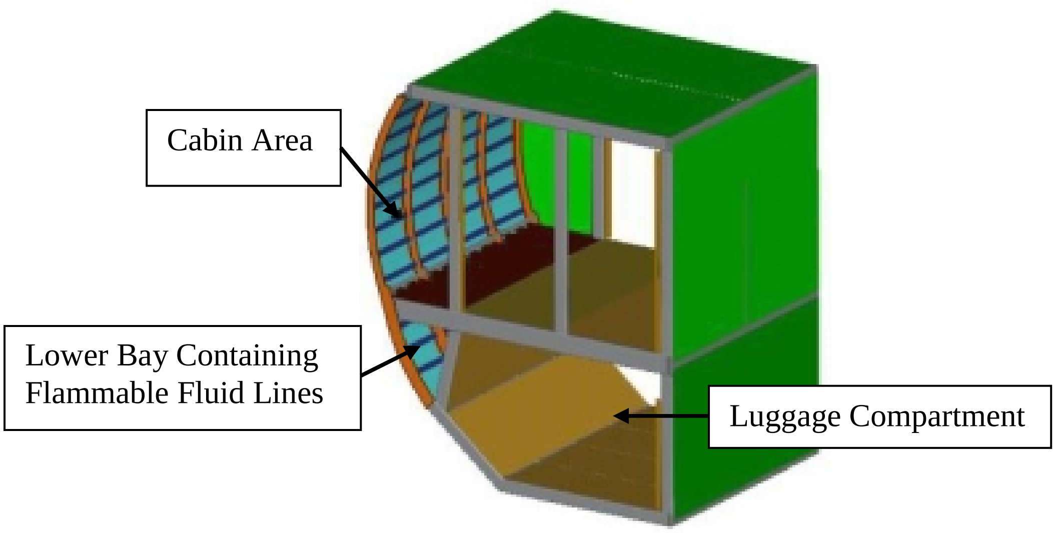

Figure 4-4. FAA Test Article Schematic

4.4 Parametric/Optimization Experiments

In Phase II, Skyward continued their impact dynamics research, with a focus on optimizing the enhanced powder panels, parametrically examining design variations, and then demonstrating the optimized panels. Panel materials, thickness, and construction techniques were optimized to reduce the panel weight and thickness, while maintaining effective powder release and dispersion.

Testing was conducted in the same simulated dry bay experimental device used for concept evaluations in Phase I, and with the same light gas gun launching 12.7mm (0.50 in.) diameter ball projectiles. Optimization test variables included panel materials and thicknesses, fire extinguishing powder loading (density of powder inserted into a given panel size), rib designs, and the assembly process. Optimization testing focused on the three primary areas of investigation outlined below:

- effectiveness optimization (maximize front face fracture and powder release),
- practicality enhancement (reduce weight, decrease panel thickness, address production issues),
- and reliability improvement (quantify reliability of measures of effectiveness, increase durability, and reduce risk of accidental leakage).

Maximizing powder release into the dry bay continued to be the defining goal, but other requirements were levied on the design effort to ensure the enhanced powder panels were as practical and reliable as possible. Weight was reduced, panel thickness was minimized, and other potential production requirements were considered. An areal density (weight per unit area) target was provided by one of the vehicle manufacturers for the design effort.

Phase II testing primarily involved the use of aluminum oxide (Al_2O_3) over Purple K ($KHCO_3$) or other powders, even though these other powders have been demonstrated to be more effective as fire extinguishing agents. At least two of the aircraft manufacturers in the powder panel survey expressed doubt that any potentially corrosive chemical powder would be acceptable by their aircraft, so there was a conscious effort made to demonstrate the effectiveness of Al_2O_3 during the optimization testing. Al_2O_3 is the only known powder panel agent to be incorporated into an aircraft due to its lack of reactivity with aircraft structure. Additionally, since Al_2O_3 has a much higher specific gravity than $KHCO_3$ (3.95 compared to 0.88), it was thought to be worst-case and would help with determining success in weight reduction efforts. The Al_2O_3 tested was 5 μm in average size compared to an average of approximately 30 μm for the $KHCO_3$, which may also mean it could pack more tightly.

Certain front face materials evaluated in Phase I testing proved to be effective and remained a focus in Phase II. These materials included thermoplastics with brittle material properties and some thermoset resins. Other unique materials were also examined that more appropriately targeted optimization requirements. Efforts were made to minimize front face and overall thickness and yet maintain sufficient strength to avoid accidental fracture. Lower density materials were examined and compared to more dense materials.

Various new and unique designs were examined for the rib structure in Phase II, including the thickness of the ribs and attachment methods to the front and back faces. Since the license agreement with Horizon's Unlimited expired at the end of Phase I testing, several options were eliminated from examination to avoid the potential for data rights infringement. The rib design was examined in detail because it directly affects the potential fire extinguishing powder loading, which can be the primary weight driver in the overall design. Various rib materials were examined for influence on powder panel performance, including some materials evaluated in the more effective Phase I designs.

Phase II testing also included examinations of back face materials and thicknesses and their influence on powder panel effectiveness. Materials examined in Phase I were once again tested along with some materials not previously evaluated. Testing included designs where the front and rear faces and the rib materials were the same and others where dissimilar materials were used.

Bonding techniques were also examined, with an emphasis on ensuring a robust overall design that reduced the risk of accidental leakage. In addition, rib-to-face bonding was examined for its influence on the performance of the powder panel. This influence was noted in Phase I testing and further examined in Phase II. Bonding materials were examined, as well as bonding patterns or techniques.

4.5 Live Fire Demonstration Testing of Optimized Enhanced Powder Panels

Phase I NGP experimental research into powder panel fire protection resulted in a demonstration of the feasibility of enhanced powder panels. As discussed in the preceding sections, unplanned, target-of-opportunity proof-of-concept live fire testing demonstrated these designs could prevent fire ignition. Phase II research then concentrated on optimizing these designs. At the end of Phase II, a series of live fire demonstration tests was conducted of the optimized designs. These tests were conducted to demonstrate the most promising enhanced powder panel designs could prevent fire ignition and be competitive with commercial powder panels in vital design criteria such as weight and thickness. These tests also demonstrated that powder dispersion and fracture mechanics results shown in the small experimental test article could be extrapolated to a larger, more realistic test article. These tests also examined attachment techniques for the powder panels, the effectiveness of Al_2O_3, historically the preferred dry chemical powder in aircraft applications, and the effect of certain variables on enhanced powder panel effectiveness. These Phase II demonstration tests were the culmination of the NGP project.

Phase II live fire demonstration testing was conducted by the Air Force 46th Test Wing Aerospace Survivability and Safety Flight, NGP's managing laboratory for enhanced powder panel research. The tests were conducted in outdoor Range 2 at their Aerospace Vehicle Survivability Facility, Wright-Patterson Air Force Base, Ohio. Demonstration testing involved baseline testing to ensure a fire could be ignited when a powder panel was not present. One test was conducted with a standard commercial powder panel to evaluate its effectiveness for the same test variables. Finally, six enhanced powder panel tests were conducted.

Testing involved a very similar setup to the JTCG/AS tests discussed in Section 4.4.1 above. A simulated dry bay/fuel tank test article was used of a larger size than the experimental test device. The dry bay measured 0.61 m wide x 0.61 m high x 1.22 m long (2 ft. x 2 ft. x 4 ft.). The fuel tank attached to one end of the dry bay measured 0.36 m wide x 1.22 m high x 0.61 m long (1.17 ft. x 2 ft. x 1 ft.). The powder panels were connected to a simulated fuel tank wall composed of 1.803 mm (0.071 in.) thick 2024-T3 for most tests. A striker plate was located 0.305 m (1 ft.) in front of the powder panel/fuel tank wall to ensure projectile functioning.

Lexan panels in the test article allowed test results to be observed directly. The ballistic projectile selected for testing was a 12.7mm API fired at approximately 757 meters per second (2,500 ft./s). Instrumentation included a couple thermocouples for temperature measurement, a threat velocity detection system, and video coverage, including high-speed and real-time video. A detailed description of the optimized panel demonstration testing is summarized in the test plan presented in Appendix A. Figure 4-5 below shows the test article setup.

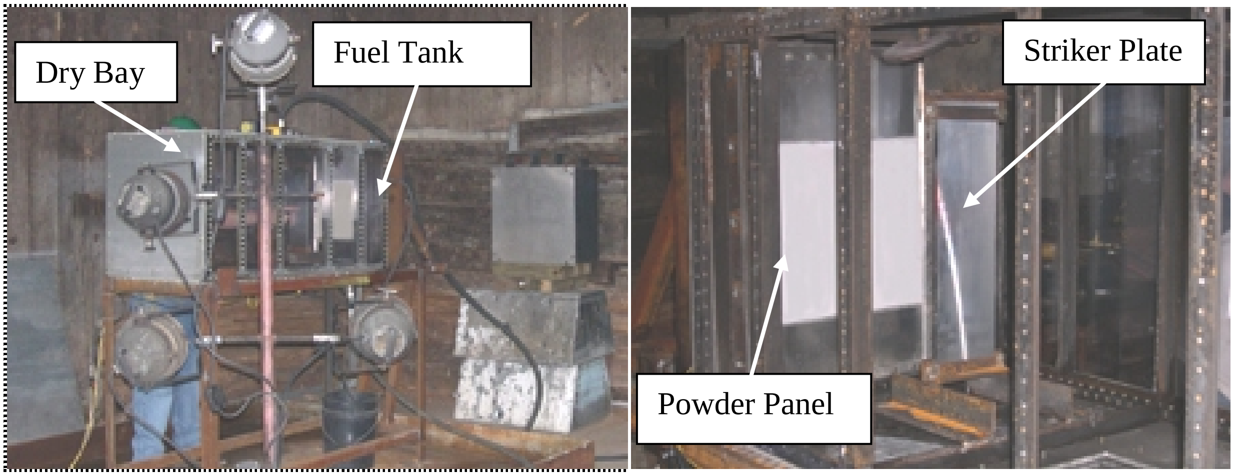

Figure 4-5. Test Article Setup

4.6 Return On Investment Predictions

The potential for combat-related aircraft dry bay fire is a known vulnerability for many aircraft. However, the infrequent use of halon fire extinguishing systems in aircraft dry bays implies that cost, weight, maintenance, and/or performance parameters have not been sufficient to justify such a system for these areas. Other fire protection methods such as solid propellant gas generator systems, void space foam filler, or even commercial powder panels have been implemented in some cases, but many dry bay areas still go unprotected. It is possible that a more effective powder panel could offer a justifiable option for previously unprotected dry bay areas or a well-supported alternative to areas protected by other means.

One of the tasks planned for this project was to perform a comparison of an enhanced powder panel protection system with a halon fire extinguishing system to demonstrate its potential as a halon alternative. The powder panel survey (Section 4.1) revealed it was very difficult to find a practical example for which to perform a direct comparison. In addition, obtaining design information for certain areas that might provide a comparison was very difficult within the resources of this program. To further complicate this task, when information was obtained on a potential aircraft area or an alternative system used in trade studies, the information was often considered proprietary and was not releasable. Therefore, an emphasis was placed on generating some estimates for integrating powder panels into forward-fit or currently unprotected areas. When possible, active system information was estimated for possible integration into the same areas. It turned out that the most practical comparisons were with current powder panels and other active fire extinguishing systems, such as solid propellant gas generators (SPGGs).

Comparisons with halon fire extinguishing systems in engine nacelles or APU compartments were considered, but are not practical. Significant additional work would be necessary to demonstrate powder panels in such an area, where airflow and hot surface ignition are concerns, before the results of the comparison would be acceptable. Additionally, in these areas where safety fires are of an equal or greater concern than ballistic threat-induced fires, powder panel protection is not currently a consideration due to the passive nature of powder panels. This eliminated some potential comparisons on the C-5 and B-1 aircraft mentioned in Section 4.1, for example.

One forward-fit example explored was the C-130 Hercules aircraft. The C-130 outer wing leading edge is not currently protected by a fire extinguishing system. The wing is divided into two segments, the center wing section (CWS) and the outer wing section (OWS). Since the outer wing fuel tanks are vulnerable to enemy fire, have no fire protection, geometric data were available, and data were available for an estimated active fire extinguishing system, it was practical to use this example.

A preliminary analysis was conducted for the OWS leading edge dry bays circa 1996 to estimate the weight of an SPGG fire extinguishing system using then off-the-shelf components. The weights were estimated for the wing leading edge dry bays between engines #1 and #2 and between #3 and #4 (referred to as inboard leading edge dry bay) and outboard of the #1 and #4 engines (referred to as outboard leading edge dry bay). This analysis also included estimates for the engine area dry bays, but for purposes of this study, the comparison is limited to the leading edge dry bays. It was estimated one inboard leading edge dry bay would require about 1,070 g (2.36 lbs.) of agent and an outboard leading edge dry bay would require about 1,186 g (2.61 lbs.). To provide this agent to each dry bay would require three 420 g (0.93 lb.) unit (maximum agent load) generators each. The weight for each unit is about 1,302 g (2.87 lbs.), for a total generator weight on one wing of 7,812 g (17.22 lbs.). One controller would weigh about 1,919 g (4.23 lbs.), which would be capable of controlling all the SPGGs in both wings. It is estimated both the inboard leading edge and the outboard leading edge would each require three optical sensors. Each sensor weighs approximately 177 g (0.39 lb.), for a total weight on one wing of 1,062 g (2.34 lbs.). For purposes of this study, the cables and braces or mounting hardware required was arbitrarily assumed to weigh about 10% of the SPGG and sensor weight for each dry bay. This weight could be more significant, depending upon were the controller is located, etc., but should provide a slightly better estimate than ignoring this weight.

Feasibility and demonstration testing of SPGGs was conducted in the C-130 Vulnerability Reduction Program, as part of C-130J Live Fire Test & Evaluation, and determined that the weight of agent in the 1996 preliminary analysis was likely overestimated (Reference 27). However, the estimates provided are the best available since a fully optimized system has not been examined. Table 4-2 provides weight estimates for each of the SPGG system components for the C-130 outer wing's leading edge dry bays.

Table 4-2. C-130 Wing Leading Edge Dry Bay Fire Extinguishing System Component Weight Estimates

Description	Inboard Leading Edge	Outboard Leading Edge
Volume	1.52 m^3 (53.5 $ft.^3$)	1.68 m^3 (59.3 $ft.^3$)
Area	2.73 m^2 (29.4 $ft.^2$)	3.43 m^2 (36.9 $ft.^2$)
SPGG Propellant Required	1,070 g (2.36 lbs.)	1,186 g (2.61 lbs.)
Number of SPGGs (420 g Units)	3	3
SPGG Weight (3)	3,906 g (8.61 lbs.)	3,906 g (8.61 lbs.)
Number of Optical Sensors	3	3
Optical Sensor Weight (3)	531 g (1.17 lbs.)	531 g (1.17 lbs.)
SPGG Controller Weight	1,919 g (4.23 lbs.)	-
Wiring, Brackets and Mounting Hardware (Estimate 10% of SPGG/Sensor Weight)	443.7 g (0.98 lb)	443.7 g (0.98 lb)
Light Enhanced Powder Panel Weight - 0.160 g/cm^2 (0.327 $lb/ft.^2$)	4,368 g (9.63 lbs.)	5,488 g (12.10 lbs.)
Heavier Enhanced Powder Panel Weight - 0.205 g/cm^2 (0.420 $lb/ft.^2$)	5,597 g (12.34 lbs.)	7,032 g (15.50 lbs.)
Commercial Powder Panel Weight - 0.192 g/cm^2 (0.393 $lb/ft.^2$)	5,242 g (11.56 lbs.)	6,586 g (14.52 lbs.)
Adhesive Weight for Powder Panels (Estimate 10% of Heaviest Panel Weight)	560 g (1.23 lbs.)	703 g (1.55 lbs.)

Table 4-2 also provides estimates for enhanced powder panel fire protection systems. Estimates are shown for both a lower weight version (areal density of 0.160 g/cm^2) and a heavier version (0.205 g/cm^2), both of which have been demonstrated to be effective in this program (Section 5.4). The lighter panel weighed 145.44 g (0.321 lb.) and the heavier panel weighed 186.50 g (0.411 lb.). Areal densities for the commercial powder panels tested in this program ranged from 0.192 to 0.208 g/cm^2. An estimate using the lower weight 174.95 g (0.386 lb.) commercial powder panel is shown. An estimate is also provided for the weight of adhesive to attach either enhanced or commercial powder panels.

Table 4-2 also shows estimated areas and volumes for the OWS wing leading edge dry bays. The SPGG agent requirements are estimated based upon volume, and, of course, the powder panel requirements are based upon wetted front spar area. Table 4-3 summarizes total weight estimates for each wing leading edge fire extinguishing system for an entire C-130 aircraft (both wings).

Table 4-3. C-130 Wing Leading Edge Dry Bay Total Fire Extinguishing System Weight Estimates

Fire Extinguishing System	Total System Weight
Solid Propellant Gas Generator System Weight	23.4 kg (51.6 lbs.)
Lighter Enhanced Powder Panel Design 1 Weight - 0.160 g/cm^2 (0.327 lb/ft.^{2})	22.2 kg (48.9 lbs.)
Heavier Enhanced Powder Panel Design 2 Weight - 0.205 g/cm^2 (0.420 lb/ft.^{2})	27.8 kg (61.3 lbs.)
Commercial Powder Panel Weight - 0.192 g/cm^2 (0.394 lb/ft.^{2})	26.2 kg (57.8 lbs.)

The data show that enhanced powder panels can be very competitive with SPGGs in terms of weight for such a system. For this example, the 0.160 g/cm^2 enhanced powder panel system would weigh about 1.2 kg (2.7 lbs.) less than the SPGG system for the entire aircraft. The lighter weight enhanced powder panel would obviously be a design objective, since for this application it could be as much as 5.6 kg (12.4 lbs.) lighter than its higher areal density counterpart. Future work will determine if further optimization is possible. The lighter commercial powder panel evaluated in this program was just under the weight of the heavier enhanced powder panel by 1.6 kg (3.5 lbs.). The powder panel weight was calculated, as if they were applied across the entire surface area of the leading edge spar. With external stiffeners located across the surface of the spar, it is likely modular powder panel sections would be inserted between stiffeners. This would further reduce powder panel weight.

