

DEVELOPMENTS IN AND IMPLEMENTATION OF GAS GENERATORS FOR FIRE SUPPRESSION

Paul H. Wierenga and Gary F. Holland
Primex Aerospace Company
Redmond, WA 98073-9709, USA

INTRODUCTION

Primex Aerospace Company (PAC) has been a world leader in the development and production of solid propellant gas generators, hybrid gas generators, and stored gas systems for the past 30 years. PAC maintains core businesses in the areas of fire suppression, automotive airbags, emergency escape slides for aircraft, buoyancy/flotation systems, and submunition dispensing systems.

PAC has been involved with the development and production of pyrotechnic devices for commercial applications since the late 1960s, with much of this activity being devoted to automobile airbag inflators. Two basic types of propellants are used in automotive airbag inflators: sodium azide-based propellant systems and non-azide propellant systems. These propellants are designed to exhaust a mixture of nitrogen, water vapor, and carbon dioxide gas. With the advent of a need for small and lightweight fire protection systems, and a desire to replace Halon 1301 as the agent of choice for fire suppression systems, PAC initiated research and development efforts to apply the airbag technology to fire suppression. This effort resulted in a new gas generator propellant ideally suited for fire suppression applications [1-4]. These devices are called Solid Propellant Fire Extinguishers (SPFE), and are at times referred to as Solid Propellant Gas Generators (SPGG) or Radial Fire Extinguishers (RFE).

Figure 1 illustrates the basic design of a Solid Propellant Fire Extinguisher (SPFE). The functioning of a SPFE is quite similar to that of conventional nitrogen-pressurized fire extinguisher in that both begin with electrical initiation. Upon receipt of an electrical signal, the SPFE initiator functions to ignite a solid propellant booster charge. This booster, in turn, ignites the main propellant grain or pellets, causing SPFE internal pressure to increase rapidly and rupture a series of hermetic seals. This process opens the SPFE's radial exhaust ports, allowing large amounts of gas to enter the fire zone in a non-propulsive manner.

Many of the design attributes that SPFEs inherited from their automotive airbag inflator counterparts make them extremely robust and ideally suited for a whole range of fire suppression applications. Some of these unique features are described below.

Tailorable agent discharge profile—The agent discharge profile of a SPFE can be precisely optimized to meet the fire suppression requirements of a specific application. The agent discharge profile is a function of the propellant formulation and physical size/shape of the propellant pellets or grain. PAC has developed and tested SPFEs with agent discharge durations ranging from a few milliseconds to in excess of 10 sec.

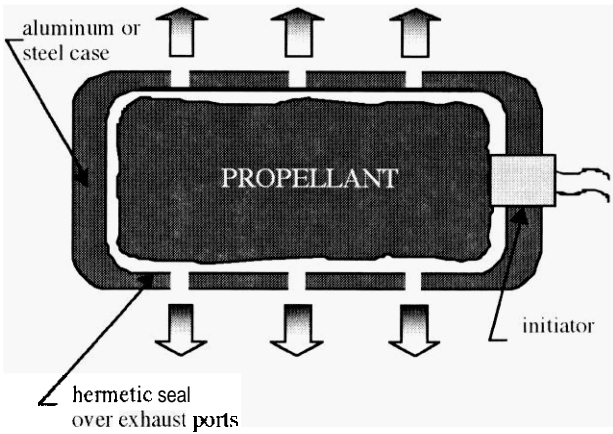


Figure 1. Solid propellant fire extinguisher.



Figure 2. Full-scale fire testing.

Small size and lightweight—Solid propellants offer the most volume-efficient means to store a gas. In addition, testing has identified inherent performance advantages associated with SPFEs that allow for reduced agent weight requirements as compared to conventional nitrogen pressurized stored agent systems. The net effect is a much smaller and lighter weight device than can be achieved with other fire suppression technologies.

No storage pressure—SPFEs do not require a nitrogen pressurant to deliver agent, hence leakage during storage is not a concern. The internal pressure of a SPFE remains at ambient until the device is functioned. This eliminates the logistics, maintainability, handling, and safety concerns associated with typical nitrogen pressurized stored agent bottles.

Orientation and acceleration insensitive—SPFEs operate the same regardless of orientation or G-loading. A nitrogen pressurized agent system will not function correctly across the operating temperature range if a vehicle is experiencing high acceleration forces from maneuvering or is oriented such that the agent is not situated over the outlet port with the nitrogen above the agent. **Long shelf life**—SPFEs are designed for a 20-year life. The PAC SPFE is based on the same design principles as automotive air bag inflators that must be capable of the rigors of a 20-year automobile life.

Hermetically sealed construction—As with the automobile air bag inflators, the SPFE is hermetically sealed to 10^{-5} scc helium/sec, which assures propellant integrity is maintained over the life of the cartridge.

Low maintainability—There are no maintainability requirements for the SPFE. It is always ready to function if the built-in-test (BIT) has verified squib bridgewire continuity. Since the SPFE has no storage pressure, leakage during storage is not a concern, as with a nitrogen-pressurized system.

Nontoxic—The exhaust products of the PAC fire suppression propellant are principally CO_2 , N_2 , and H_2O .

Noncorrosive—ASTM coupon testing has been completed using the exhaust products of the PAC SPFE. These tests have shown that the PAC SPFE complies with the stringent noncorrosive requirements of the US military aircraft community.

Environmentally friendly—None of the gases (CO_2 , N_2 , and H_2O) produced by the PAC SPFE is chemically capable of contributing to the depletion of atmospheric ozone. Therefore, the ODP equals zero. An estimate of the GWP for the agent output of the PAC SPFE is the weighted average of CO_2 emitted in the gas mixture (~ 0.31). Therefore, the GWP is very **low**.

