FURTHER ADVANCES IN THE DEVELOPMENT OF HYBRID FIRE EXTINGUISHER TECHNOLOGY

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ABSTRACT

Primex Aerospace Company **(PAC)** has a family **of** Solid Propellant Fire Extinguishers (SPFE) currently in production **for** the V-22 Osprey and the F/A-18E/F SuperHornet aircraft. While SPFE technology has pmven t~ be an excellent nonhalon fire protection solution for a broad range of applications. current SNAP approval limits the current generation of PAC SPFE technology for use only in unoccupied spaces due to oxygen depletion concerns. PAC has investigated alternative extinguisher technologies **for** use in occupied spaces. One of these exciting new technologies is a Hybrid Fire Extinguisher (HFE). HFEs use a small quantity **of** solid propellant **to** produce inert gases. These exhaust gases are used to pressurize, vaporize, and expel a liquid **or** gaseous agent from a conventional bottle. To date. PAC has evaluated CO_2, H_2O, FM-200, and PFC-614 in a hybrid for fire suppression purposes.

In 1997, TACOM initiated a ground vehicle crew compartment live fire test program. The objective of the test program was to evaluate technologies that are viable replacements for Halon 1301. PAC provided both FM200 and water HFEs for this test program. Compared to a Halon 1301 system **of** equal total agent weight. either FM-200 or water-based HFEs demonstrated equivalent fire out performance with one less extinguisher. If the same number of bottles is utilized. reduced system weight can be realized using a HFE.

During the 1960s, the FAA conducted a full-scale live fire test program to characterize fire hazards, determine suitable fire detection methods and develop techniques for controlling in-tlight tires on modern aircraft power plant installations under full-scale simulated tlight conditions. Fire testing was conducted to evaluate relative fire suppression performance of various halon fire suppressants. Additional fire testing was conducted **to** evaluate the relative effectiveness between a conventional nitrogen pressurized tire extinguishing system and a hybrid type system. At ambient conditions, the pyrotechnic gas generator system (hybrid) demonstrated an agent weight reduction ranging from 29 **to** 37%. At a simulated **30,000-ft** altitude exposure of –50 "F, the pyrotechnic (hybrid) system reduced the required agent weight by more than 50%. An HFE is merely the integration of a solid propellant gas generator and a conventional fire suppression bottle (minus the valve and nitrogen). This integration can he accomplished via several approaches, depending on the needs of the specific application. These approaches are well suited for occupied spaces (crew compartment) and applications where a distribution system **or** plumbing exists (commercial aircraft engine nacelle). In most cases, a hybrid using **a** nonhalon agent offers a drop-in replacement lor **a** halon system.

HFE system level tests have been conducted at PAC to verify bottle pressure, plume characteristics (size, temperature, and quality), and discharge time duration. Similar tests have been conducted with a conventional nitrogen pressurized HFC-227ea (FM200) blow-down system. The resting verified the performance advantages associated with a hybrid system observed during the previously described full-scale fire test programs. These include increased agent flow rate control. improved agent distribution. reduced discharge time. higher fill density, improved cold temperature performance, reduction in two-phase eflects, insensitivity to orientation. increased safety, and elimination of a fast-actuating solenoid valve.

HYBRID TECHNOLOGY AT PAC

Primex Aerospace Company has been **a** world leader in the development and production of solid propellant gas generators, hybrid gas generators, and stored gas systems for 30 years. We maintain 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. The propellants PAC has developed for airbag inflators are designed to exhaust a mixture of nitrogen, water vapor, and carbon dioxide gas. With thc advent of a need for small and lightweight fire protection systems, and a desire to replace Halon 1301 as the agent of choice for tire 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. 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).