For a full analysis of this example, other issues such as cost and complexity would also need to be examined. Obviously, the powder panel systems should be relatively simple to apply and maintenance free once applied. The complexity of integrating an active fire extinguishing system would be more complicated and involve some power requirements, safety concerns, and perhaps integration issues with other systems.

Data were available for a second comparison of enhanced powder panels, in this case with a current gas generator system on the V-22 aircraft. The outboard tip rib dry bay on this aircraft has a volume of approximately 0.258 m^3 (9.1 ft.^{3}). No airflow passes through this dry bay. Other relevant design details are part of the aircraft technical specifications and will not be described in detail. The active fire suppression system in this area consists of a 189 g (0.417 lb.) inert SPGG and a 283.5 g (0.625 lb.) sensor/detector. Testing was conducted on a larger inboard tip rib dry bay and this system was sized according to successful configurations in that area. The dry bay is monitored by a control box that currently monitors other areas of the aircraft, so no new weight was added for this equipment. Wiring and mounting hardware was added to the weight estimate, since this equipment is necessary specifically for this dry bay. The wiring would have to run to the control box in a central location. In the previous example, approximately 443.7 g (0.98 lb.) of weight was added for wiring and accessories. For this single generator and sensor, the weight for this estimate was reduced to 33% of this estimate or 147.9 g (0.326 lb.) for one wing, which is likely a favorable estimate. The total weight estimate for one wing would, therefore, be approximately 620.4 g (1.368 lbs.).

For comparison, weights for both enhanced powder panel designs discussed previously were estimated for this dry bay. The lighter weight powder panel, with an areal density of 0.160 g/cm^2 (0.327 lb/ft.^{2}), would weigh about 713.6 g (1.573 lbs.) per wing. Incorporation of the heavier enhanced powder panel, with an areal density of 0.205 g/cm^2 (0.420 lb/ft.^{2}), would weigh about 914.3 g (2.016 lbs.). The commercial powder panel by contrast, with an areal density of 0.192 g/cm^2 (0.394 lb/ft.^{2}), would weigh approximately 856.3 g (1.888 lbs.). Table 4-4 summarizes these weight estimates.

Table 4-4. V-22 Outboard Tip Rib Dry Bay Fire Extinguishing System Component Weight Estimates

Description	Outboard Tip Rib Dry Bay
Solid Propellant Gas Generator Weight(1)	189 g (0.417 lb.)
Sensor/Detector Weight(1)	283.5 g (0.625 lb.)
Wiring, Brackets and Mounting Hardware Weight (Estimate 33% of Previous Example with 3 SPGGs)	147.9 g (0.326 lb.)
Lighter Enhanced Powder Panel Design 1 Weight - 0.160 g/cm^2 (0.327 lb/ft.^{2})	713.6 g (1.573 lbs.)
Heavier Enhanced Powder Panel Design 2 Weight - 0.205 g/cm^2 (0.420 lb/ft.^{2})	914.3 (2.016 lbs.)
Commercial Powder Panel Weight - 0.192 g/cm^2 (0.394 lb/ft.^{2})	856.3 g (1.888 lbs.)
Adhesive Weight for Powder Panels (Estimate 10% of Heaviest Panel Weight)	91.4 g (0.201 lbs.)

Table 4-5 tabulates the total weight for the aircraft (both wings) for each of the fire protection systems. These data show the inert SPGG system for the total aircraft weighs about 369 g (0.81 lb.) less than the lightest enhanced powder panel in this case. The commercial powder panel system would weigh about 285 g (0.63 lb.) more than this enhanced powder panel design or 654 g (1.44 lbs.) more than the SPGG system. The heavier enhanced powder panel design would weigh about 116 g (0.26 lb.) more than the commercial powder panel system. Obviously, one major difference in this example was the existence of a controller on the aircraft for the active system, which did not add weight. Although the differences in weight for this comparison are quite small, it is well known that aircraft weight increases carry large price tags. In this example, a judgment would need to be made based upon system cost and the savings in complexity, whether or not the weight increase for the enhanced powder panel system would be worthwhile. Further optimization of these enhanced powder panel designs in subsequent programs may further reduce the weight differences between this passive fire extinguishing system and this active fire extinguishing system.

Table 4-5. V-22 Outboard Tip Rib Dry Bay Total Fire Extinguishing System Weight Estimates

Fire Extinguishing System	Total System Weight
Solid Propellant Gas Generator System	1,241 g (2.74 lbs.)
Lighter Enhanced Powder Panel Design 1 Weight - 0.160 g/cm^2 (0.327 lb/ft.^{2})	1,610 g (3.55 lbs.)
Heavier Enhanced Powder Panel Design 2 Weight - 0.205 g/cm^2 (0.420 lb/ft.^{2})	2,011 (4.43 lbs.)
Commercial Powder Panel Weight - 0.192 g/cm^2 (0.394 lb/ft.^{2})	1,895 g (4.18 lbs.)

Many other comparisons are possible between the enhanced powder panels and other fire protection methods. However, the purpose of the examples provided above was to simply demonstrate that enhanced powder panels, which have been demonstrated in live fire tests to be effective, have also been optimized to levels that make consideration of this vulnerability reduction technique valuable.

5. Technical Results

The following sections describe the results of the various enhanced powder panel test programs discussed in Section 4 above. The experimental results of Phase I are described, followed by live fire proof-of-concept demonstration test results of the most promising post-Phase I designs. Phase II experimental results are then described, as the enhanced powder panel designs were optimized. Finally, live fire demonstration test results are presented of the optimized powder panels.

5.1 Impact Dynamics Experimental Results

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 (0.406 mm thick [0.016 in.]) and aluminum foil panels. Also examined were 3.175 mm (0.125 in.) and 6.350 mm (0.25 in.) 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 in.) thickness was also tested.

The majority of tests, however, featured unique materials and designs not evaluated in previous powder panel ballistic testing. Thermoplastic and thermoset materials were the focus of most testing. For the front panel face (dry bay side), materials that exhibited brittle properties upon impact, but durability in handling, were of utmost interest. The goal was to find a front face material and powder panel design that results in significant front face material loss and powder release into the dry bay during a ballistic impact event. Front face materials evaluated included a polycarbonate (Lexan), polystyrene, polypropylene, and polymethyl methacrylate (acrylic-Plexiglass). These materials are cost-effective and easily obtainable in off-the-shelf forms. For example, some off-the-shelf forms 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 and different techniques for implementing the scoring lines. 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 in.) 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.

Plastics were also tested for the back face (fuel tank wall side) and in various configurations for the internal rib structure of the panel. The impetus for experimenting with the back panel was to determine if the fracture characteristics of the back panel influence the front panel in any way. For the dry bay/fuel tank configuration examined, there was a desire to inhibit the back panel hole size to reduce flammable fluid leakage, which could assist in reducing fire ignition probability in an actual production configuration.

A number of materials and designs were 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 in Phase I 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 in.) 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. Bonding areas could be reduced to allow for more cracking of the front face, however, the support of the honeycomb structure inhibits flexure, thereby working against crack propagation.

Several other 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. 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. This rib arrangement required several tradeoffs. Ribs that formed channels too far apart allowed powder settling or bulging of the face sheets, but allowed for flexure of the front face during impact, which optimized cracking. Rib channels that were too close together prevented powder settling, but were more prone to function like honeycomb and provide too much support to the front face, reducing the likelihood of significant cracking. In these rib arrangements, powder along the length of the panel could be released from all open channels, which afforded greater performance than a honeycomb design. In a honeycomb design, only the cells penetrated or torn around the perimeter of the impact will release powder, unless significant cracking or area is removed from the front face.

A corrugated aluminum of approximately 1.5875 mm (0.0625 in.) peak-to-peak height was also examined in some tests. The metal did not show a propensity to break up in these tests, so the front face would need to break up and separate for the panel to be effective. Some of the benefits of this design are similar to the channel design, however, the combination of metal and plastic in these trials may have some operational environment drawbacks, such as significantly different coefficients of thermal expansion. 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 could offer some improvement for assembly.

Phase I testing was able to identify novel powder panel designs with enhanced performance over more standard design concepts. Tables 5-1 and 5-2 describe some of the panels tested. Table 5-1 lists some of the more novel and effective designs, while Table 5-2 lists some designs that feature more baseline design concepts and less effective performance. Appendix B lists all of the panels tested in Phase I. The tables indicate the mass of each powder panel, which were all about 30.16 cm x 30.16 cm (11.875 in. x 11.875 in.) in size. Total powder-filled weights for panels tested in the first year of testing ranged from 428.2 g (0.944 lb.) to 1,403.0 g (3.093 lbs.). 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. By contrast, commercial panels obtained during this NGP project weighed between 175 g and 189 g for a similar size. Obviously, this was one design feature requiring optimization in Phase II testing.

Table 5-1. More Effective Powder Panel Designs In Experimental Testing

Test No.	Material Description	Thickness (mm)	Panel Weight (g)	Powder Release (g)	% Powder Released	Front Face Area Removed (cm^2)
8	2.03 mm clear acrylic faces, 9.53 mm acrylic tube ribs	13.5	1402	48	5.6	31.6
9	1.78 mm cracked ice acrylic front, 1.52 mm ABS back, two ABS ribs (3.05 mm thick)	6.9	769	23	5.0	17.7
12	2.03 mm (50.8 mm x 50.8 mm scored) clear acrylic, 2.03 mm clear acrylic back, 3.18 mm polycarbonate honeycomb rib	7.6	579	9	4.6	22.6
21	1.78 mm acrylic prismatic front, 1.52 mm ABS back, two ABS ribs (3.05 mm thick)	7.8	552	30	12.8	20.3
23	1.78 mm styrene prismatic front, 1.52 mm ABS back, two ABS ribs (3.05 mm thick)	6.5	517	28.4	12.8	25.6
27	2.49 mm polyester resin front, 1.52 mm ABS back, two ABS ribs (3.05 mm thick)	7.1	620	8.2	4.0	25.4
28	2.49 mm polyester resin front, 1.52 mm ABS back, two ABS ribs (3.05 mm thick)	7.4	876	83.3	18.7	80.6

Table 5-2. Less Effective Powder Panel Designs In Experimental Testing

Test No.	Material Description	Thickness (mm)	Panel Weight (g)	Powder Release (g)	% Powder Released	Front Face Area Removed (cm^2)
1	0.41 mm Al front, 5.33 mm polyethylene corrugated rib, 0.25 mm Al foil back	6.0	630	0.6	0.17	1.3
2	0.25 mm Al foil front, 5.2 mm polyethylene corrugated rib, 0.41 mm Al back	5.9	594	0.04	0.01	1.3
13	1.52 mm ABS faces, 9.53 mm aramid rib	13.5	1128	1.5	0.2	1.3
14	1.78 mm textured acrylic front, 2.03 mm clear acrylic back, 6.35 mm Al honeycomb rib	10.5	832	1	0.23	1.3
15	1.52 mm ABS faces, 6.35 mm Al honeycomb rib	10.2	764	1	0.25	1.3
16	2.03 mm clear acrylic faces, 6.35 mm Al honeycomb rib	10.8	942	3	0.65	1.6
18	2.03 mm (5.08 cm x 5.08 cm scored) clear acrylic front, 2.03 mm clear acrylic back, 3.18 mm Al honeycomb rib	7.2	638	2	0.82	9.5

Some measures of effectiveness are also noted in Tables 5-1 and 5-2, including powder release or loss as a result of the ballistic test, percentage of the powder released, and the front face area removed. The estimate of the powder release 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 5-1). Obviously, in these cases, a significant amount of powder was also released from the panel. The amount of powder released during testing varied from a fraction of a gram in some of the more standard designs to over 100 g.

Figure 5-1. Test Example of Significant Panel Fracture and Material Loss

A review of the Phase I test data indicated a wide disparity in the reaction of the panels. In some tests, the powder release 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 5-2), 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 g 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 for effective designs, several panels were tested with dry bay clutter and powder was still observed on all witness rods, even those in isolated areas.

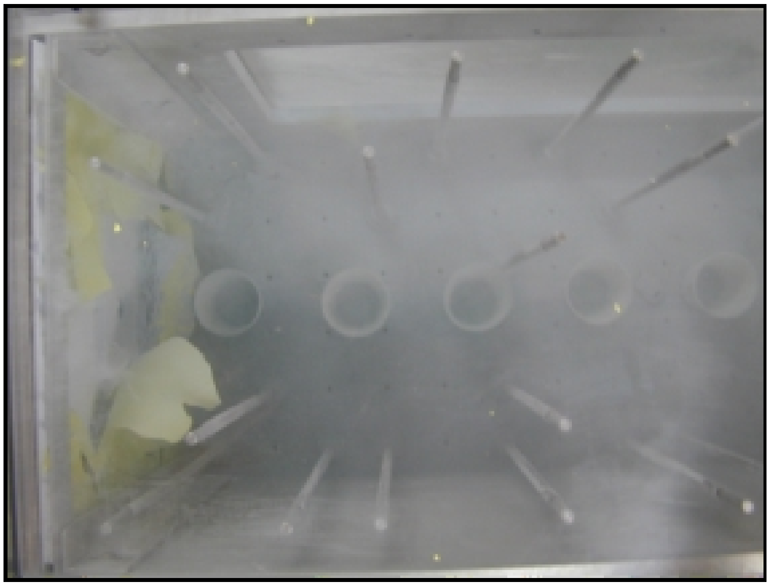

Figure 5-2. Test Example of Effective Powder Release and Dispersion

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 occurred 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 disperses only along the shotline, dissipates in tenths of a second, and the amount of dispersed powder was limited to the region of projectile penetration (approximate powder release of a few percent) (Reference 28).

Figures 5-3, 5-4, and 5-5 show major performance benefits achievable with some of the enhanced design concepts listed in Table 5-1 (by test number) over more standard powder panel designs (Table 5-2). Results indicated the powder panel front face area removed could be increased by 15 to 20 times over more standard designs (Figure 5-3). Testing also revealed the amount of powder released into a dry bay could be increased 5 to 10 times with an enhanced powder panel design (Figure 5-4). Testing also indicated that powder dispersion could be enhanced, even with dry bay clutter, ensuring the prevention of fire ignition over a wider area (Figure 5-5). In this figure, the number of witness rods with detectable powder residue is indicated for each test. Effective designs resulted in powder being suspended in the dry bay for much longer periods of time than standard powder panels (as much as four minutes in one test compared to one second or less). Finally, the design and fabrication effort revealed enhanced powder panels afforded greater design flexibility, which can be utilized to target weight, durability, and other application-specific design goals. These findings revealed that new powder panel concepts could significantly enhance the fire extinguishing effectiveness of this vulnerability reduction method, thereby demonstrating the feasibility of enhanced powder panels.

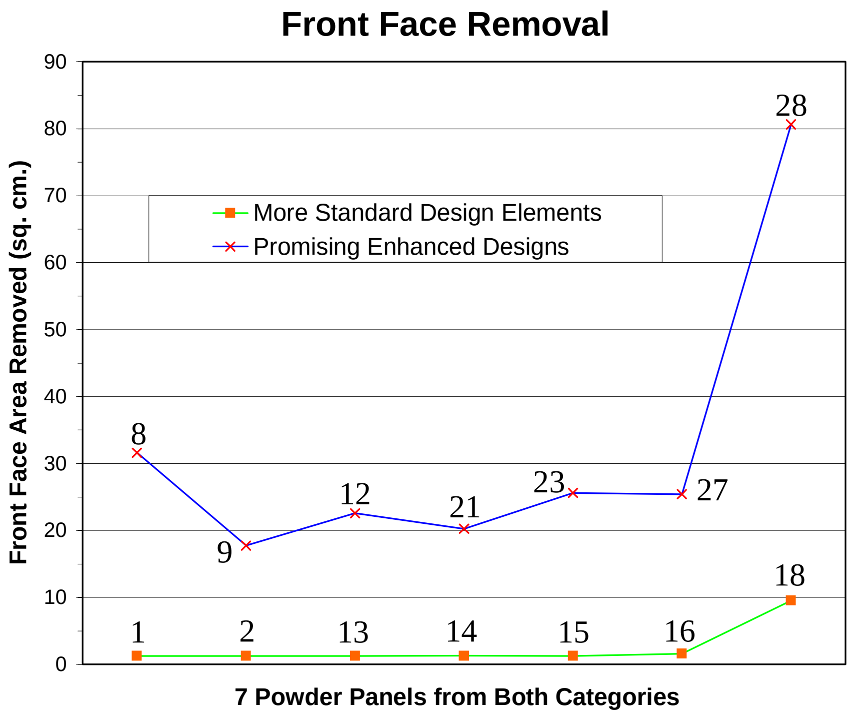

Figure 5-3. Effect on Powder Panel Fracture Area of Standard Design Features and Enhanced Designs, Showing 15x to 20x More Front Face Area Removed in the Latter

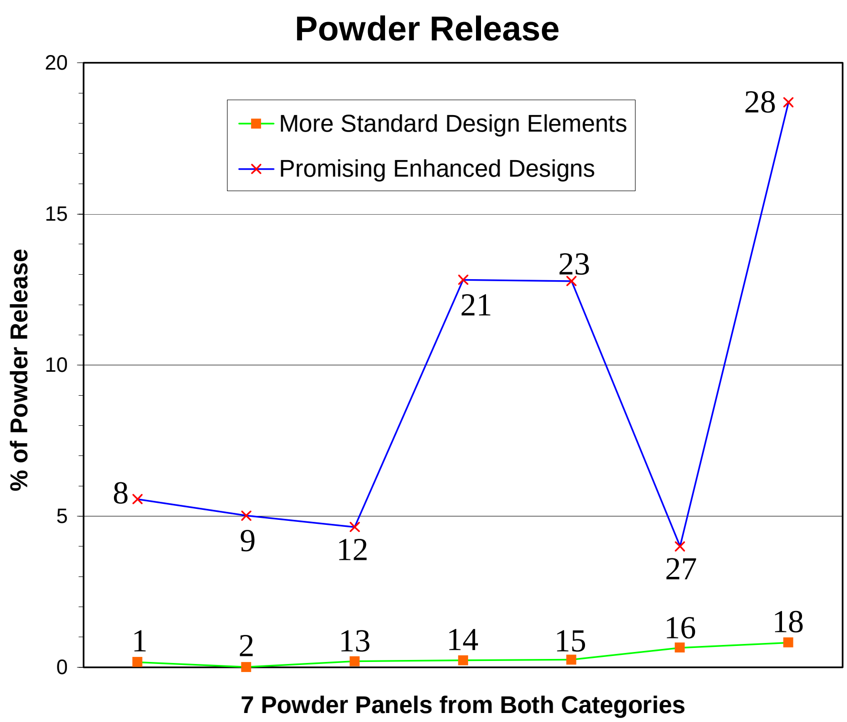

Figure 5-4. Effect on Powder Delivery of Standard Design Features and Enhanced Designs, Showing 5x to 10x Greater Powder Release in the Latter