PAC has conducted in excess of 1000 full-scale tests with SPFE systems against a variety of fire threats in a range of bay sizes and configurations (Figure 2). This full-scale live tire testing has shown that SPFEs are an efficient solution for a wide variety of fire suppression applications and platforms. In addition, this extensive test history has given PAC a unique opportunity to develop a large database of empirical test data.

PAC has used this test database to develop straightforward sizing models that incorporate a bay's volume, vent area, surface area, clutter concentration, and internal airflow to determine the SPFE configuration required to provide adequate agent concentration such that the fire is extinguished. Typically bay agent concentrations are verified using real-time concentration measurement instrumentation, in much the same way that the Halon 1301 systems have historically been qualified. This approach has been successfully employed to size and qualify PAC SPFE dry bay fire protection systems for both the F/A-18E/F and V-22 Osprey aircraft (Figures 3 and 4).

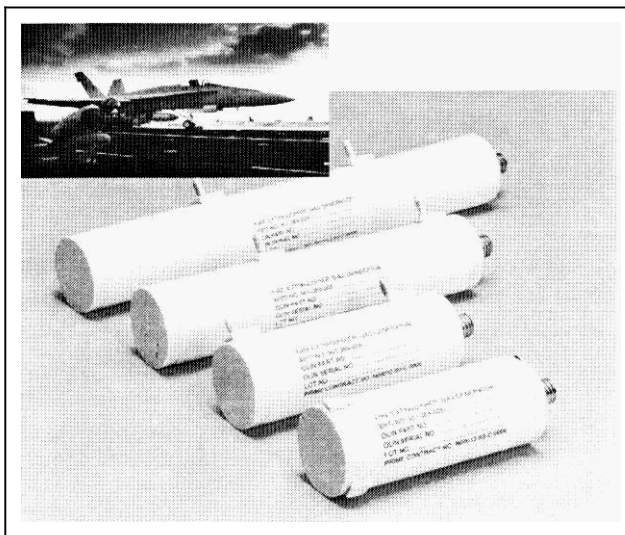


Figure 3. PAC SPFEs are currently in production for the F/A-18E/F.

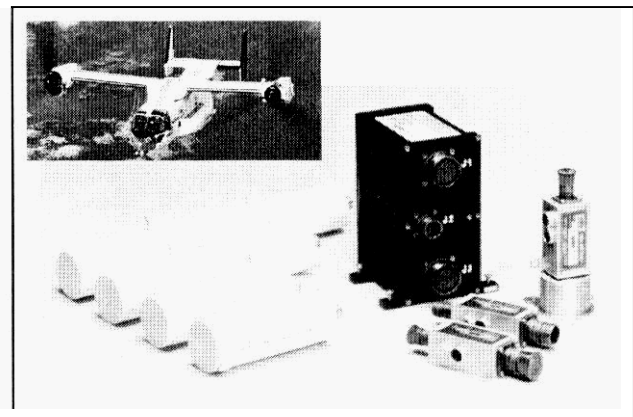


Figure 4. PAC SPFE systems are currently in production for the V-22 Osprey.

FIRE SUPPRESSION MECHANISM

An accurate and detailed understanding of the operative mechanism for flame suppression by SPFE devices is important for reasons including optimization of agent composition, agent delivery systems, and platform survivability. A definition and characterization of the critical parameters for evaluating the fire suppression efficiency of SPFE systems is therefore critical to the further development and deployment of this technology.

Review of Combustion Chemistry

Flame combustion is often modeled using a one-step chemical reaction expression [5], whereby the rate of the reaction is related to the extent of collisions between fuel molecules and oxidizer molecules. This collision frequency is related to fuel concentration [fuel], and oxidizer concentration [oxid], according to

$$\text{Rate} = k [\text{fuel}] [\text{oxid}] \quad (1)$$

and the one-step chemical rate constant k is given by:

$$k = AT^n \exp^{(-E_a/RT)} \quad (2)$$

In general, Equations (1) and (2) indicate that the rate of combustion can be diminished by (a) decreasing the concentration of the relevant species, [fuel] and/or [oxid], and (b) decreasing the reaction temperature T . At temperatures above approximately **1600 K**, air–hydrocarbon mixtures are capable of self-sustaining combustion because sufficient heat is released by the combustion process and fed back to vaporize more fuel and initiate further combustion. Any process intended to quench combustion, or extinguish a fire, must therefore reduce the chemical rate constant to some value below that self-sustaining rate.

A concise approach expressing the extinction condition in a global form was developed by Damkohler [5]. The Damkohler number D is given as the ratio of the residence time of combustion species in the combustion zone, τ_{res} (τ_{res} = flame zone length / flow-rate) and the characteristic chemical reaction time τ_{chem} (τ_{chem} = 1 / reaction rate) from one-step model expression (1),

$$D = \tau_{\text{res}}/\tau_{\text{chem}} \quad (3)$$

Conditions of extinction are possible below a critical ratio D_c . Minimizing D can be achieved by decreasing τ_{res} , or by increasing τ_{chem} . Shorter residence time can be achieved by increasing the flow rate through the flame zone. Cooling the mixture (Equation 2), diluting the reactants (Equation 1), or chemically interfering with the combustion process can produce longer chemical reaction times.

SPFE FIRE SUPPRESSION MECHANISTICS

In general, there are four primary pathways to fire suppression: dilution, cooling, chemical interference, and flow rate effects. SPFE fire suppression systems incorporate aspects of each of these mechanistic approaches in combination to affect flame extinction.