PAC has a family of SPFEs currently in production for the V-22 Osprey and the F/A-18E/F SuperHornet aircraft (Figure 1). Full-scale fire testing has repeatedly demonstrated that the PAC SPFEs require a smaller quantity of agent than Halon 1301 to extinguish a fire (on a mass basis). Also, SPFE occupies a smaller volume since the density of a solid propellant is greater than that of 1301. While SPFE technology has proven to be an excellent nonhalon fire protection solution for a broad range of applications, current SNAP approval limits the current generation of PAC SPFE technology for use only in unoccupied spaces due to oxygen depletion concerns. As a result, PAC has investigated alternative extinguisher technologies for use in occupied spaces. One of these exciting new technologies is a Hybrid Fire Extinguisher (HFE).

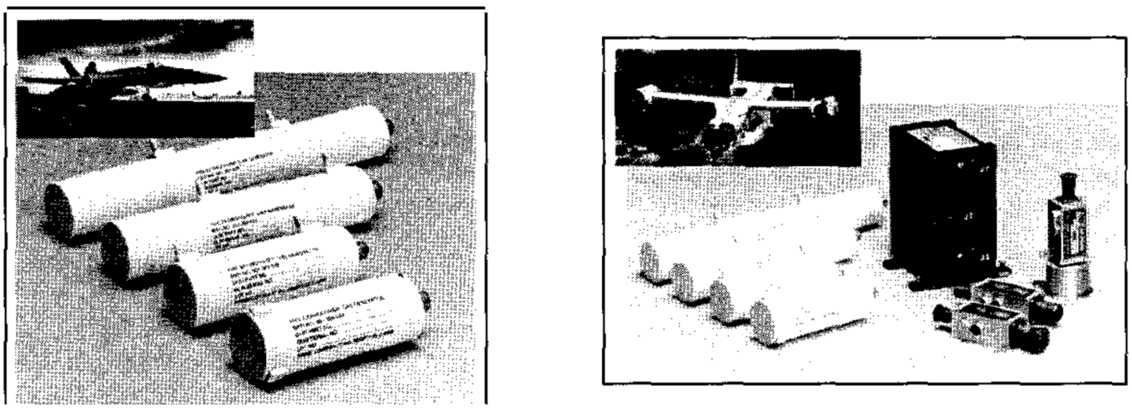

Figure 1. PAC SPFE systems are currently in production for the V-22 Osprey & F/A-18E/F.

PAC has developed hybrid gas generator technology using a variety of fluids (Freon 22, Freon 32, Halon 1301, CO_2, ammonia, H_2O, and HFC-227ea) for numerous military and commercial applications since 1969. Over the years, PAC has built thousands of hybrid systems using Freon as the liquid agent for inflation of Boeing 747 emergency escape slides. Additionally, PAC is producing hybrid systems for inflation of the Navy H-46 helicopter emergency flotation bladders. Both of these production systems are currently in service.

In 1994, PAC began developing HFE for fire protection applications. Several HFE versions have been tested in a variety of full-scale fire fixtures since then. Hybrid fire extinguishers use a small quantity of solid propellant to produce inert gases. These exhaust gases are used to pressurize, vaporize and expel a liquid or gaseous agent from a conventional bottle. To date, PAC has evaluated CO_2, H_2O, FM-200, and PFC-614 in a hybrid for fire suppression purposes. Use of a solid propellant system to pressurize, vaporize. and expel an agent offers several compelling advantages over conventional nitrogen pressurized fire extinguishers.