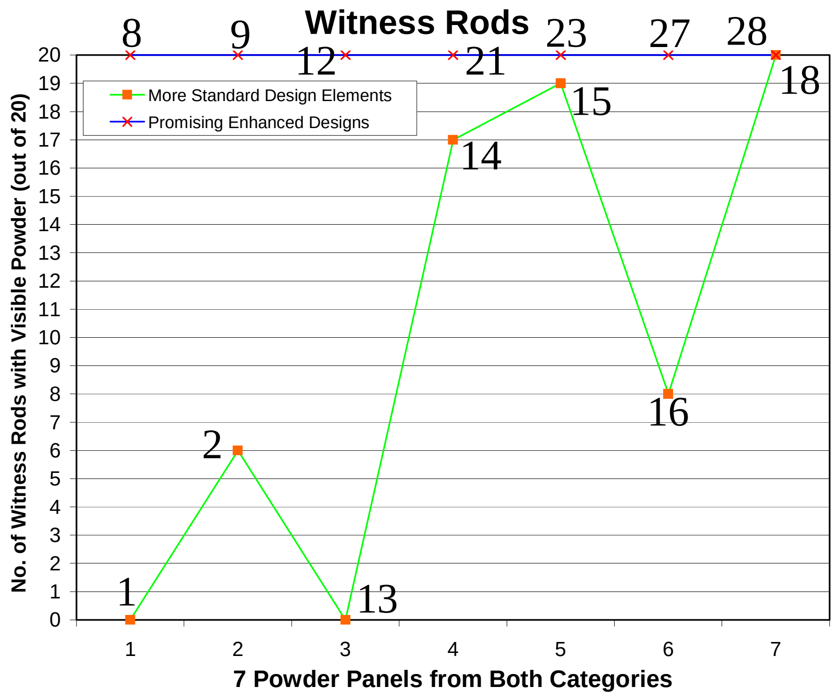

Figure 5-5. Effect on Powder Dispersion of Standard Design Features and Enhanced Designs, Showing Greater Dispersion in the Latter

Experimental 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 appears 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 5.08 cm (2 in.) and 10.16 cm (4 in.) 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 appropriate scoring designs, 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 surface area between the front face and ribs inhibited powder dispersion for the designs tested. 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 a reduced number of selected areas, such as the panel perimeter, proved effective for polycarbonate honeycomb, but not necessarily for the aluminum honeycomb. It was reasonable to conclude from the testing, weaker and fewer bonding sites would allow both designs to function more effectively, as previous work has shown. Multiple explanations were plausible for the more effective polycarbonate tests. It is probable there was a contribution from the more brittle properties of the polycarbonate, which did fracture in some locations, and the design of the aluminum honeycomb likely distributed the impact energy over a greater surface area without allowing critical flexure of the front face. 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 would be necessary for these designs between rib spacing and powder loading, as sufficient powder must be available at all potential impact sites, but more powder translates to greater weight. Testing indicated 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. A number of tests involved less brittle ABS material for the back face, since 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. This would provide a second means to increase powder panel effectiveness. The first being the use of a more brittle front face to maximize fire extinguishing powder release, while the flammable fluid leakage is minimized. Experimental testing did reveal 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. Phase I testing did 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. In the tests involving ABS, the damage sustained by the back face was a hole just larger than the diameter of the 12.7 mm diameter ball projectile.

5.2 Live Fire Proof-of-Concept Demonstration Test Results

Following the experimental testing of Phase I, the opportunity for demonstrating enhanced powder panels arose at the Navy's Weapons Survivability Laboratory. Lessons learned from the NGP Phase I experimental testing were used to design and fabricate some new, slightly more optimized powder panels. These panels again incorporated thermoplastic materials. However, thinner panel thicknesses and reduced powder loading resulted in reduced weights, and new panel designs were utilized. Weights were decreased on average 100 to 200 g (0.22 to 0.44 lb.) from those designs evaluated in experimental testing for 30.16 cm x 30.16 cm (11.875 in. x 11.875 in.) panels. Panels at China Lake varied from 320 g (0.71 lb.) to 422 g (0.93 lb.) in weight. Thicknesses ranged from 2.41 mm (0.095 in.) to 3.30 mm (0.13 in.).

In both the JTCG/AS and FAA test programs, the enhanced powder panels showed a solid improvement over current powder panel designs. Fire ignition was prevented in all five valid tests involving enhanced powder panels (four JTCG/AS and one FAA test). Conversely, fires resulted in all four valid commercial powder panel tests (two JTCG/AS and two FAA tests). Figure 5-6 shows some images captured from high-speed video in JTCG/AS testing demonstrating the fire mitigation capability of enhanced powder panel designs. Powder discharge was estimated to be at least 90% of the pretest powder loading for the enhanced powder panels, compared to 5% to 10% for commercial powder panels. Greater powder dispersion throughout the dry bays was also evident for the enhanced powder panels. Figure 5-7 compares the amount of fire extinguishing powder released from an enhanced powder panel with a commercially available powder panel in the JTCG/AS tests.

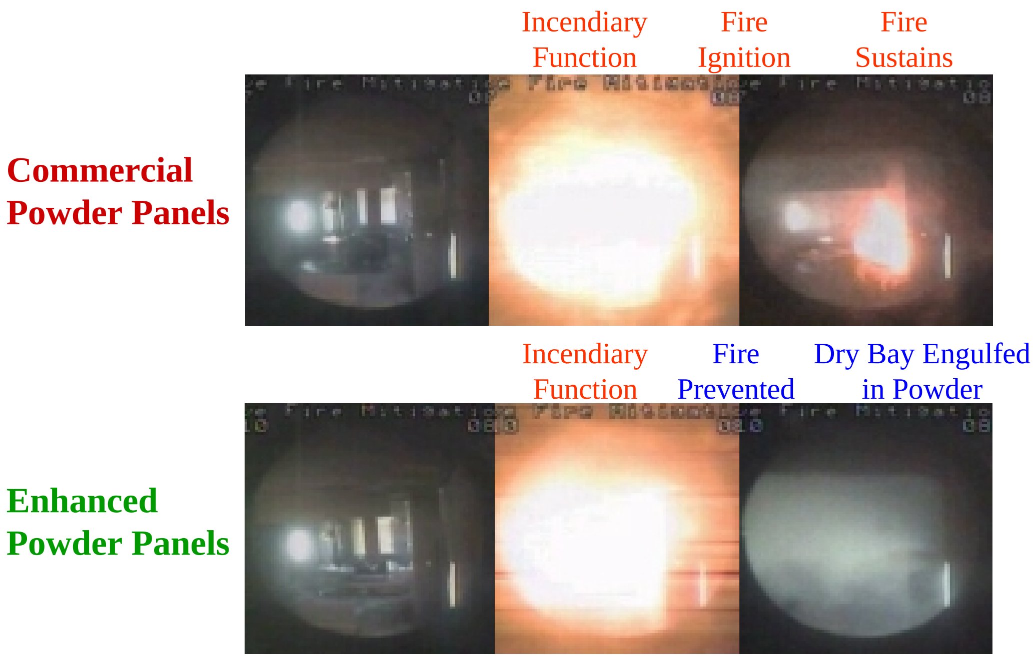

Figure 5-6. Enhanced Powder Panel Fire Mitigation Capability Demonstrated

Commercial Powder Panel ~5-10% Powder Release | **Enhanced Powder Panel ~90% Powder Release**

Figure 5-7. Comparison Of Commercial And Enhanced Powder Panel Agent Release In JTCG/AS Dry Bay Fire Extinguishing Testing

Figure 5-8 shows that impact of the enhanced powder panel by a rotor blade in the FAA test resulted in release of all the fire extinguishing agent, as it prevented fire ignition. Baseline testing showed that unprotected fuselage areas did indeed result in sustained fires.

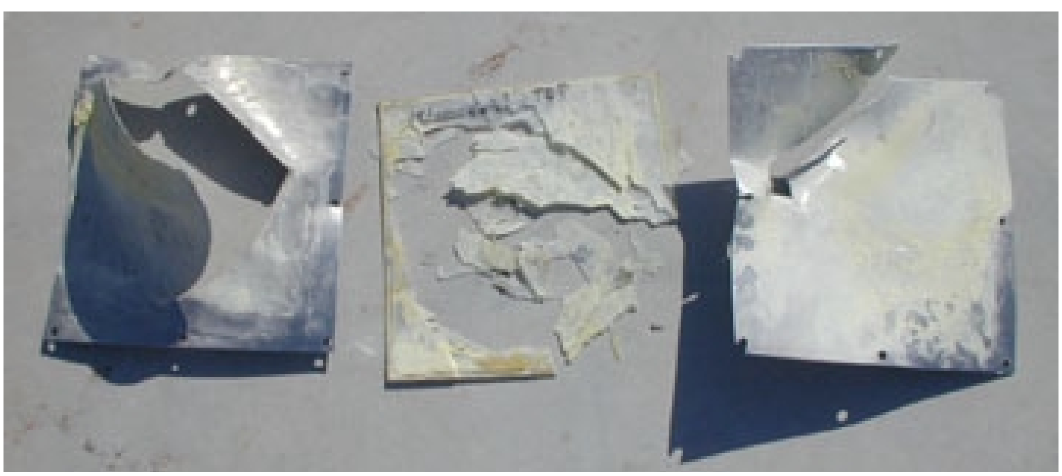

Figure 5-8. Entire Contents of Enhanced Powder Panel Released During FAA Test and Fire Prevented

5.3 Parametric/Optimization Experimental Results

Following the successful conclusion of these live fire demonstration tests, Phase II parametric experiments began with the goal of optimizing successful enhanced powder panel designs identified in Phase I. Some lessons learned from the fire tests were also incorporated into the initial designs for Phase II.

A total of 25 tests were conducted in Phase II optimization tests in Range A at the AVSF. Table 5-3 lists the panels tested and includes pretest panel weights and areal densities, along with the amount of powder release, percentage of powder released, and the estimated front face area removed. The panels are listed in descending order by the amount of powder released in each test.

Table 5-3. Phase II Optimization Testing

Test No.	Material Description	Total Thickness (mm)	Pretest Weight (g)	Areal Density (g/cm^2)	Powder Release (g)	% Powder Released	Front Face Area Removed (cm^2)
5	0.635 mm polystyrene front 1.27 mm polycarbonate ribs 0.508 mm polycarbonate back	2.41	295.00	0.324	5.15	3.2	11.1
22	0.762 mm acrylic front 0.762 mm polycarbonate ribs 0.762 mm polycarbonate back	2.29	215.34	0.237	4.03	8.4	6.03
24	0.508 mm composite front 0.762 mm polycarbonate ribs 0.381 mm polycarbonate back	1.65	141.03	0.155	3.02	6.3	1.46
8	0.762 mm acrylic front 1.27 mm polycarbonate ribs 0.762 mm polycarbonate back	3.05	347.96	0.382	2.99	1.8	11.87
18	0.635 mm polystyrene front 0.762 mm polycarbonate ribs 0.508 mm polycarbonate back	1.91	331.76	0.365	2.51	1.2	1.61
14	0.635 mm polystyrene front 1.27 mm polycarbonate ribs 0.762 mm polycarbonate back	2.67	368.46	0.405	2.17	1.9	9.75
2	0.635 mm polystyrene front 0.762 mm polycarbonate ribs 0.508 mm polycarbonate back	2.41	251.60	0.277	2.15	1.8	4.84
10	0.762 mm acrylic front 1.27 mm polycarbonate ribs 0.762 mm polycarbonate back	2.79	453.13	0.498	2.06	0.7	1.26
4	0.635 mm polystyrene front 1.27 mm polycarbonate ribs 0.508 mm polycarbonate back	2.41	330.00	0.363	1.66	0.8	24.58
23	0.508 mm composite front 0.762 mm polycarbonate ribs 0.381 mm polycarbonate back	1.65	140.02	0.154	1.61	2.8	1.67

Table 5-3. Phase II Optimization Testing (Continued)

Test No.	Material Description	Total Thickness (mm)	Pretest Weight (g)	Areal Density (g/cm^2)	Powder Release (g)	% Powder Released	Front Face Area Removed (cm^2)
17	0.635 mm polystyrene front 0.762 mm polycarbonate ribs 0.508 mm polycarbonate back	1.91	329.95	0.363	1.52	0.8	1.98
6	0.635 mm polystyrene front 0.762 mm ABS ribs 0.762 mm ABS back	2.16	201.20	0.221	1.36	1.5	9.81
11	0.635 mm polystyrene front 1.27 mm polycarbonate ribs 0.762 mm polycarbonate back	2.67	403.94	0.444	1.04	0.7	7.74
13	0.635 mm polystyrene front 1.27 mm polycarbonate ribs 0.762 mm polycarbonate back	2.67	410.54	0.451	0.82	0.5	3.02
16	0.635 mm polystyrene front 0.762 mm polycarbonate ribs 0.508 mm polycarbonate back	1.91	306.32	0.337	0.78	0.4	1.61
7	0.635 mm polystyrene front 0.762 mm ABS ribs 0.762 mm ABS back	2.16	193.48	0.213	0.75	0.9	5.81
21	0.635 mm polystyrene front 0.762 mm polycarbonate ribs 0.762 mm polycarbonate back	2.16	191.47	0.210	0.63	1.2	1.26
9	0.076 mm glass epoxy front 0.1” Nomex honeycomb ribs 0.076 mm glass epoxy back	2.69	174.95	0.192	0.26	0.2	1.11
15	0.076 mm glass epoxy front 0.1” Nomex honeycomb ribs 0.076 mm glass epoxy back	2.69	174.99	0.192	0.24	0.2	0.49
19	1.016 mm polycarbonate front 0.762 mm polycarbonate ribs 0.762 mm polycarbonate back	2.54	269.68	0.296	0.14	0.3	0.71
20*	1.016 mm polycarbonate front 0.762 mm polycarbonate ribs 0.762 mm polycarbonate back	2.54	260.74	0.287	N/A	N/A	0.71
25*	0.508 mm composite front 0.762 mm polycarbonate ribs 0.381 mm polycarbonate back	1.65	123.96	0.136	N/A	N/A	19.17

*Tests conducted with water in fuel tank; not able to accurately determine powder release.

A summary of the designs is also provided in Table 5-3, listing the front and back face materials and the material thickness. Effective front face materials tested in Phase I were evaluated, including a textured polystyrene. Some other materials were also examined, including other thermoplastics and some composite materials not evaluated in Phase I. Materials used for the back face concentrated on polycarbonate, which proved to be effective in Phase I, although some tests were conducted with ABS, a more ductile material. Table 5-3 also shows the rib materials tested and the thicknesses of the internal section of the panel. Different rib designs and manufacturing processes were examined in the optimization testing. Rib materials most often mirrored the back face material.

Optimization testing indicated significant decreases in weight were possible from Phase I test panels, while maintaining improved powder release. Enhanced powder panels weights were reduced as much as 57% in weight from the lightest panel tested in the first phase, with an increase in powder release. Figure 5-9 compares the lightest Phase II panel with the lightest Phase I panel and a commercial powder panel. Two of the lightest pretest filled panel weights were 123.96 g (0.27 lb.) and 140.02 g (0.31 lb.). By comparison, commercial powder panels tested in Phase II weighed approximately 175 g (0.39 lb.). Therefore, the enhanced powder panels were reduced as much as 29% below the commercial panel weight.

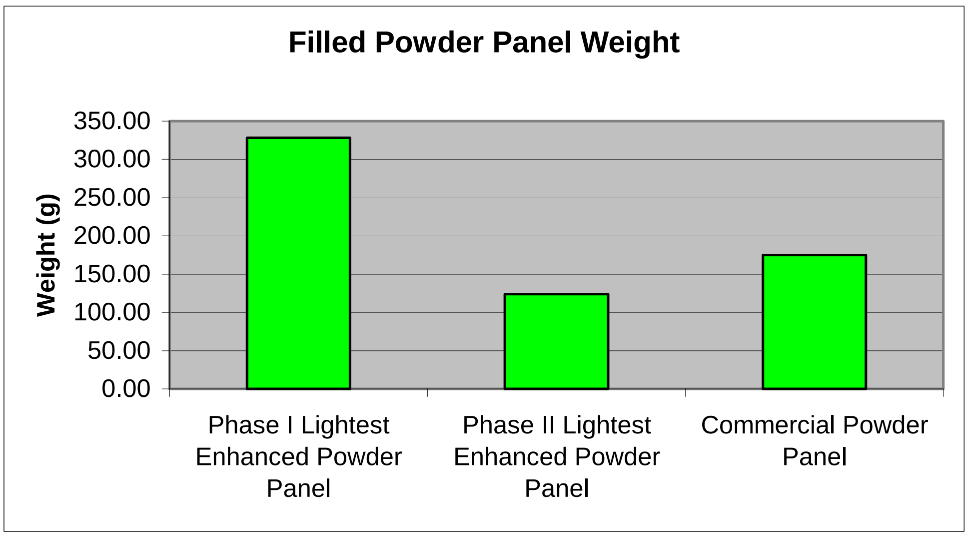

Figure 5-9. Phase II Enhanced Powder Panel Weight Reduction

Enhanced powder panel thicknesses ranged between 1.65 mm (0.065 in.) and 3.05 mm (0.120 in.) in optimization evaluations. This was a reduction of more than 60% from the thinnest panel tested in Phase I. Commercial panels evaluated in Phase II were 2.69 mm (0.106 in.) in thickness. The enhanced powder panels were, therefore, reduced about 39% in thickness below the commercial powder panel. Figure 5-10 compares the thinnest panels tested in Phase I and Phase II with the commercial powder panels. Reductions in thickness reduce the powder loading or the amount of powder in the panel, which is the significant weight consideration. However, the thickness of the panel along the shotline also reduces the potential powder release, which obviously affects powder panel effectiveness. Therefore, there is a balance necessary between panel thickness, which affects panel weight, and the effectiveness of the panel, as measured by powder release or loss. Front and back face materials and the rib structure design were other variables examined to increase performance without increasing weight.