Dilution

The effectiveness of the inert gas discharged by a SPFE is enhanced by the high specific volume of the hot gases resulting from the combustion process. On entry into an open tire zone, the SPFE exhaust displaces air, consequently dropping the oxygen concentration quickly. Hydrocarbon combustion is largely quenched when oxygen levels fall below 15%, so total inert gas concentrations of 28% are expected to be sufficient for flame extinction [6-8]. This concentration is close to levels determined for CO₂, N₂, and H₂O based upon cup-burner testing.

Full-scale fire suppression testing of SPFE technology on platforms including the V-22 wing bays, F/A-18 E/F, F-22 and C-130 drybays, as well as the F/A-18E/F and F-22 engine bays, have indicated that fires are always extinguished under conditions where oxygen levels are –12% (Figure 5). However, suppression has also been observed in conditions where oxygen concentrations were higher than 15% (Figure 6). These data, when considered in light of published

analysis for pure N₂, indicate that the oxygen dilution mechanism contribution is less than 30% of the total flame suppression mechanism, as used by SPFE technology.

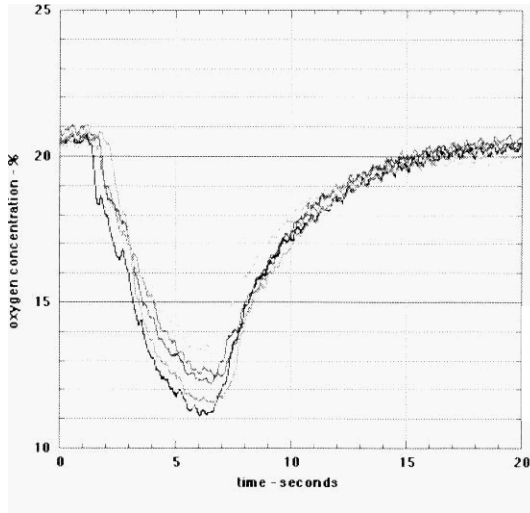


Figure 5. Suppression at 12% O₂.

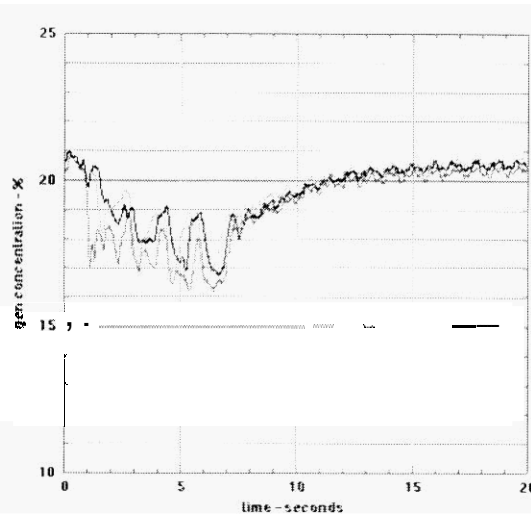


Figure 6. Suppression at 18% O₂.

Cooling

The effects of dilution and cooling are intimately intertwined. Babushok et al. [9,10] demonstrated that for pure N₂, approximately 30% of its effectiveness is due to dilution, with 70% due to the enthalpy associated with cooling the combustion reaction. The ability of agent to cool the combustion region is directly related to the temperature of the agent. The model of Huggett [11,12] suggests cooling to temperatures below 1600 K is necessary; consequently, as T_i increases in Equation (4), the overall amount of agent would also be expected to increase to effect the same degree of cooling:

$$\Delta H = \int_{T_i}^{T_f} C_p'(T) dT \tag{4}$$

In the case of solid propellant fire extinguishers, calculated adiabatic combustion temperatures are ~ 1000 to 2000 K, but thermal losses to the hardware reduce the exhaust temperature significantly. Thermal models predict, and SPFE testing corroborates, that air/agent blends have temperatures ~ 500 K/400 °F. Consequently, the cooling capacity of a SPFE discharge will be less than the cooling capacity of inert gas blends discharged at ambient temperatures. Since typical extinction concentrations for both pure inert gases and SPFE exhausts are nearly identical, effects other than pure cooling must contribute significantly to SPFEs effectiveness in fire suppression.

Further insight into this process comes from published reports by Grosshandler [13], using turbulent spray burner testing and Trees et al. [14], using counterflow burner testing. These reports indicate that for a wide variety of agents, larger minimum loads are required to obtain extinction as air temperature increases from 2 to 150 °C (420 K). The enhanced oxidizer (air) temperature has the effect of increasing the rate of fuel evaporation and flame temperature. This

results in faster chemical kinetics in the combustion zone, thereby creating a more vigorous fire scenario that requires greater agent loads for suppression. The implication from these data is that a pure cooling mechanism contributes 30–70% of the total suppressant capability of SPFEs.

Flow Rate Effects

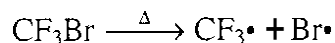
The high rate of gas production also contributes to the effectiveness of solid propellant fire extinguishers. The rapid delivery of gaseous agent to the combustion zone results in detachment of the flame from a flame holder (typically a bluff body in the fire zone). This picture is consistent with decreasing the flow time, or residence time of fuel and oxidizer species in the combustion zone. High flow rates are achievable using pelletized or granular propellants, where action times are of the order 100-250 msec; these rapid discharge times are difficult to achieve with traditional nitrogen pressurized systems.

The SPFE testing at PAC has shown that there are cases where the agent concentration is insufficient to accomplish suppression by dilution and cooling alone. In these cases, rapid agent discharge, i.e., flame strain, plays an important role in the suppression event, attributing in some cases as much as 50% of the total suppression capability.

Chemical Effects

SPFE baseline inert gas-producing propellants are considered to be physically acting agents, without any chemically active components. This approach to suppression contrasts with that of Halon 1301. The key to the ability of Halon 1301 to rapidly terminate a fire scenario is its direct interference with the chemical steps comprising the combustion process.