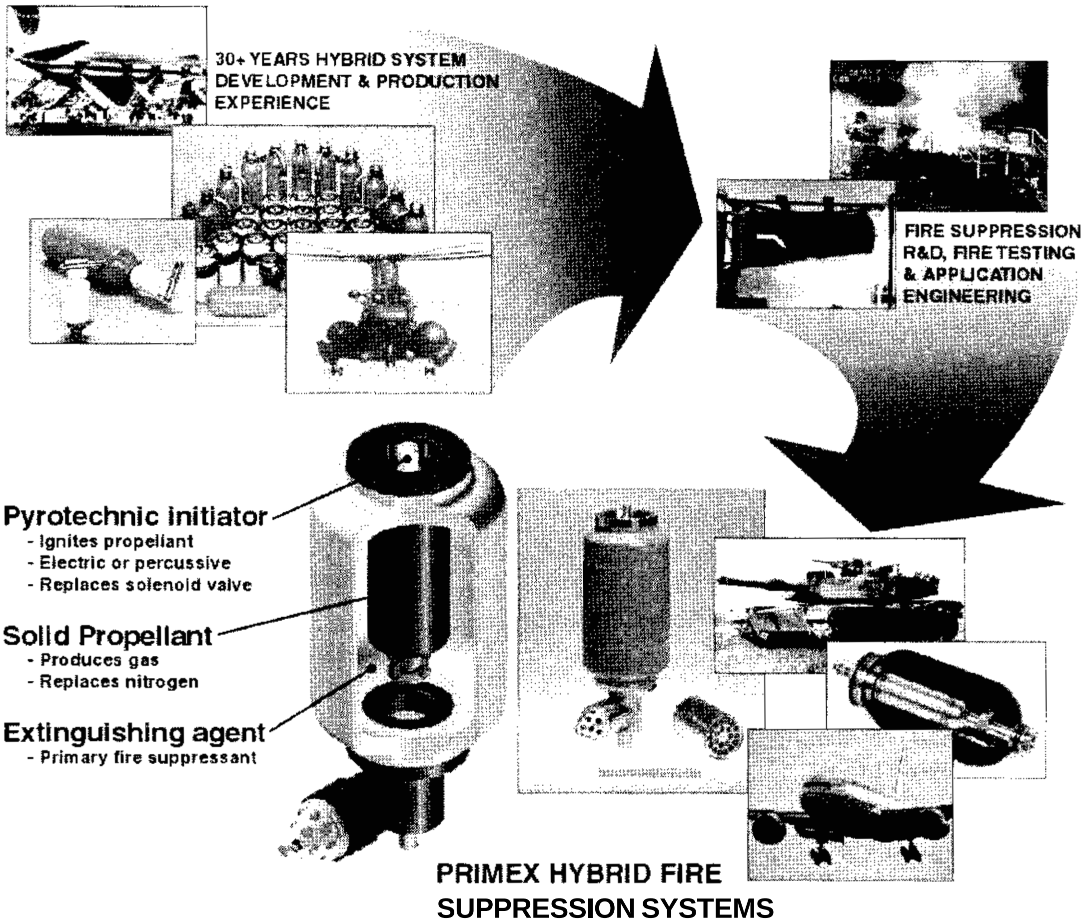

Figure 2. Hybrid Fire Extinguishers are based on a long history of hybrid development at Primex Aerospace Company.