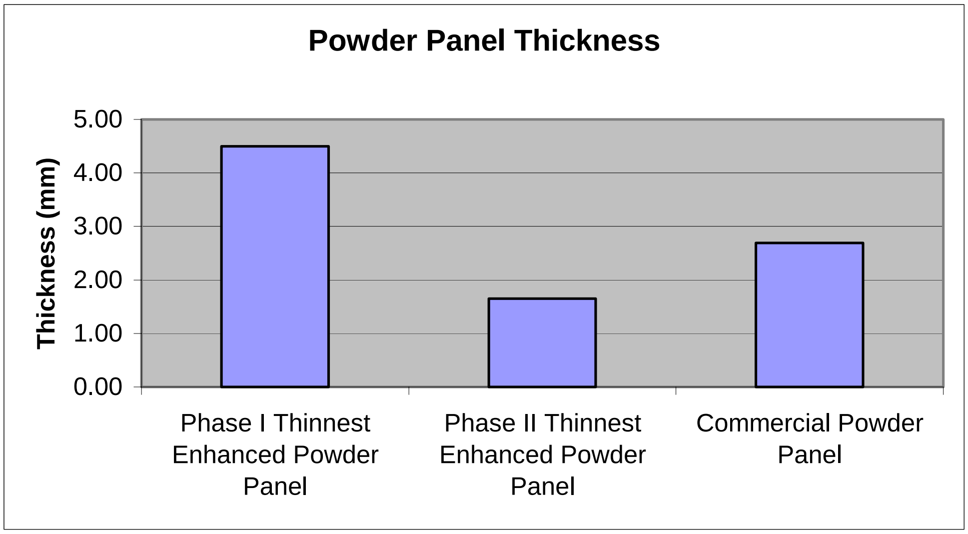

Figure 5-10. Phase II Enhanced Powder Panel Thickness Reduction

Powder release is an important factor in the testing because the greater the amount of powder dispersed in the dry bay, particularly along the shotline, the lower the chance of an ignited fire. The amount of powder released in Phase II testing ranged from as low as 0.14 g to as much as 5.15 g. This powder release or loss is not as much as the most effective panels in Phase I testing, but the panel thickness and available powder has been significantly reduced to meet likely design goals. Powder release for the commercial powder panel tests was 0.24 and 0.26 g. Figure 5-11 compares the best performing Phase II enhanced powder panel (no water in the tank) with the best performing commercial powder panel. This data shows the amount of powder released from the enhanced powder panels was as much as 21 times greater than the commercial powder panels.

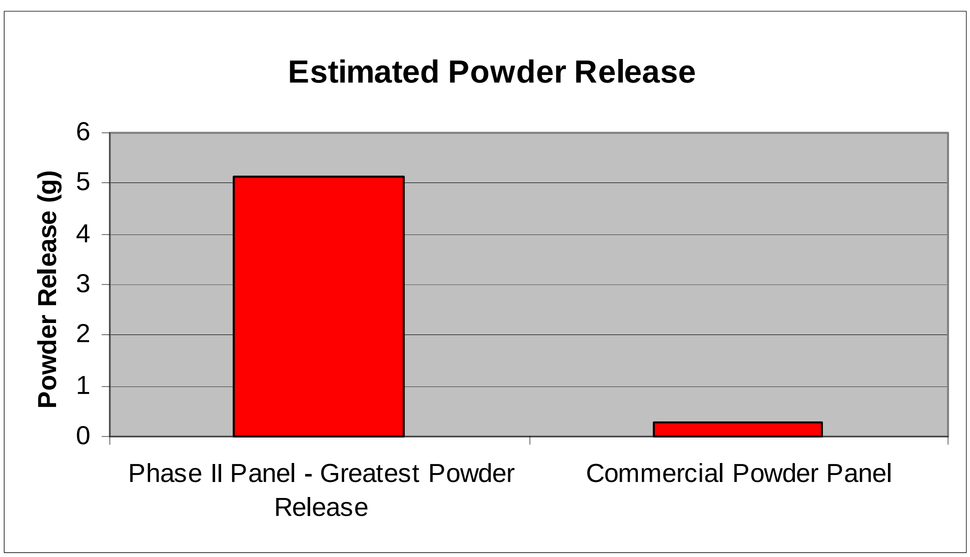

Figure 5-11. Comparing Enhanced and Commercial Panel Powder Release

The percentage of powder released (powder released or lost divided by pretest total powder loading multiplied by 100%) has also been used as a measure of powder release effectiveness. The enhanced powder panel design attempts to maximize the release of the available powder in the panel. Optimized panels tested ranged from 0.3% to 8.4% of the total powder released. The commercial panels released approximately 0.2% of the total powder contained. Figure 5-12 compares the best performing Phase II enhanced powder panel (no water in the tank) with the best performing commercial powder panel. This data shows the enhanced powder panels could increase the percentage of total powder released by as much as 42 times. A ranking of the panels using percentage of powder released does not track directly with a ranking of the panels by total powder released, since there was some considerable variance in overall pretest panel weight.

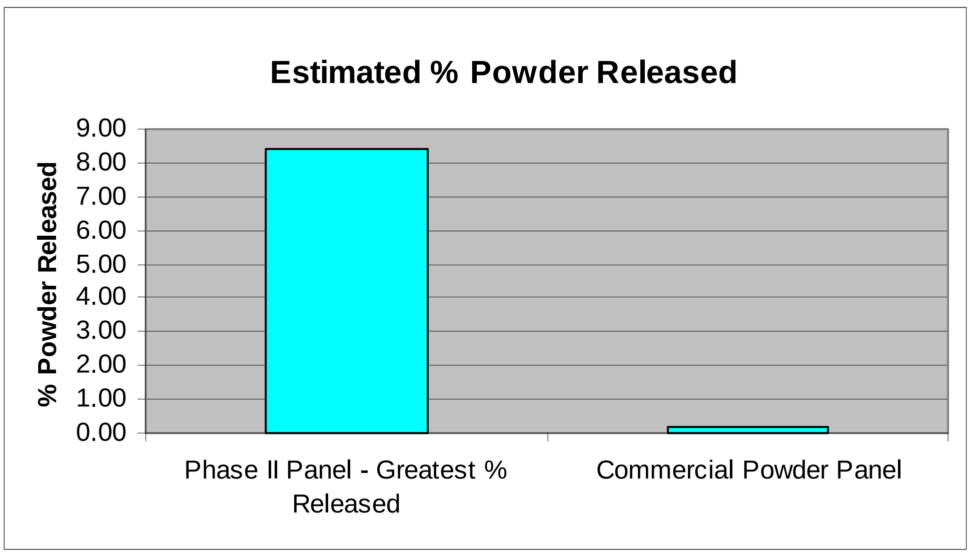

Figure 5-12. Comparing Enhanced and Commercial Panel Percent Powder Released

Tests 9 and 15 in Table 5-3 were conducted on the commercially available powder panels. As mentioned previously, these panels are composed of a honeycomb core and two thin composite face sheets. The commercial powder panels were among the lighter panels tested (empty weight and with powder), but also released nearly the least amount of powder and the smallest percentage of powder. Except for one test examining a ductile front face, the powder release and percentage of powder released for the commercial panels is less than half the next enhanced powder panel. As discovered in previous testing with Nomex honeycomb cores, powder is released from those cells directly penetrated by the projectile and those torn on the perimeter of the penetration either by the penetrating projectile or hydrodynamic ram forces acting on the fuel tank panel. However, the damage area is relatively well contained and powder is not able to escape from the rest of the panel. Enhanced powder panels offer the potential for a much greater percentage of the panel's contents to be released. It was anticipated at this point in the program that the effects of hydrodynamic ram on the powder panel will only increase the amount of improvement an enhanced powder panel can offer. Further testing would verify this assertion.

The outlier enhanced powder panel (Test 19) utilized polycarbonate throughout the design, including the front face. In this test, the entrance hole in the front face and exit hole in the rear face essentially self-sealed together and prevented virtually any powder from escaping, except through the penetration area alone. This design was also examined in Test 20 with water in the fuel tank and yielded the same damage. The front face area removed for these tests was approximately 0.71 cm^2 (0.11 $in.^2$), the worst performance by an enhanced powder panel. By contrast, Test 4 resulted in almost 25 cm^2 (3.875 $in.^2$) of the front face removed and Test 25, with water, resulted in over 19 cm^2 (2.945 $in.^2$) being removed. Figure 5-13 compares the enhanced powder panel experiencing the greatest front face area removal (no water in the tank) with the better performing commercial powder panel (1.11 cm^2 [0.172 $in.^2$]). An improvement of over 22 times is shown with this enhanced powder panel.

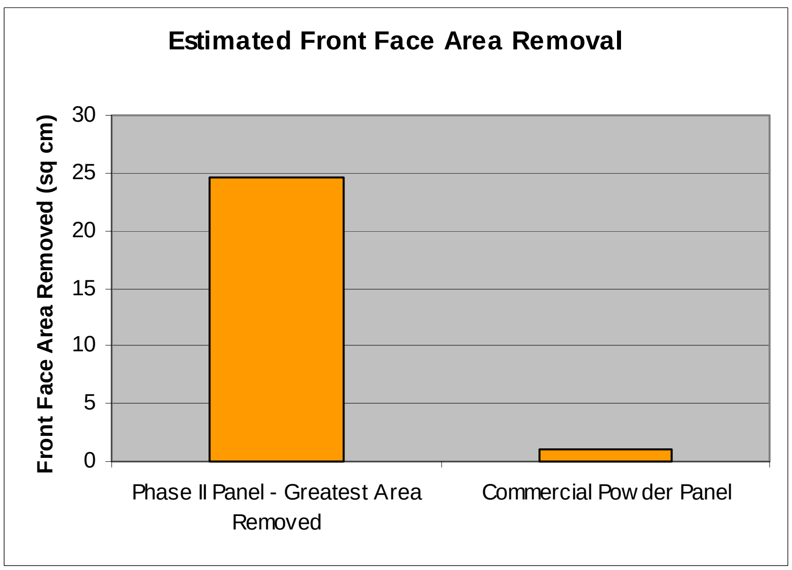

Figure 5-13. Comparing Enhanced and Commercial Panel Front Face Area Removal

For Tests 20 and 25, conducted with water in the fuel tank, a post-test weight of the panel to determine powder release or loss was not practical. The powder in both panels absorbed water as a result of the test. These two tests, however, demonstrated that hydrodynamic ram would significantly enhance front face fracture for a more brittle front face, leading to greater powder release, but would not likely assist fracture for a ductile front face. Front face area removal was increased for the same panel design by as much as 12 times (comparing Test 24 to Test 25) due to the additional forces and fuel tank panel deformation associated with hydrodynamic ram. This result demonstrated that in cases were the powder panel will be attached to a flammable fluid container, and hydrodynamic ram is expected when the container is punctured, the powder panel can be designed to take advantage of the expected hydrodynamic ram event.

Summarizing Phase II optimization testing, the data showed that an enhanced powder panel (Test 24) can be 19% lighter and 39% thinner than a commercial powder panel, yet release over 10 times more powder mass, 30 times greater the percentage of powder originally contained in the panel, and sustain at least 32% greater front face area removal. The data also showed that the effects of hydrodynamic ram would further increase the performance of an enhanced powder panel.

5.4 Live Fire Demonstration Test Results of Optimized Enhanced Powder Panels

Some of the more practical, yet effective enhanced powder panels were evaluated in live fire demonstration tests conducted at the end of Phase II. This testing involved many of the same test elements involved in proof-of-concept testing after Phase I. However, in these tests, the thinner and lower weight Phase II optimized panels were evaluated. A total of nine tests were conducted, as described in Table 5-4. The test was set up to ensure a threat function for each powder panel test. A successful powder panel test was considered to be one where no fire ignition occurred. Estimates of the front face area removed and the percentage of powder released were made. Due to the presence of JP-8 fuel, it was not possible to weigh the precise amount of powder released or lost, so an estimate of the percentage of the original powder released was made. This was a rough estimate based upon a post-test examination of the panel and area calculations. It was impossible to determine the influence of leaking fuel on remaining powder in the panel immediately after the test, but the estimates do correlate well with powder dispersion evidence and fire ignition results.

Two different enhanced powder panel designs were evaluated in the demonstration tests, with the primary differences involving material composition. Enhanced Design 1, in Table 5-4, is a lighter weight design with potentially better thermal resistance capability. Enhanced Design 2 is more robust in terms of durability, but is heavier. Test EPP-08 varied in design somewhat from the Enhanced Design 1, utilizing a self-sealing back face material, but was essentially the same in other respects.

Table 5-4. Phase II Enhanced Powder Panel Live Fire Demonstration Tests

Test No.	Powder Panel	Panel Weight (g)	Panel Thickness (mm)	Powder	Threat Function?	Fire Ignition?	Front Face Area Removed (cm^2)	Estimated % Powder Released
EPP-01	No Panel - Baseline	N/A	N/A	N/A	Yes	No	N/A	N/A
EPP-02	No Panel - Baseline	N/A	N/A	N/A	Yes	Yes	N/A	N/A
EPP-03	Commercial	189.05	2.69	Al_2O_3	Yes	Yes*	50	8
EPP-04	Enhanced Design 1	145.44	1.905	Al_2O_3	Yes	No	156.5	70
EPP-05	Enhanced Design 1	140.78	1.905	Al_2O_3	Yes	Yes*	145.5	83
EPP-06	Enhanced Design 2	186.5	1.905	Al_2O_3	Yes	No	309.2	88
EPP-07	Enhanced Design 2	227.02	1.905	$KHCO_3$	Yes	Yes, but powder extinguished fire	329.4	83
EPP-08	Enhanced Design 1	157.06	2.134	Al_2O_3	Yes	No	54.1	61
EPP-09	Enhanced Design 2	226.34	2.159	$KHCO_3$	Yes	No	252.2	62

*Panel dislodged from fuel tank wall during test

Two baseline tests were conducted at the beginning of the test program. The purpose of these tests was to ensure threat functioning and the ignition of a fire in an unprotected or inadequately protected dry bay. For these conditions, a successful powder panel would prevent fire ignition, despite the functioning threat, and an unsuccessful powder panel would not prevent fire ignition. In the first baseline test, the fuel tank panel was a 2.032 mm (0.08 in.) thick 7075-T6 plate. This was the same material and thickness used as the simulated fuel tank panel in all Range A experimental tests. In EPP-01 a fire was not ignited, as a large deluge of fuel was seen engulfing the dry bay almost immediately, creating an extremely fluid rich environment. The threat did function, but the fuel tank panel resisted the significant hydrodynamic ram pressures and peeled away from the fasteners attaching it to the fuel tank. The fuel tank panel deformed significantly before its edges at the fastener locations tore through, but the impact hole was not significantly larger than the threat size. The toughness of this material was also evident in the Range A tests, where hydrodynamic ram was most often not a variable and worst-case conditions were desired. In these demonstration tests, it was desired to allow hydrodynamic ram damage to occur. Without hydrodynamic ram forces and minimized fuel spurting, it is possible an inaccurate judgment could be made regarding powder panel effectiveness. In this first baseline test, the panel resisted hydrodynamic ram forces such that the weakest failure point was the fuel tank panel attachment mechanism.

Since a fire was not ignited in this first test (and the potential for fire was essential for the powder panel evaluations), modifications were made to the test article and setup to better ensure fire ignition. For the second baseline test, the fuel tank material was changed to 1.803 mm (0.071 in.) thick 2024-T3 and a structural frame was used to hold the fuel tank panel to the fuel tank without interfering with the powder panel positioned between its boundaries. In addition, the planned projectile velocity was lowered to 762 m/s (2,500 ft./s) to mirror proof-of-concept testing after Phase I and to reduce energy somewhat. The fuel level was lowered from completely full (about 64.35 l [17 gal.]) to about ¾ full (49.21 l [13 gal.]) to permit pressure relief in an ullage area and reduce the amount of fuel that might immediately spill out into the ignition zone and create another over-rich condition. These modifications proved worthwhile, as EPP-02 did result in a fire. The fire was visible for about four seconds, but appeared to be self-extinguishing near that time. This would provide an adequate burn time for an evaluation of the powder panels, but an alteration to the test article was envisioned to be necessary.

The third test (EPP-03) involved a commercial powder panel, as Table 5-4 indicates. The threat functioned as planned, however a fire was ignited. The fire only lasted a short duration, as the fire appeared to be lean and seeking oxygen. A long jet of flame actually shot out of the entrance hole at the front of the dry bay. The fire lasted over a second, but thick black smoke from the combustion filled the dry bay and lasted for many minutes afterward. The temperature in the dry bay climbed about 120°F. The conclusion was that the panel was not successful in inhibiting fire ignition or preventing a sustained fire, rather a self-extinguishing fire occurred due to a lack of oxygen. Closer inspection of the dry bay and the high-speed video revealed the commercial powder panel did not remain adhered to the fuel tank panel with the two-part epoxy used. The panel was dislodged after the threat flash and started coming loose as the fire was ignited below and almost behind the panel as it flew off. The powder release was not sufficient to allow powder to remain suspended in the dry bay, however, its effectiveness could remain in question since it did not adhere properly. Black markings evident of not only a flash, but of an ignited fire, were present in the dry bay. No powder residue was found in the dry bay following the test, although the panel did break up better than in non-fluid tests in Range A (Figure 5-14). The damage area was approximately 10.2 cm high x 6.4 cm wide (4 in high x 2.5 in. wide). It is estimated from an inspection of the panel that the front face area removed was approximately 50 cm^2 (7.75 in^2) and about 8% of the powder was released.