Hydrocarbon (e.g., jet fuel, JP-8) combustion is a process driven by reactive fragments known as chemical radicals, such as OH• and H•. Combining with, or “trapping,” these radical species removes them from the combustion process, thereby diminishing the heat available to sustain the combustion process. One highly efficient means for radical trapping utilizes another radical species, or radical trap. For Halon 1301 the ability to terminate radical combustion reactions comes via formation of atomic bromine, or Br•, a radical trap for the critical combustion intermediates, e.g., OH• and H•:



In the absence of heat (or fire), Halon 1301 does not generate the Br• radical traps and therefore has no chemical activity. Since 80% of Halon 1301 activity derives from its chemical action [15], this reduced effectiveness significantly decreases Halon 1301 capability for relight inhibition. Since in the absence of heat source, CF₃Br is a purely physical (cooling/dilution) agent.

FULL-SCALE TESTING

Since 1993, PAC has conducted live fire testing in a multitude of full-scale test articles (Figure 7) representing diverse applications with various flammable fluids, including JP-8, JP-4, gasoline, high and low pressure Mil-H-83282, and Mil-C-87252 hydraulic fluids. Typical bay volumes evaluated ranged between 7 and 140 ft³. SPFE technology successfully extinguished

fires initiated by 12.7 mm API, 23 mm HEI, and 30 mm HEI rounds as well as traditional spray and baffle-stabilized pool fire configurations. Internal airflow during the tests ranged from 0.0 to 4.0 lbm/sec. In some cases, external airflow (representing flight conditions) was present for aircraft applications. This air velocity ranged between 200 and 400 knots. In total, this represents

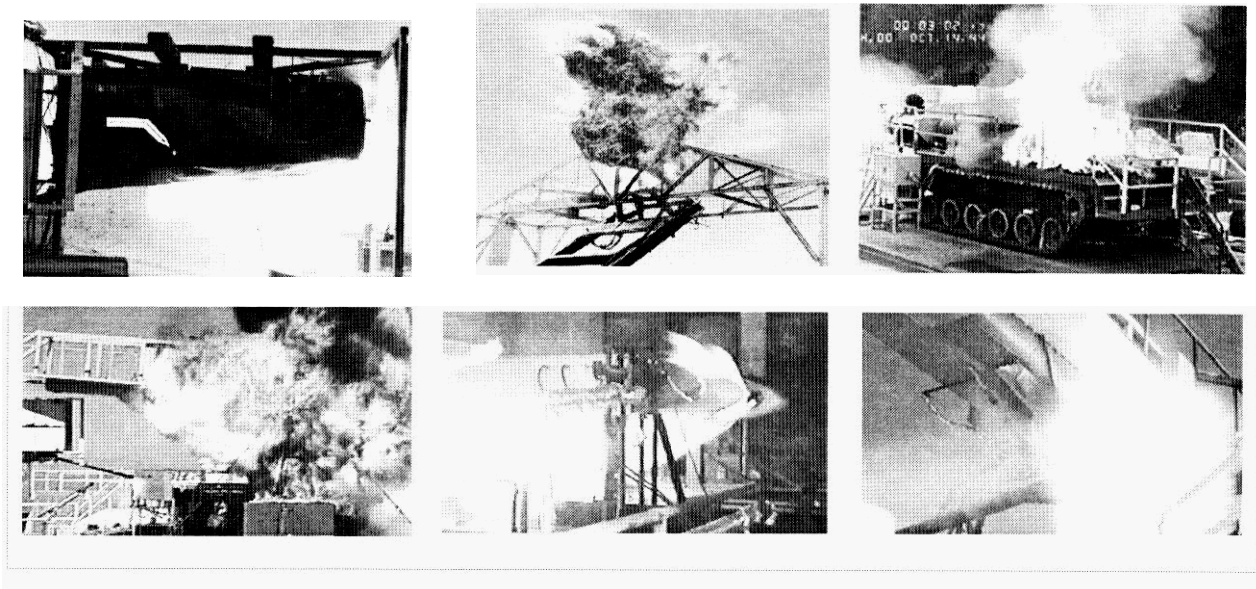
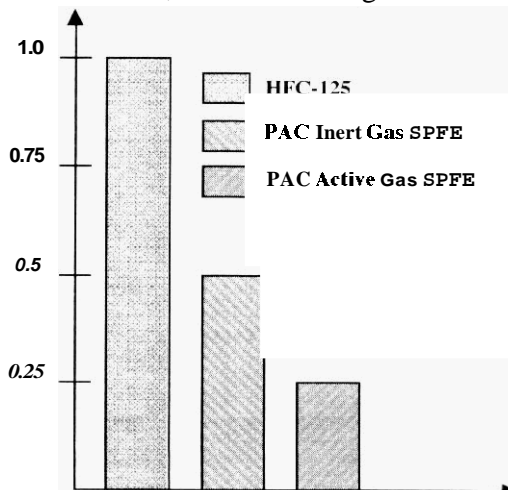


Figure 7. PAC has participated in extensive full-scale fire testing

1000+ individual fire tests in 25+ full-scale test articles. Table I identifies a few of these test programs. Based on the extensive test configurations and the sheer quantity of tests conducted, one could argue that PAC SPFE technology has been more thoroughly tested in representative full-scale test articles than any other nonhalon fire suppression technology.