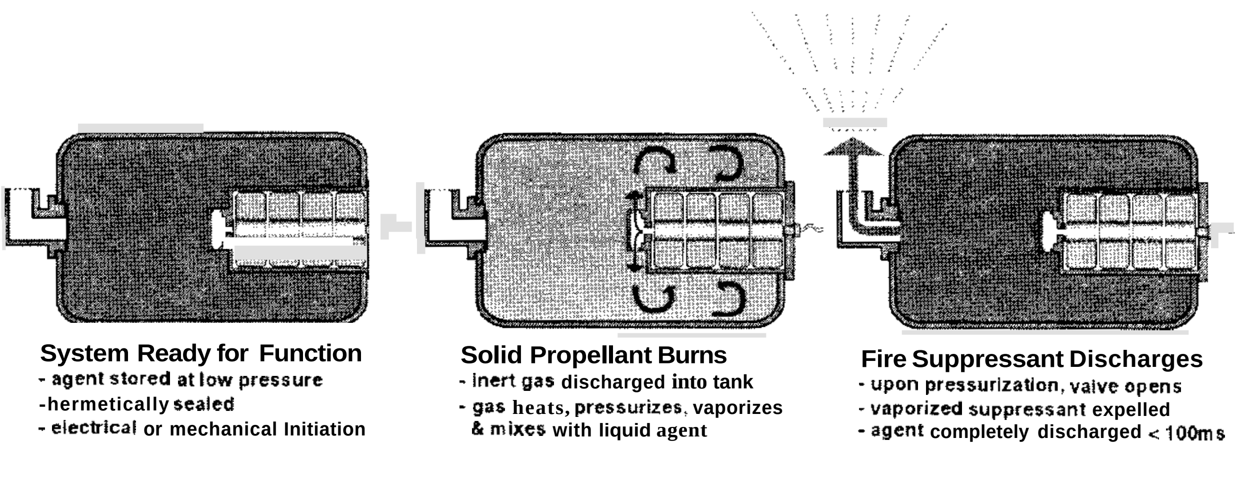

Figure 3. Schematic of a hybrid fire extinguisher discharge process.

Environmentally friendly—PAC HFEs combine SNAP approved inert gas producing solid propellant gas generators with nonozone depleting / nontoxic fire extinguishing agents such as HFC-227ea (FM200) and H_2O. Upon discharge, the mixing and heat transfer between SPGG gases and liquid agent promote the existence of vapor-phase agent, increasing the discharge vapor quality even at low temperatures. This improves the homogeneous distribution of agent in the protected space. Thus, hybrid technology is very suitable for the so-called streaming agents such as HFC-227ea and HFC-236fa. These agents are usually considered less favorable for use in blow-down systems since their boiling points are high and vapor pressures low at discharge.

Reduced system ***weight***—PAC hybrid fire extinguishers require less agent than conventional blow-down systems. The solid propellant facilitates vaporization of a liquid agent improving dispersion upon discharge. Testing has shown that the improved agent vaporization and distribution associated with hybrid extinguishers results in reduced agent concentration requirements for equivalent fire suppression performance. Additionally, storage volumes of liquid agents are considerably smaller than gaseous agents. Since the pressurizing gas is stored in solid form until activation, the HFE requires no nitrogen charging. Therefore, the agent storage pressure is much lower. For FM-200, the storage pressure of an HFE is around 60 psig at room temperature (which is the vapor pressure of FM-200). This compares favorably to the 750 psig of a typical nitrogen charged system. Thermodynamically, this implies the agent loading density can be significantly increased without incurring the danger of over-pressure at higher storage temperatures. As a result, the extinguisher can be packaged in a smaller volume. The combination of an improved dispersion of a liquid agent via a solid propellant system, reduced agent concentration requirements, the elimination of a nitrogen pressurant, and the reduced volume of a liquid agent make the hybrid system an attractive fire suppression solution. The result is a bolt-in replacement for current halon systems.

Faster fire out times—Testing has shown that a hybrid system extinguishes the fire more rapidly than a pressurized system. Typically, a hybrid system discharges its entire agent load in half the time of a conventional blow-down system (discharge time can be further reduced if desired). This reduces the amount of agent required, and minimizes fire damage and the formation of toxic decomposition and combustion products.

Improved ***safety***—Actively pressurizing the agent with a solid propellant reduces the agent storage pressure resulting in a reduced system weight and a safer system for occupied applications. Personnel are no longer required to handle or sit next to a highly pressurized steel/composite cylinder. Additionally, personnel are not susceptible to the frost bite exposure common to blow-down systems. Typical hybrid agent temperatures (upon discharge) measured within inches of the nozzle range from 0 to 300 "F. Within one foot of the nozzle, the temperatures have been measured to be less than 50 °F above ambient.

Reduced maintenance ***costs***—Since the liquid agent is stored at ambient pressure (70 psig for FM200 and 0 psig for water), the storage cylinder is not subjected to the considerable pressure cycles that a conventional nitrogen pressurized bottle witnesses. The result is reduced fatigue stresses and maintenance requirements, therefore improved life cycle costs. Additionally, negligible storage pressures reduce leakage potential.

Nitrogen solubility ***is not*** a ***concern***—Without the need for nitrogen as a pressurant, there are no solubility issues. The result is a longer system life and improved life cycle costs.

Temperature compensating design—As compared to a pressurized system, the PAC hybrid has negligible mass flow rate (performance) variation across the operational temperature range.