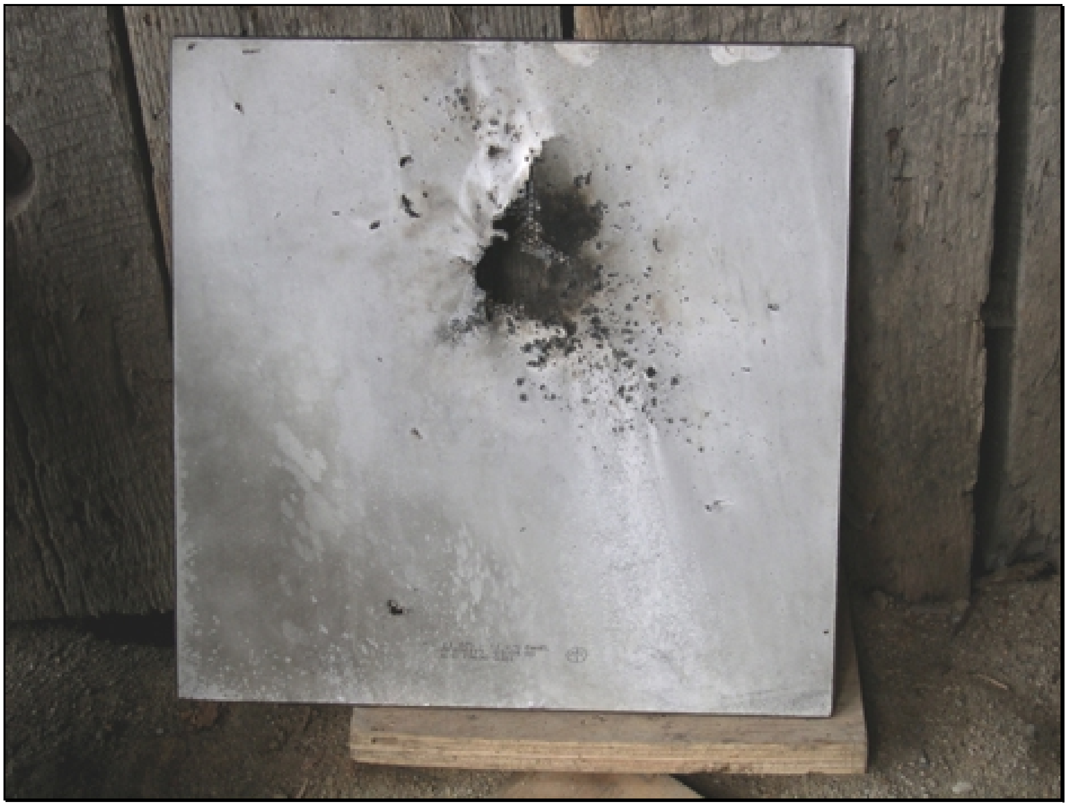

Figure 5-14. Post-Test Damage Image of EPP-03 Commercial Powder Panel

The fourth test (EPP-04) involved an enhanced powder panel. For this test, modifications to the test article were considered to allow more venting or fresh oxygen to be available to the combustion process. However, since more enhanced powder panel tests were to be conducted, it was desired to conduct at least one with the exact same conditions as the commercial powder panel for a direct comparison. In this test, the threat functioned as expected, with the high-speed video indicating a flash duration of approximately 0.008 seconds or more, which was comparable to the previous two tests. However in this test, as soon as the flash dissipated, the dry bay was engulfed in fire extinguishing powder, and no fire ignition occurred. The temperature in the dry bay around the flash climbed only about 20°F. A review of the video confirmed that no combustion occurred after the threat function. Powder was visible on the walls of the dry bay, with powder on the Lexan window all the way to the end of the four ft. long dry bay. A significant amount of powder also covered the striker panel on the surface facing the powder panel. Powder was also visible in the dry bay for a number of minutes after the test. The panel was adhered with a two-part, fast curing epoxy, which was the same adhesive used in the commercial panel test. However, in this case the panel held fairly well, although some loss of adhesion occurred. Figure 5-15 shows a post-test image of the powder panel, demonstrating the front face fracture. The damage area was approximately 14.4 cm high x 17.8 cm wide (5.675 in high x 7 in. wide). It is estimated from an inspection of the panel that the front face area removed was approximately 156.5 cm^2 (24.25 $in.^2$) and about 70% of the powder was released.

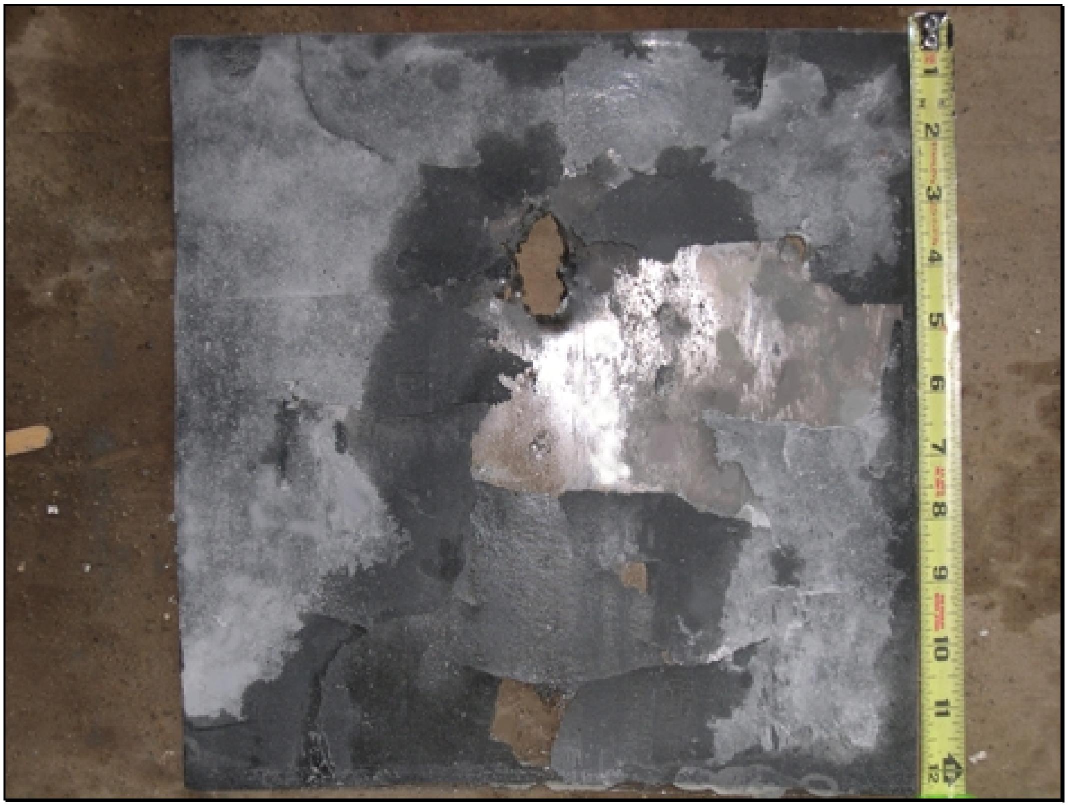

Figure 5-15. Post-Test Damage Image of EPP-04 Enhanced Powder Panel

In preparation for EPP-05, the dry bay test article was modified to allow for more fresh air to vent into the fire zone. A 7.62 cm (3 in.) diameter hole was drilled into the aluminum side wall of the dry bay. It was centered along the length of the dry bay, 0.61 m (2 ft.) from the fuel tank wall and down about 13.3 cm (5.25 in.) from the top of the dry bay. In this test, a double-sided adhesive tape was used to adhere the powder panel, versus a two-part epoxy. The threat functioned in the test, as planned, and the high-speed video showed a fire ignited about 0.02 seconds after the flash dissipated. The fire lasted several seconds and the temperature climbed about 349°F in the dry bay near the fuel tank. In the real-time and high-speed video, the powder panel was visible being dislodged from the fuel tank and slamming into the side Lexan panel. The fire started behind the powder panel in the corner opposite the direction the powder panel flew off. Powder was visible in the video emanating from the panel into the Lexan and down onto the floor. As the panel lay against the Lexan, continued powder leakage was visible onto the floor and it suspended in the vicinity of the dry bay. It is unclear if the continued release of powder was responsible for the fire extinguishing later or if the fire self-extinguished. Inspection of the test article did indicate some black residue around the new dry bay opening, so the extra vent did provide an oxygen source to the fire. In this test, the powder panel design was exactly the same as in EPP-04. In addition, the powder panel broke up at least as effectively as in EPP-04, so it was surmised that if the panel had not dislodged from the fuel tank wall, it would likely have prevented a fire. However, further tests were required to determine if the additional oxygen available would hinder the effectiveness of the enhanced powder panels. The post-test damaged powder panel is shown in Figure 5-16. The front face damage area was approximately 17.8 cm high x 15.2 cm wide (7 in high x 6 in. wide). The front face area removed was approximately 145.5 cm^2 (22.55 $in.^2$). About 83% of the powder was released, but as described, much of this may have exited the panel as it flew into the Lexan side panel and then rested against it.

Figure 5-16. Post-Test Damage Image of EPP-05 Enhanced Powder Panel

Test EPP-06 involved a different enhanced powder panel design, primarily involving a change to the front face material. It also marked the first test using MIL-S-8802 aircraft sealant, rather than a faster curing epoxy sealant, as the adhesive to attach the powder panel to the fuel tank wall. All tests conducted after EPP-05 used this adhesive. This powder panel and all the panels utilizing this sealant remained well adhered to the fuel tank during testing. In this test, the flash was visible in the high-speed video, and then powder was seen once again engulfing the dry bay with no fire ignition occurring. The temperature in the dry bay climbed no more than about 26°F near the flash. Powder seemed to distribute well and quickly. Powder was still lingering in the dry bay nearly fifteen minutes after the test, when the side panel was removed (Figure 5-17). Upon inspection of the fuel tank, powder was visible along the length of the Lexan window and across the surface of the striker plate facing the powder panel (Figure 5-18). Some large pieces of the powder panel front surface were actually stuck to the striker plate along with the powder. Powder was also detected on the aluminum side panel nearly the length of the dry bay. Powder was also visible on the structural framework of the dry bay. In all of the powder panel tests, sufficient fuel leaked into the dry bay to make visible powder on the surface of the fuel very difficult to distinguish.

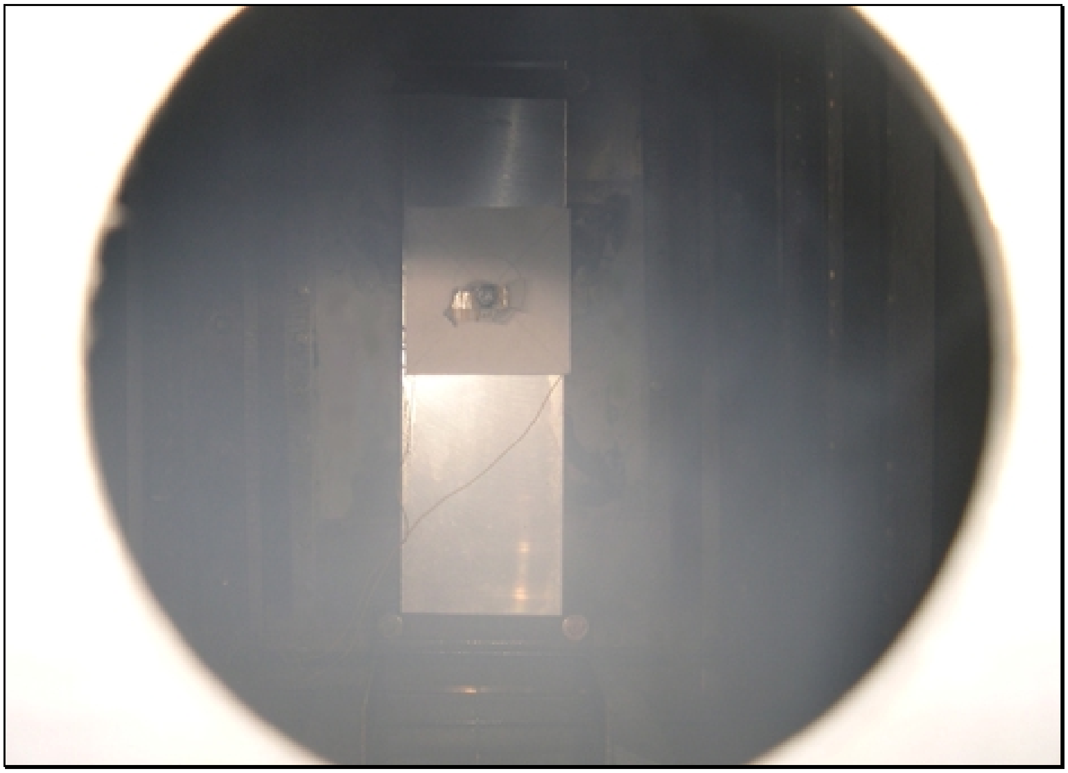

Figure 5-17. Powder Suspension in the Dry Bay Well After the Test

Figure 5-18. Powder Dispersion on Striker Plate and Side Lexan Panel

As shown in Figure 5-19, the powder panel was fractured in EPP-06 similar to the previous enhanced powder panel tests. The front face damage area extended nearly to edges of the panel, measuring approximately 30.2 cm high by 27.3 cm wide (11.875 in high x 10.75 in. wide). The front face area removed was approximately 309.2 cm^2 (47.92 $in.^2$) and about 88% of the powder was released.

Figure 5-19. Post-Test Damage Image of EPP-06 Enhanced Powder Panel

In Test EPP-07, $KHCO_3$ was used as the fire extinguishing powder, rather than Al_2O_3, to examine any difference in powder release or powder dispersion. The panel design was the same as in EPP-06. In this test, however, powder loading was increased and the panel weighed approximately 22% more. In this test, the threat functioned as planned for a duration of less than 0.016 second. After the flash dissipated, the powder is seen in the video beginning to engulf the dry bay. However, a fire is ignited in the lower corner of the dry bay near the fuel tank panel and Lexan panel. It lasted only about 0.28 second as the powder is seen reaching this area about the time it is extinguished. The temperature in the dry bay climbed no more than 30°F near the fuel tank. A small leak was evident from the fuel tank in pretest preparations and it occurred in this corner. It is plausible that some fuel remained in this corner of the dry bay after the leak was fixed. This likely allowed for an ignition of fuel already present in the dry bay, before fuel from the threat penetration hole fully began to spray into the dry bay. Based upon the evidence provided, this powder panel was considered successful, despite the brief ignition of a fire, because the powder was considered responsible for extinguishing the fire. Upon inspection of the test article, powder was evident on the Lexan panel and aluminum side panel similar to the previous test. Powder was also evident on the dry bay structural framework, top panel, and striker plate. As expected, the $KHCO_3$ was somewhat easier to distinguish than the Al_2O_3. The powder panel front face fracture was similar to EPP-06, as shown in Figure 5-20. The front face damage area extended nearly to edges of the panel again, measuring approximately 30.2 cm high x 27.3 cm wide (11.875 in high x 10.75 in. wide). The front face area removed was approximately 329.4 cm^2 (51.05 $in.^2$) and about 83% of the powder was released.

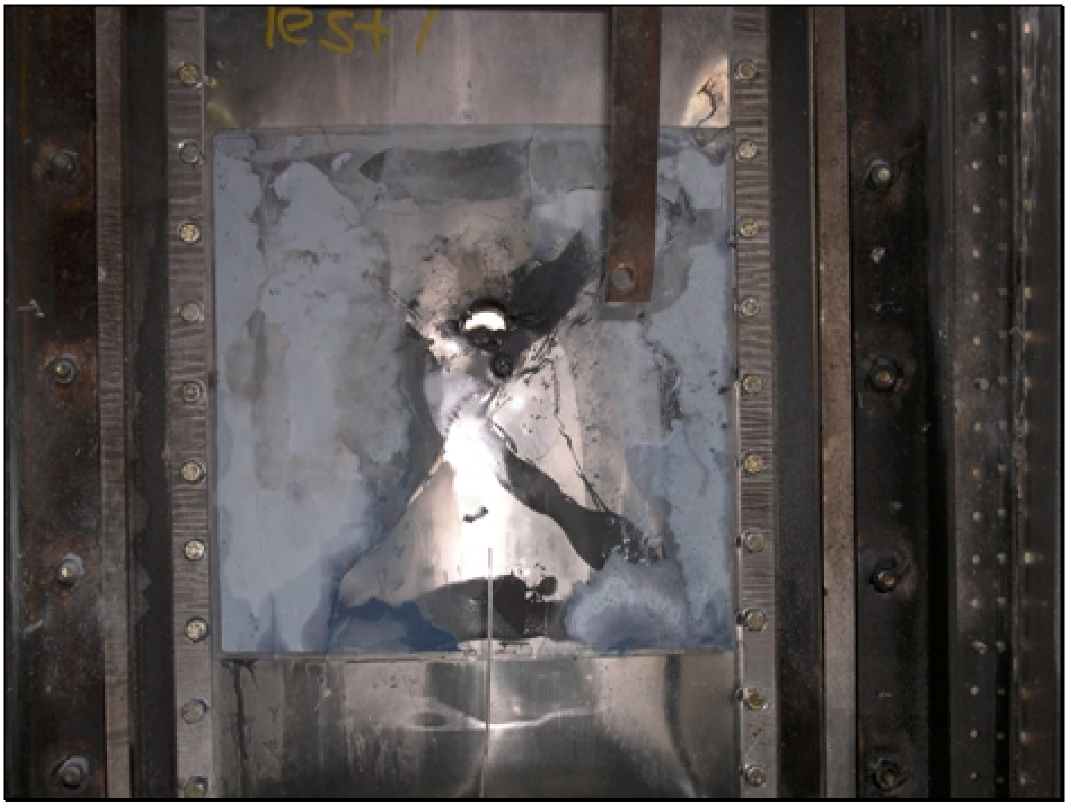

Figure 5-20. Post-Test Damage Image of EPP-07 Enhanced Powder Panel

Test EPP-08 utilized Al_2O_3 and used the same front face material evaluated in Tests EPP-04 and EPP-05. This panel had a slightly wider total thickness (2.134 mm [0.084 in.]) than these previously tested enhanced powder panels, but still weighed less than the commercial powder panel tested. This test also involved the use of a self-sealing material for the back face. In this test, the threat functioned as planned and no fire was ignited. The cloud of powder quickly moved throughout the dry bay. The temperature in the dry bay climbed no more than 23°F. Powder was evident along the length of the Lexan panel and the other aluminum side panel. It was also found on the striker plate facing the powder panel and the dry bay top wall and back wall. The front face area removal was somewhat reduced from previous panels using the same front face, but cracking was extensive, allowing large flaps of material to easily release powder (Figure 5-21). The damage area extended about 28.9 cm high x 23.8 cm wide (11.375 in. high x 9.375 in. wide). The front face area removed was approximately 54.1 cm^2 (8.39 $in.^2$) and about

61% of the powder was released. The hole in the back face of the powder panel was approximately 1.27 cm x 1.27 cm (0.5 in. x 0.5 in.), resulting in an area removal about 66% less than any of the other enhanced powder panel tests. It is, therefore, likely that less fuel was immediately available for fire ignition than in tests without a self-sealing back face. It is believed the thickness of the back face could be increased for such a design to improve self-sealing capability, while still maintaining an overall weight and thickness comparable to commercial powder panels. A test to verify this assertion was not possible during this test program.