Many test variables affect the amount of agent required to extinguish a fire. Typically, the fire intensity increases with the threat size. For example, testing has shown that a fire zone induced by an HEI round requires more agent than a fire started by an API threat or spray fire. Raffle stabilized pool fires are more difficult to extinguish than spray fires. JP-8 fires generally require more agent than heptane fires. Bays with significant internal airflow or venting flush out fire suppressant more rapidly and are more susceptible to a fire reignition than bays with minimal internal airflow and venting. Finally, some bays are more challenging as a result of their aspect ratio, clutter, and other design-related features. Although all of these parameters affect minimum



agent requirements for fire suppression. PAC has determined that it is possible to tie SPFE agent requirements to a few key parameters and achieve successful fire extinguishment every time.

Testing has shown that the inert gas blends produced by SPFE technology consistently outperform, on a weight basis, other nonhalon fire suppression technologies, regardless of bay size or configuration. The test data show that an inert **gas** SPFE agent weight is typically 25 to 50% that of a nitrogen pressurized HFC-125 system, needed to extinguish a given fire (Figure 8).

Figure 8. Relative agent weights.

This was observed during PAC's very first full-scale test program in 1993, conducted at NAWC China Lake, and was reconfirmed most recently on a dry bay test program conducted at WPAFB in Dayton.

TABLE 1. PAC SPFE TEST PROGRAMS HAVE SPANNED THE PAST DECADE.

| Test Programs | Tests est. | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 |
|-------------------------|------------|------|------|------|------|------|------|------|
| F-18 dry bay (NAWC) | 50+ | █ | | | █ | █ | | █ |
| V-22 dry bay (NAWC) | 30+ | | █ | | █ | | | |
| Dry bay (WPAFB) | 30+ | | █ | | | | | |
| Engine nacelle (WPAFB) | 30+ | | █ | █ | | | | |
| F-18 Engine bay (NAWC) | 300+ | | █ | █ | █ | | | |
| Tank Engine bay (APG) | 40+ | | █ | █ | █ | | | |
| Fuel Tank Ullage (NAWC) | 5+ | | | | █ | | | |
| Dry bay (NAWC) | 5+ | | | | | █ | | |
| F-22 Engine bay (WPAFB) | 40+ | | | | | █ | | |
| F-18 Engine bay (APG) | 20+ | | | | | █ | █ | |
| Tank Crew Area (APG) | 50+ | | | | | | █ | █ |
| F-22 dry bay (WPAFB) | 30+ | | | | | | █ | █ |
| Auto engine bay | 10+ | | | | | | █ | █ |
| C-130 dry bay (WPAFB) | 20+ | | | | | | █ | █ |
| Navy handheld (NAWC) | 4 | | | | | | | █ |

Review of the test data confirms that a solid propellant fire extinguisher suppresses a fire via a combination of fire suppression mechanisms. Specifically, an inert gas producing SPFE takes advantage of three of these mechanisms (dilution, cooling, and strain). The performance advantages demonstrated by a SPFE illustrate the advantages of using multiple fire suppression mechanisms in unison, rather than relying on a single mechanism (i.e., dilution or cooling) for suppression. Additionally, the testing has shown that the performance advantage ratio (SPFE versus other nonhalon technologies) has remained the same, regardless of bay size or test configuration. This suggests that the relative effect that each separate fire suppression mechanism (dilution, cooling, and strain) contributes to the performance of the SPFE remains approximately the same.

It is important to emphasize that the fire suppression event time associated with a SPFE (designed for a rapid discharge) is an order of magnitude faster than any other event timeline inside the bay. For example, a SPFE discharges most of its agent within 100 msec., as compared to a typical bay that might see as much as one air exchange per second. The agent discharge overwhelms all other factors that typically contribute to fire suppression effectiveness. In addition, this rapid discharge provides the agent with significant momentum and therefore better agent

distribution. As a result, internal airflow, venting, and clutter have a reduced impact on SPFE system performance as compared to a traditional nitrogen pressurized nonhalon system.

Because of the active role PAC has played in the design, development, and testing of SPFEs for fire suppression, PAC has been in the unique position to accumulate a large database of test and performance data. We have used these empirical data to develop several analytical methods and computer codes for sizing SPFE systems to various applications. Given the bay volume, vent area, surface area, clutter concentration, and internal airflow, the SPFE configuration necessary to provide adequate agent concentration such that the fire is consistently extinguished can be determined. Typically, bay agent concentrations are verified using real-time concentration measurement instrumentation during a full-scale test program. This approach has been used very successfully during various development programs.

More recently, PAC has identified several simple relationships to help designers identify SPFE agent weight requirements for their particular application. This approach represents a marriage of fire suppression science and practical real-world test experience. These relationships are based on data collected during all of the full-scale and lab-scale fire suppression test programs PAC has participated in and describe a minimum agent concentration for the energy levels associated with various fire threats (more specifically, an SPFE agent requirement per cubic foot of bay volume to be suppressed). PAC has developed such a relationship for both the inert gas SPFE and the chemically active SPFE. Figure 9 describes these relationships for PAC inert and chemically active gas SPFEs as well as a similar relationship for HFC-125 (based on empirical test data) for comparison purposes.

Using these concentration/threat relationships, a fire protection system can be sized, agent concentrations measured, and a system designed and qualified without the need for expensive full-scale live fire testing. If a very robust design approach is desired, one could size a system based on a fire threat in excess of what is realistic for the desired application. This methodology parallels the approach taken for designing Halon 1301 systems during the past 30 years.