Insensitive *to* orientation — Unlike nitrogen pressurized fire extinguishers, hybrid extinguishers operate the same regardless of their orientation.

Qualified systems — Primex solid propellant **is** SNAP approved and qualified to MIL-D-2 162.5. PAC hybrid systems are currently in use on both commercial aviation and military platforms.

Refurbishable design — Depending on the hybrid design, the entire SPGG can be replaced with a new unit (discarding the old unit in the trash) and the bottle can be refilled with agent.

TACOM ARMORED VEHICLE CREW FIRE PROTECTION TESTS

During 1998-2000, TACOM conducted a ground vehicle crew compartment live fire test program. The program objective was to evaluate technologies that are viable replacements for Halon 1301. The program was conducted by Aberdeen Test Center personnel (APG, MD). The TACOM crew Compartment test program consisted of two phases. A Basic Contract Requirements (BCR) phase provided initial screening of contractor's extinguisher. A follow-on Option I phase was awarded by TACOM based upon the performance achieved in the BCR phase. In both phases, threats tested against included spray fire (fireball) and ballistic (shape-charge) events. Test data were compared to technical requirements and performance demonstrated with conventional H-1301 nitrogen-charged extinguishers. ATC personnel performed the H-1301 testing using existing 5-lb (144-in^3) and 7-lb (204-in^3) halon extinguishers.

Pertinent test data measured included fire out time (IR and video), acid gas production, heat flux, temperature, pressure, agent, and oxygen concentration. Test requirements of the contract included (1) fire out time <250 ms, (2) acid gas production <1000 ppm, (3) heat flux <2400 °F-sec, (4) pressure <1 1.6 psid, (5) O_2 level >16%, and (6) agent level <NOAEL. Real time measurements of fire out time and acid gas production were used to make test configuration decisions.

The test fixture used during the program was representative of a standard armored vehicle (crew compartment) and had an internal volume of approximately 4.50 ft^3 (gross). A total of four extinguisher locations were provided but were not always utilized. During the BCR phase, no clutter was utilized. Clutter added to the Option I testing included mannequins and TOW missile simulators to further challenge the extinguisher's capabilities.

PAC provided both FM200 and water-based HFEs for this test program. During the BCR test series, experiments were set up to evaluate the HFE design parameters deemed important to minimize fire out time. heat flux, and acid gas production. Test data were compared to contract performance specifications and with baseline H-1301 data. As a result of the design of experiments, the PAC FM200 HFE demonstrated *superior performance* to H-1301 on a weight basis.

The HFE system was selected by TACOM for Option I testing. These tests further challenged the extinguisher's capabilities by adding clutter to the fixture and evaluating performance at cold conditions. During ballistic testing. both the FM-200 and water-based HFE showed superior fire out performance to Halon 1301 on the basis of weight, volume, temperature. and bottle quantity. Acid gas levels are significantly lower with FM-200 HFE and nonexistent with water-based HFE. Compared to the Halon 1301 system of equal total agent weight, either FM-200 or water-based HFE demonstrated equivalent fire out performance with one less extinguisher. If the same number of bottles is utilized, significant weight improvements can be realized using a HFE.

FAA FIRE PROTECTION TESTS

Between October 1964 and September 1966, the FAA conducted a full-scale live fire test program to characterize explosive and fire hazards on modem aircraft powerplant installations under full-scale simulated low altitude flight conditions. Additional testing was conducted to determine suitable fire detection methods and to develop techniques for controlling in-flight fires. The test program was conducted at the Naval Air Propulsion Test Center (Trenton, NJ). The test program consisted of five studies: (1) environmental conditions producing thermal ignition of combustible mixtures and ignition characteristics; (2) characteristics of nacelle fires; **(3)** system performance and installation requirements for fire and over-heat detection; (4) requirements for extinguishing and controlling fires; and ***(5)*** effects of fires and explosions on the power plant installation. The facility consisted of an open circuit induction-type wind tunnel (Figure 4). Ambient air is drawn through the IO-foot diameter tunnel test section by ejector pumping action of the exhaust **gas** of two J-75 turbojet engines. The facility was capable of producing airflow around the power plant installation in the speed range existing between takeoff and cruise flight of jet-transport-type aircraft and at limited simulated altitude conditions.