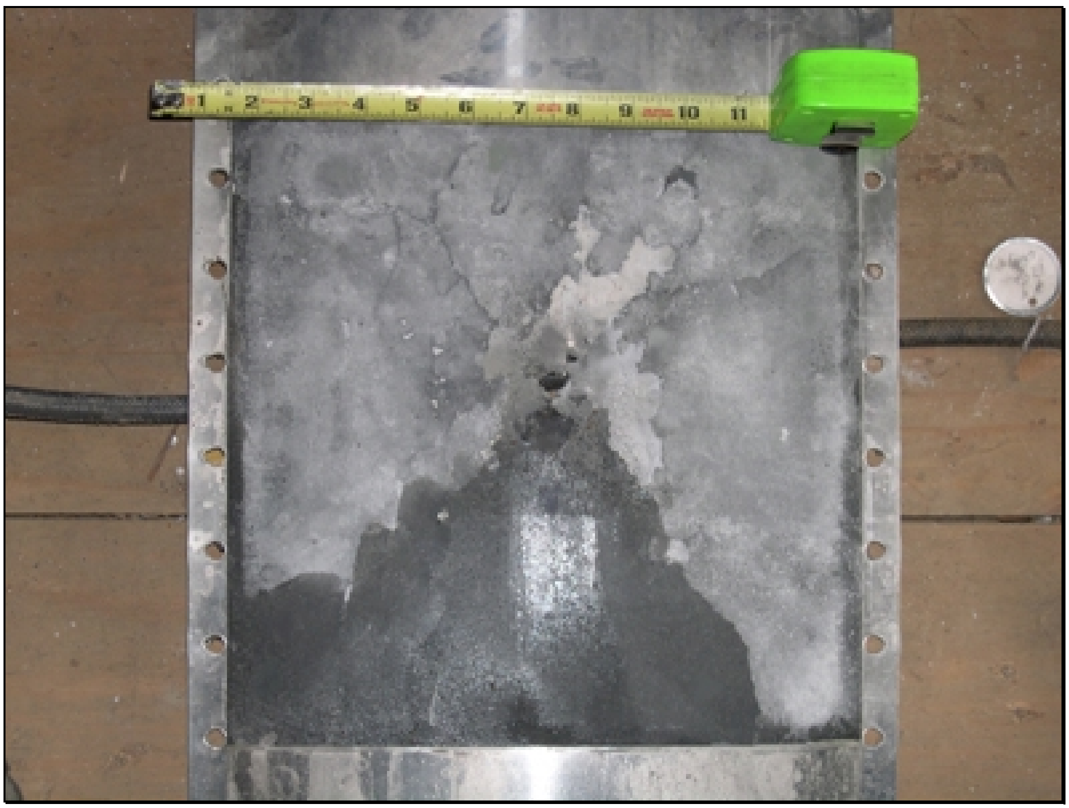

Figure 5-21. Post-Test Damage Image of EPP-08 Enhanced Powder Panel

The final Phase II live fire demonstration test (EPP-09) again involved $KHCO_3$. The same design used in Tests EPP-06 and EPP-07 was used, except the panel internal width was wider, and, therefore the overall panel was wider (2.159 mm). Despite the increased thickness, powder loading was such that it was very close in weight to EPP-07, which also examined $KHCO_3$. A large flash was evident in this test upon review of the high-speed video. However, no fire was ignited. The temperature in the dry bay near the flash climbed on average around 37°F. A large cloud of powder enveloped the dry bay and powder was visible striking the Lexan wall. Both side walls had visible powder deposits, as well as the top panel beyond the striker plate, and the striker plate itself. When the side wall was removed more than five minutes after the test, a large cloud of powder was still evident in the dry bay (Figure 5-22). The damage to the enhanced powder panel front face was significant, as shown in Figure 5-23. The damage area extended about 30.2 cm high x 25.7 cm wide (11.875 in. high x 10.125 in. wide). The front face area removed was approximately 252.2 cm^2 (39.09 $in.^2$) and about 62% of the powder was released.

Figure 5-22. Powder Evident in Dry Bay More Than Five Minutes After EPP-09 Test (Side Wall Removed)

Figure 5-23. Post-Test Damage Image of EPP-09 Enhanced Powder Panel

The results of the Phase II live fire demonstration tests were very promising. Out of six enhanced powder panel tests, only one test was considered unsuccessful, and it was likely due to the lack of adherence of the panel to the fuel tank. This problem was associated with the selection of adhesive for attaching the panel to the fuel tank, not the panel design itself. The same panel design was able to prevent fire ignition in two other tests. The commercial powder panel was unsuccessful in preventing fire ignition, but it too failed to adhere to the fuel tank panel. The amount of powder released, however, did not make the chance for success seem likely, even if it did adhere. Demonstration testing after Phase I at China Lake, with many of the same test conditions including the ballistic threat, showed these panels were not effective under these conditions. In these NGP demonstration tests, the enhanced powder panels released at least 87% more powder than the commercial powder panel. Except for one enhanced powder panel, which still released significantly more powder, the size of the front face area removed was at least 34% better for the enhanced powder panels compared to the commercial powder panel.

Thinner enhanced powder panels appeared to release more of the total panel's powder content. However, they also likely contained less powder, so the total powder release may have been fairly close to the thicker panels. The powder panel utilizing a self-sealing back face (EPP-08) did appear to sustain less front face break-up than other enhanced powder panels. This could have been a result of this design variation. However, the reduction in the size of the back face hole, also likely contributed to the panel effectiveness by reducing immediate fuel leakage.

Both tests with $KHCO_3$ resulted in successes, although Test EPP-07 did show evidence of a very brief fire ignition. It appeared the powder release did, however, result in the fire being extinguished. $KHCO_3$ was expected to be at least as effective as Al_2O_3, however, the grain size of the $KHCO_3$ was on average around 30 microns compared to the 5 micron Al_2O_3. As previous testing has shown, a smaller grain size has proven to be more effective in fire extinguishing. It is inconclusive, however, in these few tests, whether or not grain size was even a factor.

It was conclusive that sufficient powder was released from each of the enhanced powder panels to significantly reduce the likelihood of a dry bay fire, regardless of the powder type. It is estimated that at least 40 g of powder was released in most of the enhanced powder panel tests, with as much as 60 or 70 g from the heavier panels. It is estimated the commercial powder panel likely released less than 10 g of powder.

6. Important Findings and Conclusions

This NGP project accomplished its original objectives to identify fire extinguishing powder panel concepts for enhancement (relative to current capability and halon 1301) and demonstrate proof-of-concept designs. It demonstrated the feasibility of enhanced powder panels and revealed enhanced powder panel designs could afford a number of benefits over current commercial powder panel designs. It also expanded upon the original objective and was able to optimize more promising enhanced powder panel designs to make them even more competitive with alternative fire extinguishing systems, including halon 1301. Finally, these optimized designs were then evaluated in live fire tests, demonstrating their ability to mitigate fire ignition in realistic dry bay areas. Although additional work is necessary to address manufacturing issues and ensure enhanced powder panels meet the requirements of individual aircraft programs, they are in a position to be considered as a potential alternative in future fire protection evaluations.

Phase I NGP investigations examined current powder panel applications, baselined current powder panel design features, screened potential design and material improvements, and demonstrated the feasibility of more promising enhanced powder panel concepts. Phase II NGP investigations examined halon applications for comparison with enhanced powder panels, identified likely production requirements and issues for enhanced powder panels, parametrically examined design features to result in optimized enhanced powder panels, and demonstrated the optimized designs through live fire testing in a realistic dry bay. Findings from this research revealed that realistic powder panel concepts can significantly enhance the fire extinguishing effectiveness of this vulnerability reduction method. Enhanced powder panel designs can afford the following benefits over current commercial powder panel designs:

- greater powder release into dry bay,
- better dispersion of powder to prevent ignition off-shotline,
- longer powder suspension to prevent fire ignition for longer period of time,
- greater front face area removal to allow more powder to escape,
- design flexibility of enhanced powder panels can be utilized to target weight, durability, and application-specific design goals,
- and significantly improved fire extinguishing effectiveness over commercial powder panels can be achieved at an equal or lighter weight and thickness.

Optimization goals were achieved for enhanced powder panels in this project. These goals were to lower enhanced powder panel weight and thickness to the levels of current commercial powder panels or below and demonstrate greater performance in live fire testing. Enhanced powder panels evaluated in final demonstrations ranged in weight from 140.78 g (0.31 lb.) to 227.02 g (0.50 lb.), with four of the six panels being lighter than the commercial powder panel evaluated (189.05 g or 0.42 lb.). Thicknesses ranged from 1.905 mm (0.075 in.) to 2.159 mm (0.085 in.), while the commercial powder panel thickness was 2.69 mm (0.106 in.).

Live fire testing conducted in a dry bay of realistic size for an aircraft (0.45 m^3 [16 $ft.^3$]), with an actual ballistic threat (12.7mm API), and at least 49.21 l (13 gal.) of JP-8, resulted in the prevention of fire ignition in four out of six tests. In a fifth test, a fire starting from an existing pool of fuel was quickly extinguished (after only 0.28 second) by an enhanced powder panel. The cause of a lone unsuccessful test resulting in a fire was attributed to an inadequate attachment adhesive on the back of the enhanced powder panel. The test of a commercial powder panel resulted in a fire, however the attachment adhesive again failed to hold. Although the commercial panel test was not conclusive, a further examination of the test results indicated a significant increase in vital performance characteristics for the enhanced powder panels. Despite being as much as 26% lighter and 29% thinner, the enhanced powder panel tests resulted in at least 34% greater front face area removal and at least four times greater powder release. Powder was evident on surfaces throughout the dry bay following enhanced powder panel tests and was visibly suspended in the dry bay up to five minutes after some of the enhanced powder panel tests. No evidence was present of dispersed and/or suspended powder in the commercial powder panel test.

A number of lessons were learned about effective powder panel design. Some, previously discovered, were reaffirmed. Among the key lessons learned were:

- brittle or frangible front face materials outperform ductile or tough materials,
- front face crack growth optimization can be designed into the powder panel through the use of particular front face materials, thicknesses, rib designs, attachment methods to the ribs, and even surface scoring,
- a strong synergism exists between the rib structure and the front face design,
- and the back face can be designed to aid in powder dispersion and/or reduce fluid leakage.

Another key finding in this program is that there are design features associated with enhanced powder panels that can make them very resistant to accidental leakage. With the use of plastics and certain composites, there are adhesives to attach the various elements of the panel that form extremely tight bonds. The selection of a front face material and thickness can take into account the likely harsh environment to which the powder panel will be exposed. Accidental leakage has been a significant concern for aircraft designers considering powder panels and is the primary reason that Al_2O_3 has been the only chemical fire extinguishing powder finding production usage. With this resistance to accidental leakage in certain designs, perhaps other lighter weight and improved performance fire extinguishing agents can be considered. Not only are other powders lighter in weight, but improved effectiveness of these powders may lead to reduced requirements for powder loading.

To fully take advantage of the potential benefits from enhanced powder panels, further examination of the more promising designs should be performed for potential qualification test requirements. These may include, but are not limited to operating temperature, chemical exposure, vibration, impact resistance, and moisture absorption. These issues were considered in the selection of materials for Phase II optimization testing, but qualification testing for these parameters was not conducted.

Despite significant increases in powder release for enhanced powder panels, a balance must be achieved between weight/thickness and effectiveness. For protection against larger threats, it may be warranted to consider higher powder loading, which is the significant weight driver. For strict weight restrictions, testing may be required for the given powder panel to determine the type and size of the threat for which protection is afforded.

The principles that govern the final design features uncovered in this project were focused on ballistic testing and aircraft (fixed, rotary, tilt-rotor, and unmanned). However, they do not apply solely to simple projectile impact or these types of vehicles. Enhanced powder panels should be effective, even if subjected to other forces or if employed in any number of other applications. Further studies continue to determine the depth and breadth of these applications and the various factors influencing enhanced powder panel performance in these areas.

7. Significant Hardware Developments

As the previous section detailed, enhanced powder panels have been developed with increased effectiveness over current powder panel designs at equivalent or better weight and size. These enhanced powder panel designs can now be examined for various applications, particularly in military aircraft, as a trade-off with other fire extinguishing systems. Additional work will be required with the examination of production design requirements, which may cause some adjustments in the selection of materials or sizing, but the design principles should be in place. Some manufacturing concepts were developed and others conceived as a result of this work, which will need to be optimized for production application.

8. Implications for Further Research

The developments initiated by this project have sparked other research and development proposals and an internal research and development investment by Skyward itself. A Joint Aircraft Survivability Program Office (JASPO) proposal has been evaluated favorably and may lead to further investigations into design requirements and qualification testing that could result in a production-ready form of the enhanced powder panels. Other efforts are underway to achieve this goal regardless of the success of this proposal. Interest has been shown by a number of aircraft programs seeking alternative fire protection methods, including lightweight, passive means. Efforts will continue to address their concerns and potential commercialization of enhanced powder panels.

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Presented the following papers:

- Cyphers, D.C., Frederick, S.A., and Haas, J.P., "Enhanced Powder Panels", *The Proceedings of the 12th Halon Options Technical Working Conference*, Albuquerque, NM, Paper 10, pp. 1-12, Albuquerque, NM, April 30 - May 2, 2002.
- Cyphers, D.C., Frederick, S.A., and Haas, J.P., “Demonstrating Enhanced Powder Panels”, *The Proceedings of the 13th Halon Options Technical Working Conference*, Albuquerque, NM, May 13-15, 2003.
- Haas, J.P., Cyphers, D.C., and Frederick, S.A., “Enhanced Powder Panel Concepts”, *Twenty Seventh Annual American Institute of Aeronautics and Astronautics Dayton-Cincinnati Aerospace Science Symposium*, Dayton, OH, March 5, 2002.

Presented the following poster papers:

- Cyphers, D.C., Frederick, S.A., and Haas, J.P., “Enhanced Powder Panels”, Aircraft Survivability 2002 - Combat Survivability: UAVs and Manned Aircraft, Monterey, CA, November 18-21, 2001.
- Cyphers, D.C., Frederick, S.A., and Haas, J.P., “From Concept to Demonstration - The Evolving Enhanced Powder Panel Story”, Aircraft Survivability 2003: Reclaiming the Low Altitude Battlespace, Monterey, CA, November 3-6, 2002.

The following paper was accepted and is pending publication:

- Cyphers, D.C., “Enhanced Powder Panels - Applying New Ideas to an Old Fire Extinguishing Method”, Military Fire Protection Systems Edition, FS-World.com Magazine.

11. Appendices

APPENDIX A

PHASE II OPTIMIZED POWDER PANEL LIVE FIRE DEMONSTRATION TEST PLAN

ENHANCED POWDER PANEL DEMONSTRATION TEST PLAN

PROJECT 5E/1/12

NEXT GENERATION FIRE SUPPRESSION TECHNOLOGY PROGRAM (NGP)

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JUNE 2003

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TABLE OF CONTENTS

1.0 Introduction

Powder panels are not a new concept for extinguishing ballistic threat-induced fires in aircraft. They have in fact been around for many years. However, a number of factors have renewed interest in powder panel technology. First, the production of halon has been banned due to its ozone depleting potential. New techniques will be needed to fill the role of halon in aircraft fire extinguishing. Also, new materials, powders, and construction techniques have been developed which may allow for improved powder panel performance (both system weight and fire extinguishing capability). Therefore, this test program is being performed to assist in identifying fire extinguishing powder panel concepts for enhanced performance.

2.0 Testing Approach

The purpose of this testing is to demonstrate enhanced powder panels optimized in Phase II of NGP Project 5E/1/12 can effectively prevent fires in a dry bay/fuel tank simulator. These demonstration tests will show that optimization of materials and designs did not degrade the effectiveness of enhanced powder panel prototype designs in suppressing ballistic threat-induced dry bay fires. Phase II of this two-phase NGP project concentrated on optimization of the more promising designs identified in Phase I. Design variations were examined to optimize size, weight, durability, and practicality, while maintaining increased performance over standard powder panels. While threat encounter parameters are likely to be important to the overall output response, the limited scope of this program will necessitate fixing those parameters related to the threat. These tests will include parameters conducive to starting a fire and a test article more representative of a full-scale dry bay compared to the test device used in previous experiments.