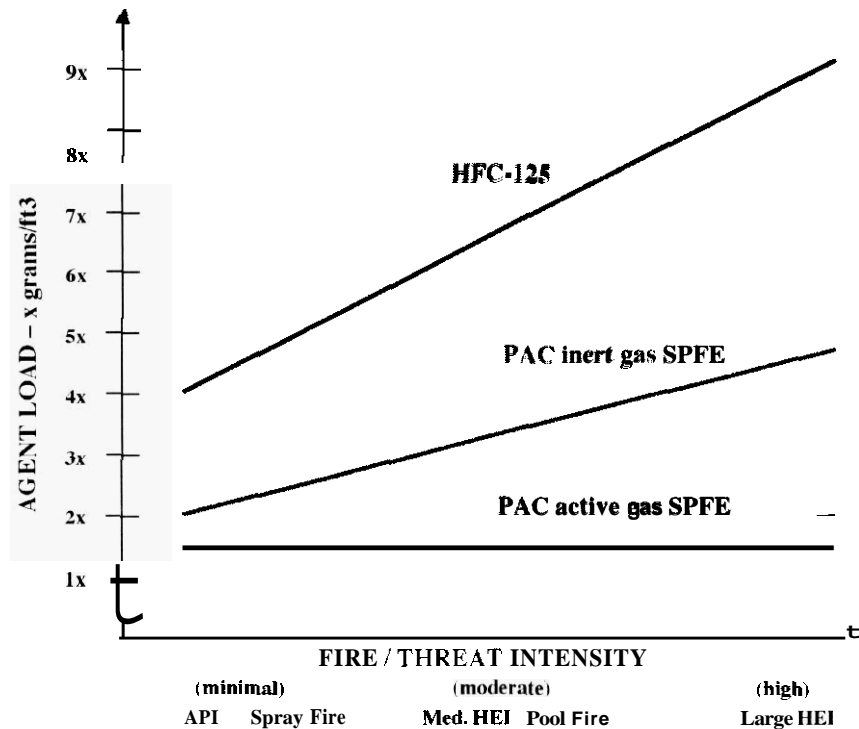


Figure 9. Suppressant requirements as a function of fire threat.

CHEMICALLY ACTIVE AGENTS / ADDITIVES

One shortcoming of inert gas producing solid propellant fire suppression systems is a total reliance upon physical, as opposed to a more efficient chemical activity. The incorporation of chemical activity into solid propellants adds to the previously cited advantages of greater efficiency and lower unit weight, lower overall gas temperatures, and the possibility for even faster suppression action. Furthermore, the use of pyrotechnic techniques for generation of chemically active agents results in particles of very small size and consequent high activity.

The advantages of chemically active powders have been well documented by Ewing et al. [16], in which the effectiveness for several powders approached 10X greater than that observed for Halon 1301 on a mass basis. The greatest activity was found for powders of small particle size. Particles of several different chemical compositions were observed to offer enhanced fire suppression efficiencies when particle sizes were less than approximately 30 μm. Some compositions demonstrated to be effective were K₂CO₃, Na₂CO₃, and NaCl.

By incorporation of suitable reagents into a propellant composition, chemically active agents are generated pyrotechnically [17]. The combustion process allows formation of thermodynamically stable materials that are derived from more energetic materials (fuels or oxidizers). Because of the high temperatures encountered in propellant combustion, solid byproducts are formed in micron size. Proper selection allows these resulting materials to be effective in fire suppression applications: taken together with the high combustion temperatures, the result is pyrotechnic generation of very small particles of chemically active agents. The gaseous byproducts of propellant combustion carry the chemically active agents through a delivery system, which directs the

agents into the fire zone. The greater reactivity of these pyrotechnically generated small particle size solids translates into significant improvements in the mass efficiency of solid propellant systems used for fire suppression.

Suitable combinations of energetic fuels and additives with oxidizers, such as potassium nitrate or potassium perchlorate, can be used for pyrotechnic generation of K_2CO_3 or KCl , which can be used to affect chemical suppression of fires. Potassium species have been shown to possess significant levels of chemical activity, but their mechanisms of action appear to be quite different. Among the halides, iodide salts would be anticipated to show the greatest efficiency because of the greater stability of their atomic radicals. On delivery to the fire zone, elevated temperatures would cause the thermal dissociation of these salts; for example,



where here M = alkali metal and X = halogen species

The thermally generated atomic radicals can then combine with radical species present in the combustion process, thereby terminating or quenching the combustion process.

A combination of sub-scale and full-scale testing has demonstrated that the incorporation of chemically active additives can yield substantial improvements in fire suppression efficiency in several embodiments of SPFE fire suppression technology. PAC research explored powdered candidate agents by injection into an axially flowing turbulent airstream and carried into a jet fuel (JP-8) spray plume in a sub-scale test fixture known as a turbulent spray burner (TSB). Candidate powders were selected from the family of substances known as alkali and alkaline earth halides and pseudohalides like common table salt, sodium chloride ($NaCl$), and "road salt," or calcium chloride ($CaCl_2$). The outcome of this comparative testing yielded a relative ranking of the most effective powdered suppression agent tested.

Turbulent Spray Burner (TSB) Subscale Tests

PAC used a turbulent spray burner based on the design developed by NIST [18], in order to rank fire suppression capability of powder compounds. A solid agent delivery system was incorporated upstream from the air flow inlet, whereby the powder was injected horizontally through an open orifice. The powders were initially prepared by ball-milling and sieving through a 325-mesh US Standard Testing Sieve (Tyler eq. 325 mesh) to produce a particle size $< 40 \mu m$. All agents were dried at 85 °C until the time of testing. The injection port was inserted into the agent line between the blow-down vessel and the spray burner. The blow-down vessel was a standard compressed air tank regulated to 46 psig. Experimental testing demonstrates that for TSB flames under identical conditions and evaluated on a per mass basis, the order of fire suppression efficiency is shown in Figure 10.