A Number 4 power plant installation of **a** 720B aircraft was used as the test bed. The installation included nacelle, strut, and JT3D-1 turbofan engine (Figure *5).* The wind tunnel provided the airflow around the nacelle and the aerodynamic conditions within the nacelle similar to those that exist in flight over a range of Mach 0.1 to 0.7 and pressure altitudes from sea level to 10,000 ft.

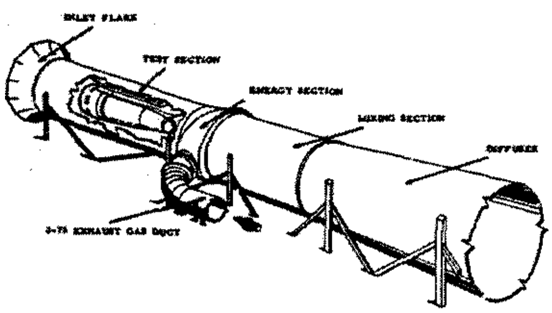

Figure **4.** FAA Engine Nacelle Test Facility.

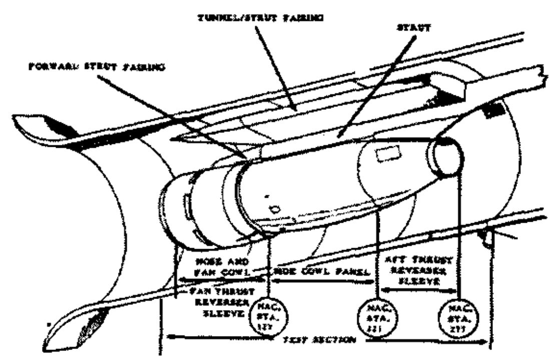

Figure *5*. Power plant installed inwind tunnel.

Fire testing was conducted to evaluate relative fire suppression performance of four extinguishing agents:

- Halon 1301 – Bromotrifluoromethane ($CBrF_3$)
- Halon 1202 – Dibromofluoromethane (CBr_2F_2)
- Halon 1211 – Bromochlorodifluoromethane ($CBrClF_2$)
- Halon 1011 – Chlorobromomethane (CH_2BrCl)

Additional tire testing was conducted to evaluate the relative effectiveness between a conventional nitrogen pressurized fire extinguishing system and a pyrotechnic gas generator pressurized (hybrid) type system. Both systems were discharged into the nacelle bay using a standard two-zone tire extinguisher distribution system. A consistent test procedure was followed:

- Facility Mach number and engine power stabilized
- Spark igniter activated

- Fuel spray release initiated
- Test engine retarded to cutoff
- Spark igniter deactivated
- Fire extinguishant discharged
- Fuel spray release discontinued (only after complete agent discharge)

AI ambient conditions, the pyrotechnic gas generator system (hybrid) demonstrated an agent weight reduction ranging from 29 to 37% for Halon 1301 ($CBrF_3$), Halon 1211 ($CBrClF_2$), and Halon 1011 (CH_2BrCl). The relative effectiveness of the pyrotechnic (hybrid) and nitrogen pressurized systems were also examined for a simulated 30,000 ft altitude exposure to approximately –50 °F temperature environment. The pyrotechnic (hybrid) system reduced the required agent weight of the three extinguishants tested (Halon 1301–$CBrF_3$, Halon 1211–$CBrClF_2$, and Halon 1011–CH_2BrCl) by more than 50%.

HYBRID FIRE EXTINGUISHER SIZING

Hybrid fire extinguishers have demonstrated equivalent fire suppression performance using reduced agent loads during various full-scale live fire test programs. This is attributed to the improved agent vaporization and distribution characteristic of the hybrid discharge mechanism. Additionally, a hybrid fire extinguisher does not require nitrogen pressurization. As a result, **the** volume typically occupied by the nitrogen pressurant can be used for additional fire suppression agent. The combination of these factors makes it possible to design a hybrid fire extinguisher containing a nonhalon agent that is a drop-in replacement for an existing halon system, without system size or performance penalties.