Optimized enhanced powder panel designs will be tested in a realistic dry bay/fuel tank test article by penetrating the panels with a realistic ballistic threat. Testing will be conducted in Range 2 of the Aerospace Vehicle Survivability Facility (AVSF). Range 2 is capable of housing tests involving JP-8 fuel and 12.7mm armor piercing incendiary (API) projectiles, including the ability to extinguish a fire generated during the course of such testing. The velocity and obliquity chosen for testing will be fixed and replicate as closely as possible a realistic combat encounter. The testing will be designed to characterize the ballistic threat interaction with the leaking fuel from a penetrated fuel tank and the potential for fire suppression from fire extinguishing powder released by the penetrated powder panel.

2.1 Objectives

The overall objective of this project is to identify powder panel concepts for enhancement, relative to current capability and halon 1301, and demonstrate proofs of concept. In order to satisfy the project objective, current powder panel technology will be characterized and recent improvements in powder panel materials and construction will be assessed. The ultimate goal of this work is the development of 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.

The Phase II test objective is to optimize effective designs identified in Phase I. The objective of this test series is to demonstrate through proof-of-concept testing the most promising enhanced powder panel concept.

This test series objective will be met by:

- Performing baseline ballistic tests without protection,
- Performing a ballistic test with a standard commercial powder panel
- Performing ballistic tests on optimized enhanced powder panels
- Measuring the temperature achieved within the test article dry bay
- Capturing video of ballistic test event
- Determining whether or not the fire was suppressed
- Observing the powder distribution following each test event

2.2 Data Requirements

The primary data collected will involve optical footage of the events transpiring within the dry. Primarily, the data must show whether or not conditions were appropriate for a fire to start without protection, and whether or not enhanced powder panels were able to prevent dry bay fires. Factors that affect how the powder is dispersed, including threat and panel responses, will also be collected. Impact dynamics data will be analyzed, such as panel fracture characteristics and damage mechanisms.

2.2.1 Instrumentation

<u>Threat Velocity Measurement Equipment</u> - The projectile velocity at impact will be calculated for each test. The projectile impact velocity is calculated by measuring the elapsed time required to travel from the gun barrel muzzle to the target (striker plate in this case). A gun break wire is installed in a small hole drilled in the side of the barrel near the exit end. The wire is severed as the projectile exits the muzzle. A break-paper grid is located at the intended impact point on the striker plate. The break-paper grid is broken when the projectile impacts the target. With the break wire and break paper time increments determined and the standoff distance known, the impact velocity can be calculated. If the paper grid and strain gage should fail before impact, the projectile velocity can still be estimated using the gun break signal and the pressure transducer signal recorded on the Nicolet data acquisition system.

<u>Thermocouples</u> - Temperature magnitude-time histories will be collected to obtain a temperature profile for the dry bay test article. Thermocouples will be located within the dry bay (2). All thermocouples will operate in the 0° to 2,400°F range with a 1 kHz sampling rate. One thermocouple will be located on the back side of the striker plate below the target location and the other near the fuel tank wall above the powder panel. Exact locations are not critical. Thermocouples will be inspected and tested prior to each test to assure proper functioning.

<u>Optical Records</u> - A high-speed video camera (approximately 500 frps) will be mounted beside the test article and will record the view looking through a lexan panel on the side of the test device. Skyward will provide a digital video camera (approximately 30 frps) that will also

record the event through the lexan panel. Both cameras will be aimed toward the powder panel, but cover as much of the dry bay as possible. A standard video camera (30 frps) will be positioned more distant and will focus on the overall test article to capture the entire event.

2.3 Testing

Up to ten ballistic tests will be conducted, including unprotected and powder panel-protected configurations of the dry bay/fuel tank simulator. The test article and test setup will be very similar to enhanced powder panel tests conducted in Aug 02 at the Weapons Survivability Laboratory at China Lake, California. These tests involved proof-of-concept testing of enhanced powder panels.

2.3.1 Test Facilities

The testing will be conducted in Range 2 (Figure 1) of the 46th Test Wing Aerospace Survivability and Safety Flight (AVSF). This range is located at Wright-Patterson Air Force Base, OH, and is operated by the Aerospace Survivability and Safety Flight (46 OG/OGM/OL-AC). Range 2 is typically utilized for such programs as fuel cell inerting, hydrodynamic ram evaluations, ballistic flammability, material and component ballistic tolerance, and threat characterization.

Figure 1. AVSF Range 2

2.3.2 Test Article and Setup

The test article consists of two parts. The first consists of an aluminum/steel/Lexan box representing an aircraft dry bay (Figures 2 and 3). Its dimensions are 2 feet wide x 4 feet long x 2 feet high for a dry bay volume of 16 ft^3. Steel L-angle forms the structure of this box. The top, bottom, and one side (length direction) of the box will consist of aluminum panels in the test configuration. The other side panel will be composed of Lexan to allow viewing of the event by the video cameras during testing. The one end of the test article positioned toward the West (projectile entrance direction) in the test setup will consist of an aluminum panel with an approximately 3 inch diameter or 3 inch x 3 inch square hole. This hole will allow the projectile to enter the test article. The other end of the dry bay simulator will consist of an aluminum frame panel to allow a second box to attach. This frame will be used to attach the second box, but will sized so it does not overlap the 1 foot x 1 foot powder panel positioned in its center, as the conceptual view of the overall test article shows in Figure 4. A striker plate will be attached to the internal frame of the dry bay approximately one foot in front of the fuel tank front face. The striker plate, composed of 0.250 inch thick 7475 aluminum, will be no more than 6 inches in width to allow fire extinguishing powder from the powder panel to disperse around it. If the striker plate can be secured from lower attachment points, it will not extend to the top of the dry bay.

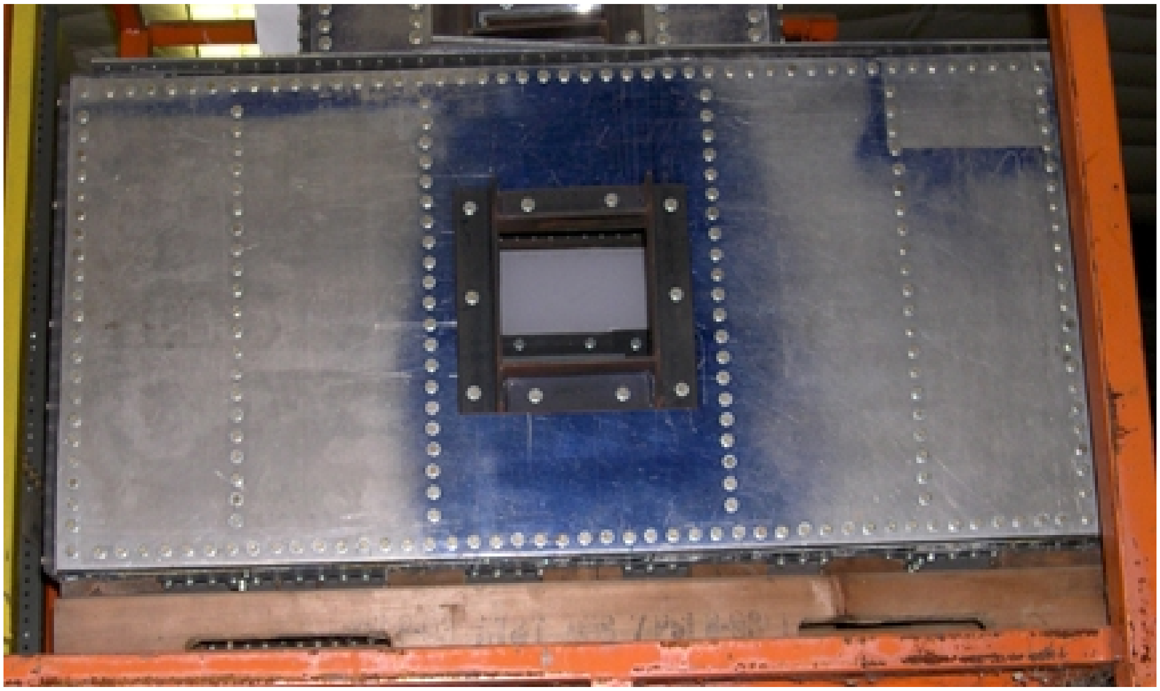

Figure 2. Side View of Dry Bay, Prior to Modification for Test-Ready Configuration

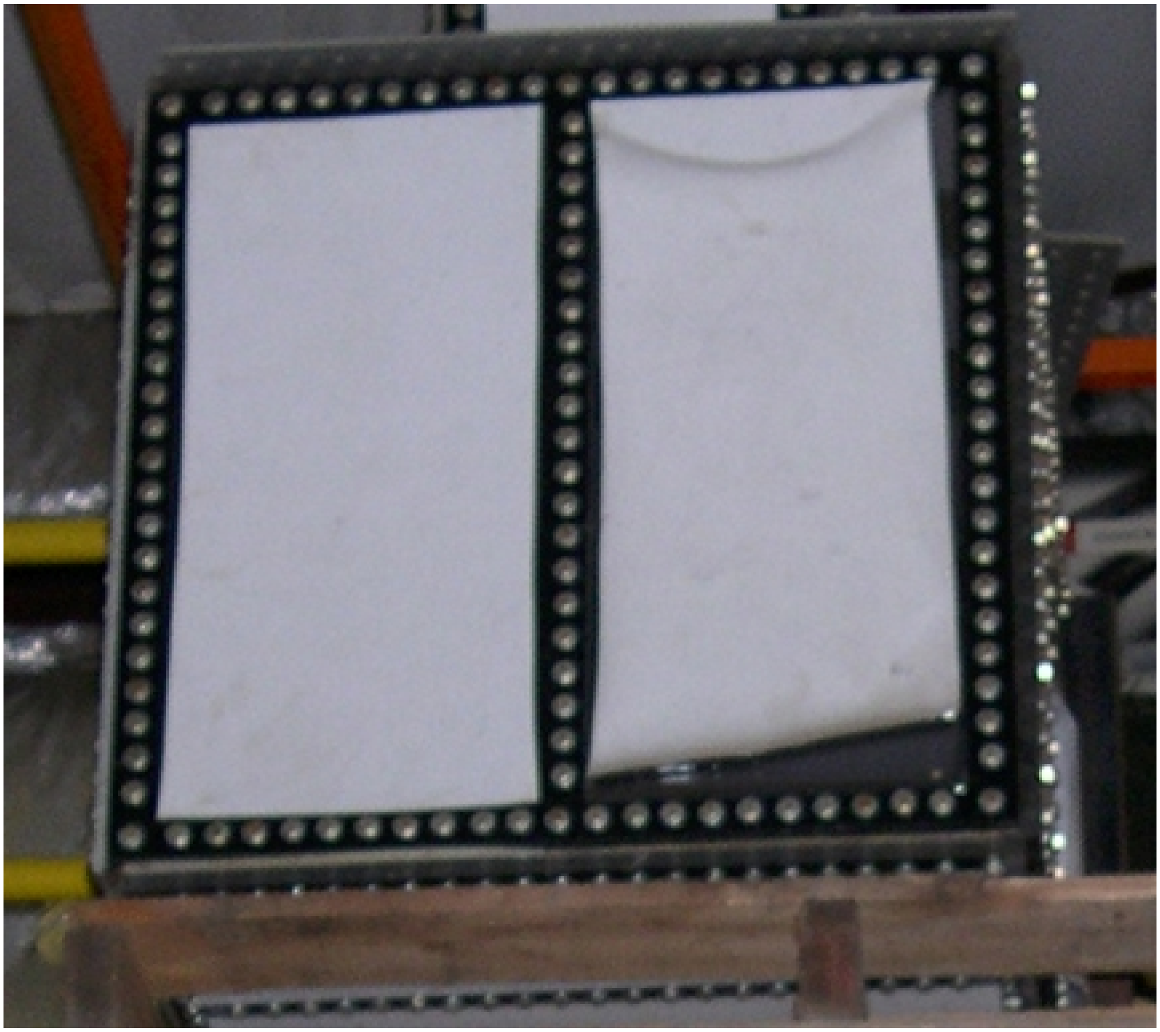
Figure 3. End View of Dry Bay, Prior to Modification for Test-Ready Configuration

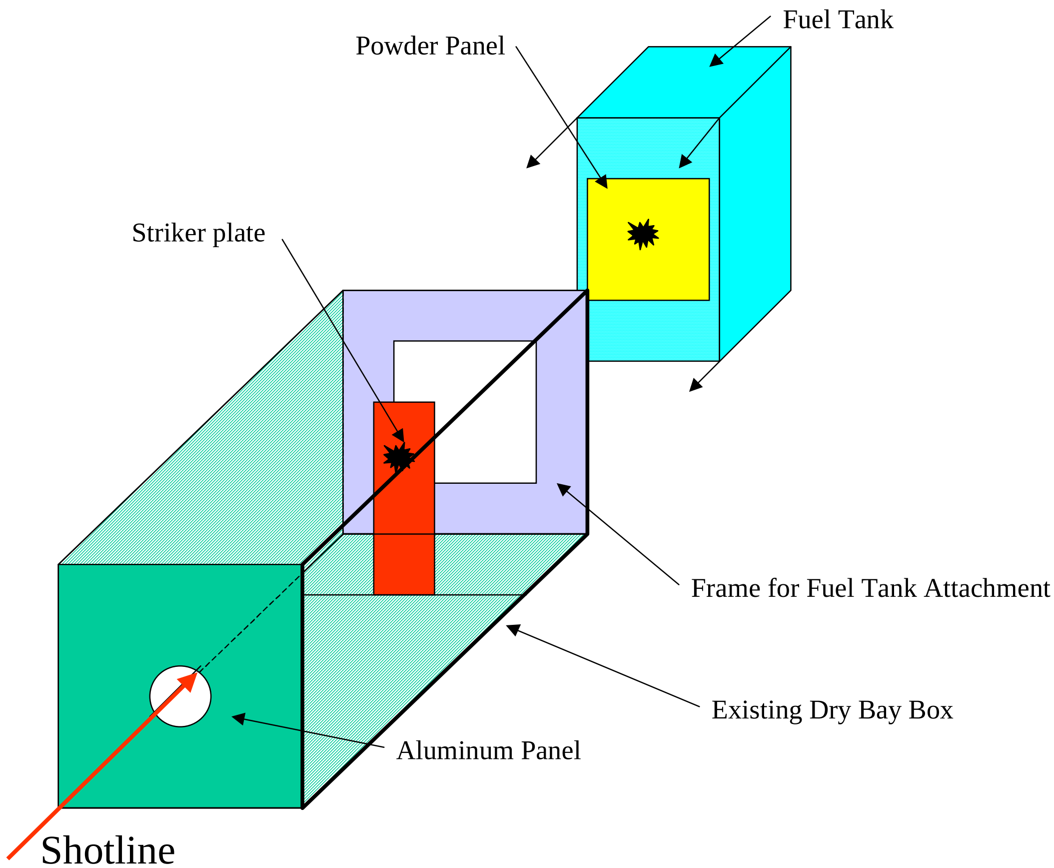

Figure 4. Overall Test Article Concept (Top and Lexan Side Removed for Clarity)

The fuel tank will measure at least 1 foot 2 inches wide by 1 foot deep (along shotline) by 2 feet high. The width of the tank must allow for the powder panel to be adhesively bonded to the center of the front face and still allow it to be attached to the dry bay simulator. The volume below the powder panel location may be sectioned off to lower the amount of required fuel. The fuel level does not have to be completely full, but must be at least 6 inches above the impact location. The volume of the fuel tank will, therefore, be approximately 1.75 cubic feet, holding just less than 13 gallons of JP-8 fuel. The front face of the fuel tank will allow for removable panels. These removable panels will be 0.08 inches thick and composed of 7075-T6 aluminum, unless sufficient hydrodynamic ram damage is not observed. A decision may be made to use 2024-T3 aluminum of 0.071 inch thickness in subsequent tests, if not. This panel will be secured to the fuel tank with L-angle stiffeners and bolts. The remaining panels of the fuel tank will likely be composed of steel to sustain repeated hydrodynamic ram pressures. The back panel will be reinforced with a “soft” aluminum panel in front of it to capture the armor piercing rounds. No air gap will be allowed to exist between the dry bay and fuel tank once attached. A drain will be placed in the fuel tank and dry bay, but fuel will not be drained from the dry bay until powder dispersion is documented by digital photographs and video. It is vital that the powder dispersion be documented before the dry bay is drained and rinsed out.

The powder panels will be approximately 1 foot by 1 foot by 0.1 inch thick in size. They will be centered along the shotline and mounted to the front of the fuel tank front face panel using epoxy bonding or double-sided tape. The powder panel will fit inside of the frame of the back panel of the dry bay simulator to avoid any interference with the performance of the panels.

The test article will be placed near the East wall of AVSF Range 2, with the fuel tank on the East side. The gun will be positioned to the West of the test article. The gun will be fired from the West toward the East wall of the range. This configuration is planned as a safety measure to ensure projectiles do not leave the range enclosure. Figure 5 shows the relative position of the test article and gun setup.