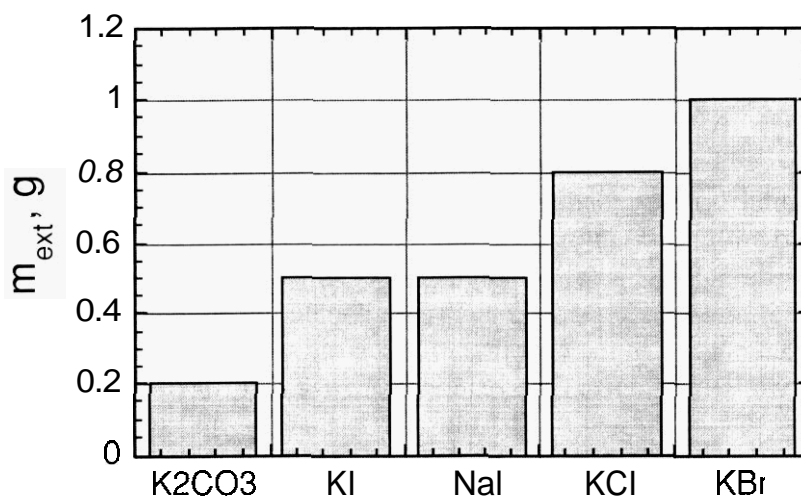


Figure 10. Active powder performance in PAC TSB testing.

Powder effectiveness among alkali halides was highest for the iodide salts, as might be expected on the basis of the greater stability of the iodide atomic radicals. The observed performance for the bromide and chloride does not fit the trend anticipated on these same grounds. A comparison of KI vs. NaI indicates a small effect from the alkali metal, with the potassium species' activity higher on a molar basis. More puzzling is a comparison of potassium carbonate with the metal halides, suggesting a more complex explanation of powder effectiveness than the parallel between halogen contribution to suppression effectiveness in the alkali halides and Halon 1301.

Babushok and coworkers at NIST have explored the chemical limits to flame inhibition, comparing the chemical kinetics of hydrocarbon flames in the presence of Halon 1301 and various "superagents," examining the reaction rates in light of measured extinction concentration data [19]. They found that the rate constants for iron pentacarbonyl flame quenching were $\sim 100\times$ faster than found for Halon 1301, and that this represented a limiting case for chemical effectiveness. This means that chemically active flame suppression *could not occur more quickly* than in the presence of $\text{Fe}(\text{CO})_5$; this observation of $\sim 100\times$ increased effectiveness has been supported by suppression testing. The key to this enhanced effectiveness was determined to be the more efficient regeneration of radical scavengers from $\text{Fe}(\text{CO})_5$ as opposed to CF_3Br . Since the key radical scavengers in Halon 1301 are the halogen atoms Br^\bullet , the Babushok finding indicates that the $\text{Fe}(\text{CO})_5$ -based scavengers are more efficient at regeneration and hence, flame suppression.

The Babushok work implicates flame chemistry similar to that of iron pentacarbonyl—but more complex—for powder species such as sodium bicarbonate, NaHCO_3 . In the same vein, the greater efficiency of K_2CO_3 vs. alkali halides, MX, can be explained in similar terms if alkali atoms, rather than halogen atoms, are the primary agents for chemical effectiveness. Further it appears that the M–X combination leads to inferior catalyst regeneration, i.e., more "dead ends," for M atoms in the MX case, whereas the K-oxide chemistry of K_2CO_3 is richer in terms of recycling capability, thereby requiring less agent to achieve the effectiveness.

FULL-SCALE TESTING

Starting in 1996, PAC began testing chemically active SPFE technology in full-scale fire test fixtures. All of this testing was conducted in parallel with ongoing testing programs, which were evaluating inert gas SPFE technology for various aircraft and land vehicle applications. Typically, the active SPFE technology was tested in addition to the inert gas SPFE technology. This enabled PAC to evaluate the advantages of chemical activity on a truly level playing field, one that is representative of real-world fire protection applications.

The full-scale testing clearly demonstrated the advantages of adding chemical activity to SPFE technology [20]. (Solid propellant fire suppression technology had already proven itself as having a significant performance/weight advantage over other nonhalon fire suppression technologies.) The addition of chemical activity improved the performance/weight advantage of inert gas producing SPFEs by a factor of 2 (Figure 9). More importantly, full-scale testing identified several additional benefits.

The chemical activity introduced by the PAC chemically active SPFEs creates a more robust fire extinguishment mechanism, one that is not susceptible to slight bay configuration changes, as inerting type fire suppression systems can be. During video review of full-scale fire suppression tests, a difference is observable between a dilution/cooling/strain extinguishment vs. one that incorporates chemical activity. Typically, during a dilution/cooling/strain extinguishment event, one can observe the fire rapidly jumping to zones inside a bay that still offer a stoichiometrically balanced environment. Eventually, as all of the oxygen in the bay is sufficiently diluted, the fire is extinguished.

During a chemically active fire suppression event, the fire does not jump around. Instead the fire appears to rapidly vanish. One can observe the interference of the combustion reaction by the active radical species as a function of time. It appears as though the agent is engulfing (or absorbing) the fire. As a result, the fire does not have an opportunity to move outside the bay or hide. This observation has been made during several full-scale test programs involving various fire threats. This increased robustness offers significant advantages when one is dealing with fires that are induced by large ballistic threats or bays that have excessive vent areas (such as some land vehicle engine compartments).

As an aside, it is important to note that a true fire reignition (or re-light) only occurs if exposed surfaces exist inside the bay with temperatures above the hot-surface-ignition-temperature (HSIT) of the associated fuel. This situation can occur when a fire is allowed to burn for an extended time prior to the discharge of the fire suppression agent, thereby heating the internal surfaces of the bay. This is more prevalent in engine nacelles, where the pilot is required to activate the fire suppression system manually. Aircraft dry bays, or other applications that incorporate an autonomously activated fire suppression system, generally do not exhibit a re-light condition. However, on several occasions during full-scale live fire testing, re-light like events have been observed. This occurs when a fire suppression system has been discharged, thereby extinguishing the fire inside the bay. Yet the fire lingers (or is pushed) outside the bay, only to reenter the bay as soon as the extinguishing agent has been flushed out and the oxygen concentration has returned to levels that support combustion. This phenomenon is most common when a fire suppressant is used that relies on dilution and does not incorporate any chemical activity, and it highlights the merits of incorporating chemical activity into the fire suppression system.

An additional advantage demonstrated during full-scale testing is a result of the higher performance/weight ratio afforded by a chemically active SPFE. Since a 2X-performance increase results in 50% reduction in gas production, there is less gas being discharged into the bay, making chemically active SPFEs attractive for applications that incorporate tightly sealed bays with minimal venting or airflow. A 50% reduction in gas production equates to similar reductions in the SPFEs use of dilution, cooling, and strain as the principal fire suppression mechanisms. The performance differences, recorded between inert gas SPFE technology and chemically active SPFE technology during full-scale testing, suggest that PAC chemically active SPFE technology extinguishes fires via a mechanism that is approximately 10% dilution, 20% cooling, 20% strain, and 50% chemical (Table 2). Real-time discrete-point concentration measurements conducted during full-scale test programs demonstrated that robust fire extinguishment consistently occurred when oxygen concentrations of $\sim 19\%$ were achieved.

TABLE 2. RELATIVE USE OF FIRE SUPPRESSION MECHANISM.

| Mechanism | Suppressant Type | | | | |
|--------------|------------------|----------|------|----------------|-----------------|
| | Halon 1301 | Nitrogen | HFCs | Inert Gas SPFE | Active Gas SPFE |
| Dilution - % | — | 30 | 20 | 20 | 10 |
| Cooling - % | 20 | 70 | 80 | 40 | 20 |
| Chemical - % | 80 | — | — | — | 50 |
| Strain - % | — | — | — | 40 | 20 |

Chemically active SPFE technology performance parallels that of Halon 1301. As Sheinson et al. [15] have discussed, halon extinguishes fires via a mechanism that is approximately 20% dilution and 80% chemical. Published design equations for Halon 1301 identify oxygen concentrations of $\sim 20\%$ as sufficient to achieve consistent fire extinguishment, nearly the same as measured during chemically active SPFE testing.

These test results and observations are important since they tie the full-scale test results to the lab-scale test results and highlight the parallels between traditional Halon 1301 fire protection philosophies and SPFE technology fire protection philosophies. Both technologies can be sized and qualified (via concentration measurements) using a straightforward design approach.

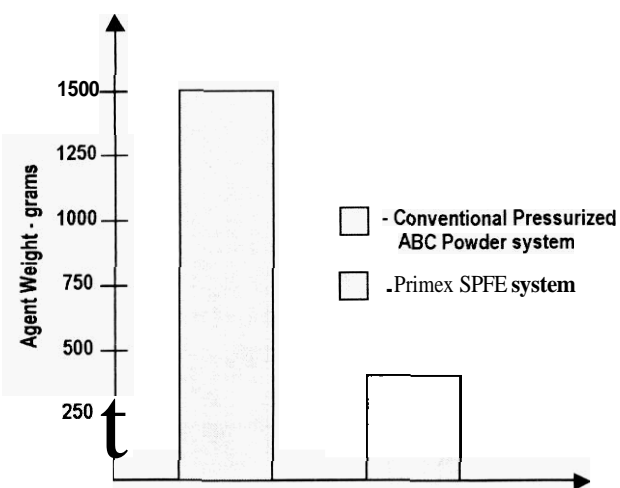


Figure 11. SPFE delivery is more efficient.

Full-scale testing has also shown how the rapid agent delivery associated with SPFE technology augments the effectiveness of a chemically active agent. This was demonstrated recently during a fire test program involving a highly ventilated bay. The fire threat included both a spray fire and a pool fire. The test program evaluated various fire suppression technologies. The two most effective technologies (by a long shot), both incorporated a chemically active agent. One approach used a powder delivered via a traditional nitrogen pressurized system; the other was a

chemically active SPFE. The chemically active SPFE outperformed the nitrogen-pressurized powder system, on an agent weight basis, by a factor of ~4. The results are shown in Figure 11.

These test results highlight the advantages associated with a high velocity agent discharge. The agent is delivered with much higher momentum, giving it better flame front penetration characteristics and better distribution throughout the bay.

Full-scale testing has demonstrated the advantages of using a chemically active fire suppressant. Solid propellant fire extinguishers offer a highly effective means for delivering a chemically active agent. The chemical activity works hand-in-hand with SPFE technology. The synergism of SPFE technology and chemically active agents offer a fire suppression technology that is more efficient and robust than is currently available with other fire suppression technologies.

SUMMARY

SPFE systems have been shown to be effective for providing fire suppression protection in a whole range of nonoccupied applications. These systems require no distribution lines and provide fire protection at volume/weight requirements comparable to Halon 1301. Sizing models have been developed and validated to determine the required agent loading for a number of fire scenarios and fire threats, thereby obviating extensive and expensive full-scale testing. The SPFE approach maximizes its efficiency by taking full advantage of the synergistic interactions of dilution, cooling, flame strain, and chemical interference to effect fire suppression. SPFE delivery of chemical agents offers advantages of lightweight, small size, rapid action, and robust performance in a variety of fire scenarios. SPFE systems should be considered for all nonoccupied applications requiring a robust suppression system, such as aircraft drybays and vehicle engine compartments, where a small and lightweight fire protection system is desired.

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