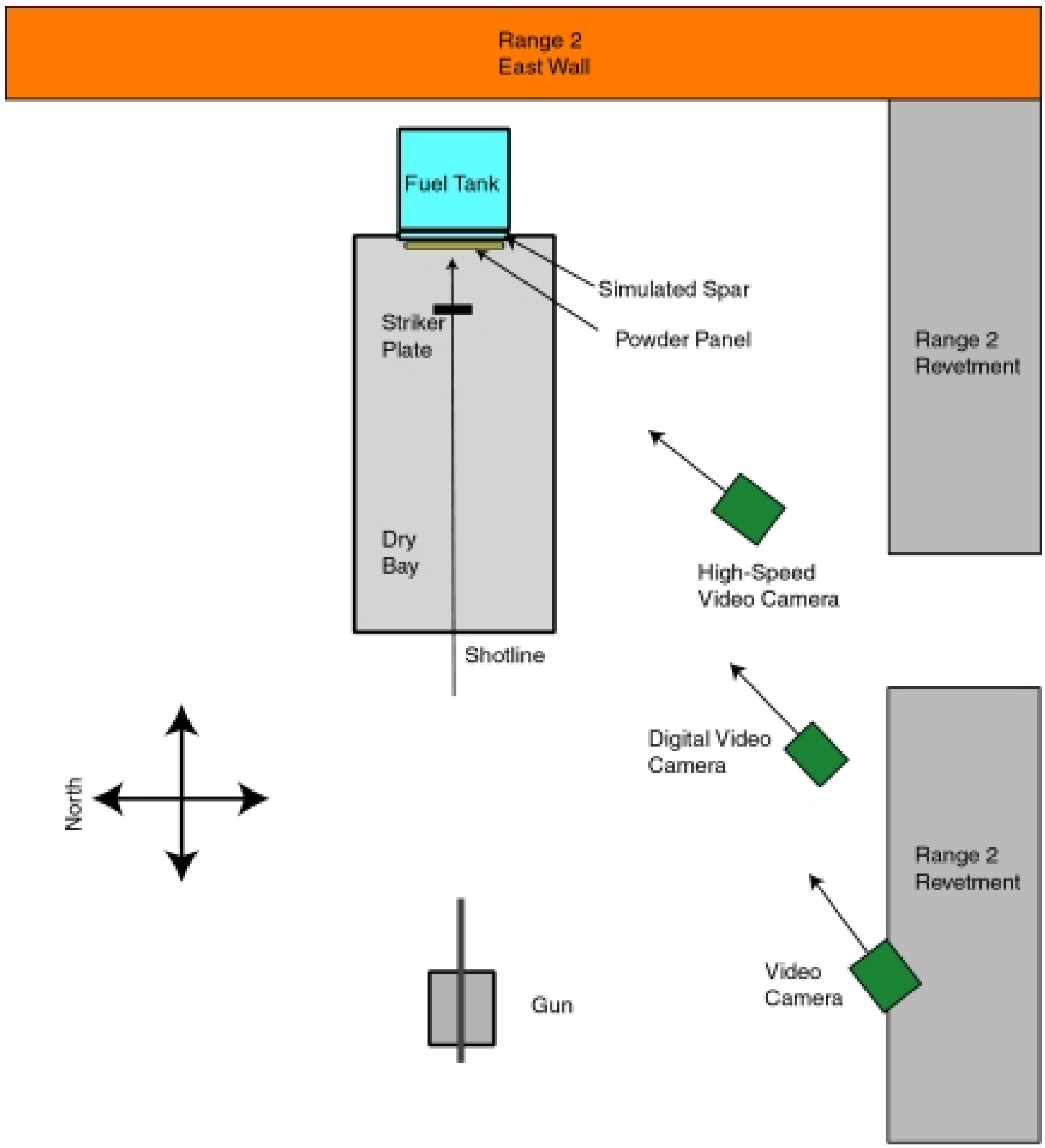

Figure 5. Test Article Setup in Range 2

2.3.3 Threat Description

A single threat type will be used for each of the enhanced powder panel tests. The 12.7mm API Type B-32 projectile will be fired through the center of the test article at a velocity of approximately 2,750 fps for the first baseline test and 2,500 fps for subsequent tests. Up to ten total ballistic tests will be conducted to gather data on the performance of the powder panels. A physical description of the projectile is provided in Figure 6. The projectiles will be fired from Mann barrels at close range to minimize targeting error, and the projectile powder weight will be modified, if necessary, to achieve the desired impact velocity.

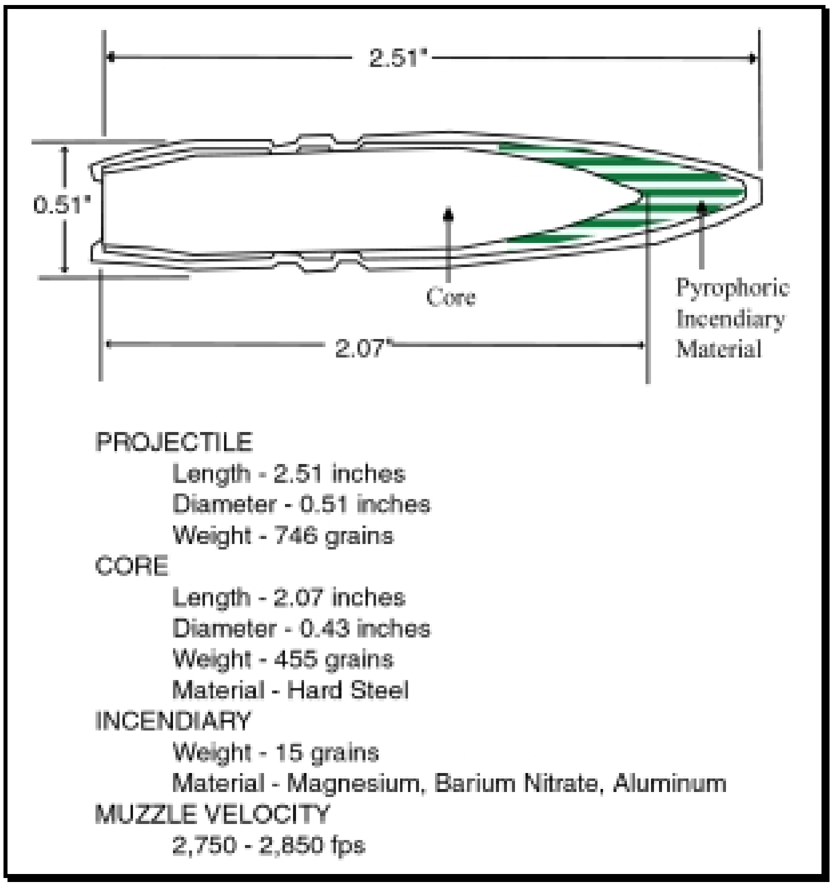

Figure 6. 12.7mm API Type B-32 Projectile Description

2.3.4 Test Matrix

The planned test matrix is listed in Table 1. No more than ten tests are planned for this program. The first test will be a baseline test without powder panel protection. The purpose of this test will be to demonstrate that the conditions specified in this program will indeed result in a dry bay fire, if no fire protection is included. If the results of this first test are inconclusive regarding the probability of a dry bay fire, a second baseline test may be conducted. The first primary test will involve a 12 inch by 12 inch commercial powder panel. This test will be conducted to determine if a current powder panel could prevent a fire for the given conditions. The subsequent primary tests will be conducted with enhanced powder panels. These tests will attempt to determine if the optimization techniques used to modify promising designs demonstrated in Phase I of this NGP project affected performance at all.

Table 1. Test Matrix.

Test No.	Powder Panel	Fuel / Quantity	Striker Plate / Location	Fuel Tank Panel	Obliquity Angle (°)	Threat (Type)	Impact Velocity (fps)
EPP-01	None	JP-8 / Full	0.25 inch 7475 / 1 foot before powder panel	0.08 inch 7075-T6	0°	12.7mm API	2,750
EPP-02	None	JP-8 / 18 inches (3/4)	0.25 inch 7475 / 1 foot before powder panel	0.071 inch 2024-T3	0°	12.7mm API	2,500
EPP-03	Commercial	JP-8 / 18 inches (3/4)	0.25 inch 7475 / 1 foot before powder panel	0.071 inch 2024-T3	0°	12.7mm API	2,500
EPP-04	Enhanced 1	JP-8 / 18 inches (3/4)	0.25 inch 7475 / 1 foot before powder panel	0.071 inch 2024-T3	0°	12.7mm API	2,500
EPP-05	Enhanced 2	JP-8 / 18 inches (3/4)	0.25 inch 7475 / 1 foot before powder panel	0.071 inch 2024-T3	0°	12.7mm API	2,500
EPP-06	Enhanced 3	JP-8 / 18 inches (3/4)	0.25 inch 7475 / 1 foot before powder panel	0.071 inch 2024-T3	0°	12.7mm API	2,500
EPP-07	Enhanced 4	JP-8 / 18 inches (3/4)	0.25 inch 7475 / 1 foot before powder panel	0.071 inch 2024-T3	0°	12.7mm API	2,500
EPP-08 (If $ permits)	Enhanced 5	JP-8 / 18 inches (3/4)	0.25 inch 7475 / 1 foot before powder panel	0.071 inch 2024-T3	0°	12.7mm API	2,500
EPP-09 (If $ permits)	Enhanced 6	JP-8 / 18 inches (3/4)	0.25 inch 7475 / 1 foot before powder panel	0.071 inch 2024-T3	0°	12.7mm API	2,500
EPP-10 (If $ permits)	Enhanced 7	JP-8 / 18 inches (3/4)	0.25 inch 7475 / 1 foot before powder panel	0.071 inch 2024-T3	0°	12.7mm API	2,500

2.3.5 Test Procedures

The procedures to be followed for each individual test are presented in Tables 2 and 3. These procedures must be followed to ensure the test objective is met for each test. The test setup must be reviewed prior to each test to ensure test preparations are in accordance with the test plan. This includes making sure the test objective will be satisfied and the correct data will be collected to support the post-test analysis. The key test procedures for this program involve the setup of the test article to ensure the appropriate powder panel is installed in the proper location, the fuel tank is filled, and the appropriate impact location on the striker plate is targeted.

Table 2. Pretest and Test Procedures

PRETEST
Pretest briefing.
Weigh powder panel.
Install fuel tank and striker plate panels.
Install powder panel, if any.
Attach fuel tank to dry bay.
Fill fuel tank with JP-8 fuel.
Locate impact point on striker plate.
Dry fire and aim weapon.
Console key to Range Safety Officer (RSO).
Raise the flag.
Ready cameras.
Instrumentation check.
Clear and activate range.
Check specimen CO_2 valve and put in off position.
Facility CO_2 check.
Take zeros and calibrations.
TEST
Load and arm weapon.
Turn master range power on.
RSO gives key to console operator.
All systems ready (Veridian test engineer, Skyward, safety).
Arm the Nicolet system.
Start 20 second countdown.
T-15 seconds, turn on videotape recorders.
T-8 seconds, arm weapon.
T-2 seconds, start instrumentation data acquisition.
T-0.5 second, start high-speed video camera.
T-0 seconds, gun fired under computer control.
T+5 seconds, if fire exists, activate HFC-125 @ test engineer's discretion.
If fire escapes test article, activate CO_2 @ test engineer’s discretion.
End instrumentation data acquisition.
End test.

Table 3. Post-Test Procedures

POST-TEST
Backup instrumentation data.
Turn off videotape recorders.
Turn master range power off.
Download weapon.
RSO safety checks Range 2.
RSO deactivates range.
Turn off beacon and lower the flag.
Visually document damage and powder dispersion.
Drain fuel to proper location (Manifold or scrap).
Remove remaining powder panel and weigh.
Rinse dry bay test article and prepare for subsequent test.
Review instrumentation data and video.
Reduce raw data.

3.0 Safety Issues

All testing will be accomplished in AVSF Range 2. All safety precautions for AVSF Range 2 will be followed throughout the course of testing. Hazardous material handling, including the handling and firing of foreign fuzed shells, will follow applicable Safety Permits. Protection of personnel and government property during testing will be the responsibility of the Range Safety Officer (RSO). If the RSO determines safety procedures/rules are not being followed, testing will be suspended or canceled.

The principal safety issue with this testing will be the safe containment of the ballistic threat. The principal method of stopping the threat will be through a catch plate located on the back wall of the fuel tank test article. The East wall of Range 2 will be behind the test article if the projectile escapes. An external catch plate will be positioned on this wall as well.

The powders to be used for testing are all non-toxic to humans. However, because the dry powder is a finely divided solid material, it can become suspended in the air causing a mild discomfort similar to that experienced in any dust-laden atmosphere. To minimize the exposure to the dust, all participants should be advised to use dust masks during test clean-up.

4.0 Documentation

All data will be recorded and analyzed following each test. A draft test report will be prepared and submitted to the Technical Program Manager (TPM) of the National Institute for Standards and Technology for the Next-Generation Fire Suppression Technology Program (NGP) in FY03. The final test report will incorporate government comments and be submitted back to the NGP TPM.

The subject reports shall contain test conditions, a description of any deviations approved subsequent to the preparation of the Enhanced Powder Panel Test Plan, test results, and conclusions. The emphasis of the test report will be to document in as much detail as possible the results of optimized enhanced powder panel demonstration tests and their effectiveness.

APPENDIX B

PHASE I POWDER PANEL CONFIGURATIONS TESTED

Test No.	Material Description	Total Thickness (mm)	Pretest Weight (g)	Powder Release (g)	% Powder Released	Front Face Area Removed (cm^2)	Rear Face Area Removed (cm^2)
1	0.406mm Al front, 5.33mm corrugated polyallomer, 0.254mm Al back	5.99	630.04	0.59	0.17	1.26	1.26
2	0.254mm Al front, 5.23mm corrugated polyallomer, 0.406mm Al back	5.89	594.21	0.04	0.01	1.26	1.26
3	Double wall polypropylene	4.50	427.20	0.83	0.27	1.26	1.26
4	Double wall polycarbonate	6.58	561.65	3	0.67	3.23	2.84
5	Double wall polycarbonate, scored	6.58	704.56	3	0.51	2.84	3.87
6	1.524mm ABS faces, 9.525mm acrylic eggcrate rib	12.40	962.90	minimal*	minimal*	1.26	1.26
7	1.778mm (peak) acrylic prismatic faces, 9.525mm acrylic eggcrate rib	12.90	1038.20	7	1.14	1.29	6.45
8	2.032mm clear acrylic faces, 9.525mm acrylic tube ribs	13.49	1401.60	48	5.56	31.61	31.61
9	1.778mm textured acrylic front, 1.524mm ABS back, two ABS ribs (3.048mm thick) at 10.16cm and 20.32cm	6.91	769.40	23	5.02	17.74	1.29
10	1.778mm acrylic prismatic front, 1.524mm ABS back, two ABS ribs (3.048mm thick) at 10.16cm and 20.32cm	7.19	829.50	10	3.39	1.94	1.29
11	10.16cm x 10.16cm scored clear 1.524mm acrylic front, 2.032mm clear acrylic back, 3.175mm polycarbonate honeycomb rib	6.91	574.00	7	3.55	16.13	2.84
12	5.08cm x 5.08cm scored clear acrylic, 2.032mm clear acrylic back, 3.175mm polycarbonate honeycomb rib	7.59	579.00	9	4.64	22.58	3.23
13	1.524mm ABS faces, 9.525mm Nomex rib (PN2-1/8-6.0)	13.49	1128.00	1.5	0.2	1.26	2.84
14	1.778mm textured acrylic front, 2.032mm clear acrylic back, 6.35mm Al honeycomb rib (PAMG-XR1-8.1-1/8-002-5052)	10.49	831.80	1	0.23	1.29	3.23
15	1.524mm ABS faces, 6.35mm Al honeycomb rib (PAMG-XR1-8.1-1/8-00205052)	10.21	764.00	1	0.25	1.26	2.84
16	2.032mm clear acrylic faces, 6.35mm Al honeycomb rib (PAMG-XR1-8.1-1/8-002-5052)	10.80	942.00	3	0.65	1.61	5.03

Test No.	Material Description	Total Thickness (mm)	Pretest Weight (g)	Powder Release (g)	% Powder Released	Front Face Area Removed (cm^2)	Rear Face Area Removed (cm^2)
17	1.524mm ABS faces, 9.525mm hollow acrylic tube ribs	13.31	1268.30	1	0.13	1.29	1.29
18	5.08cm x 5.08cm scored 2.032 mm clear acrylic front, 2.032mm clear acrylic back, 3.175mm Al honeycomb rib	7.19	638.10	2	0.82	9.55	2.84
19	0.076mm epoxy primer sheet front, 1.524mm ABS back, two ABS ribs (3.048mm thick) at 10.16cm and 20.32cm	5.59	441.40	135	57.23	426.45	1.29
20	1.778mm acrylic prismatic front, 1.524mm ABS back, 1.5875mm Al corrugation	5.59	433.70	4	2.52	7.26	2.84
21	1.778mm acrylic prismatic front, 1.524mm ABS back, two ABS ribs (3.048mm thick) at 10.16cm and 20.32cm	7.80	552.00	30	12.82	20.26	2.84
22	1.778mm styrene prismatic front, 1.524mm ABS back, 1.5875mm Al corrugation	5.41	328.30	1	1.75	5.03	1.29
23	1.778mm styrene prismatic front, 1.524mm ABS back, two ABS ribs (3.048mm thick) at 10.16cm and 20.32cm	6.50	516.80	28.4	12.78	25.61	2.00
24	1.499mm fiberglass polyester resin front, 1.524mm ABS back, two ABS ribs (3.048mm thick) at 10.16cm and 20.32cm	6.30	721.70	Unable	Unable	153.23	2.00
25	1.524mm polyester resin front, 1.524mm ABS back, two ABS ribs (3.048mm thick) at 10.16cm and 20.32cm	6.50	746.10	1.6	0.58	1.29	2.00
26	Double wall polypropylene, scored, panel - on dry bay wall	4.29	402.26	2.22	0.56	2.00	3.03
27	2.489mm polyester resin front, 1.524mm ABS back, two ABS ribs (3.048mm thick) at 10.16cm and 20.32cm	7.06	620.00	8.19	4	25.42	2.00
28	2.489mm polyester resin front, 1.524mm ABS back, two ABS ribs (3.048mm thick) at 10.16cm and 20.32cm	7.39	875.80	83.3	18.7	80.65	2.00
29	2.54mm epoxy resin front, 1.524mm ABS back, two ABS ribs (3.048mm thick) at 10.16cm and 20.32cm	7.11	790.60	10	3.33	24.52	2.00

Test No.	Material Description	Total Thickness (mm)	Pretest Weight (g)	Powder Release (g)	% Powder Released	Front Face Area Removed (cm^2)	Rear Face Area Removed (cm^2)
30	1.27mm clear acrylic front, 1.524mm ABS back, two ABS ribs (3.048mm thick) at 10.16cm and 20.32cm	6.70	597.40	18	6.77	31.42	2.00
31	1.27mm clear acrylic front, 1.524mm ABS back, two ABS ribs (3.048mm thick) at 10.16cm and 20.32cm, dry bay clutter	6.20	596.20	35	13.61	28.19	2.00
32	2.489mm polyester resin front with embedded border rib, 1.524mm ABS back, two ABS ribs (3.048mm thick) at 10.16cm and 20.32cm, dry bay clutter	7.25	660.48	8	3.35	28.00	2.00