With the search for a Halon 1301 replacement. much ofthe fire suppression community has focused on a 'drop-in' agent that is environmentally friendly, effective. and nontoxic. A number of agents have been evaluated (Table 1). Unfortunately. all of these agents have an Achilles heel (poor performance, poor dispersion or toxicity issues). Many of these next-generation agents suffer from higher boiling points than Halon 1301 and are generally classified as streaming agents. A low boiling point provides Halon 1301 with good vaporization and dispersion qualities when released from a nitrogen pressurized bottle. Using a solid propellant gas generator

TABLE I. PROPERTIES OF SIX COMMON FIRE SUPPRESSION AGENTS.

Agent	Halon I301	HFC-I25	HFC-227ea	HFC-236fa	FIC-131I	H_2O
Chemical Formula	$CBrF_3$	C_2F_5H	C_3F_7H	$C_3F_6H_2$	CF_3I	H_2O
Boiling Point (°C)	-58	-49	-17	-2	-23	100
Min. Design Concen. (Vol. %)	*5.0*	10.9	***7.0***	6.2	3.6	NA
Halon 1301 Pert'. Ratio (Wt.)	1.0	**1.9**	**1.7**	1.5	1.0	NA

rather than nitrogen, enough energy can be added to the agent prior to discharge such that the agent is vaporized and expelled as a gas. As a result, boiling point is a non-issue and these streaming agents become much more viable halon replacement candidates. Three excellent agents for use in a hybrid are HFC-227ea, HFC-236fa, and water. If one considers HFC-227ea, published data indicate that an agent weight increase of 70% is required to produce equivalent performance as Halon 1301. Given a fixed bottle size, it is not feasible to remove the existing Halon 1301, replace the agent with HFC-227ea, and expect equivalent fire suppression performance. However, if one considers using a hybrid approach, it is possible.

If one considers a conventional 800-in^3 commercial aircraft engine nacelle fire suppression bottle, such a bottle generally contains approximately 18 lbm Halon 1301, with a percentage of the volume being occupied by pressurized nitrogen. Without the nitrogen, this bottle can hold up to 21.5 lbm Halon 1301 (using a loading density = 46.5 lbm/ft^3), an increase of approximately 20% (by weight). The FAA engine nacelle fire test program demonstrated performance advantages resulting from using a pyrotechnic gas generator (hybrid) to pressurize and expel a halon fire suppressant. When one considers the 25–50% agent weight reduction demonstrated during the FAA test program, an engine nacelle application that previously required 18 Ibm Halon 1301 will only require 9.0–13.5 lbm Halon 1301. Given the 1.7 Halon 1301 performance ratio for HFC-227ea, this same application will require 15.3–23.0 Ibm HFC-227ea.

Using a standard HFC-227ea loading density (72 lbm/ft^3) for the aforementioned 800-in' bottle, this bottle can hold 33.3 lbm of agent. It should be noted that this loading density could be increased since this bottle will not be supercharged with nitrogen. In any case, 33.3 Ibm of HFC-227ea is much more than the 15.3–23.0 lbm defined as a minimum agent weight. The analysis demonstrates that an 18-lbm Halon I301 bottle can be replaced by hybrid system without size or performance penalties. This analysis is validated by the fire suppression performance demonstrated by HFC-227ea and H_2O hybrids during the Ground Vehicle Crew Compartment Fire Protection Program at TACOM. Both hybrids demonstrated equivalent performance as the baseline halon system using equivalent agent loads or fewer bottles.

Considering the 20% weight savings associated with replacing the nitrogen pressurant with a solid propellant gas generator, and the 25–50% performance improvement achieved via better agent vaporization and distribution, a hybrid offers several options. One could reduce the weight/size of an existing Halon 1301 system, or one could replace the Halon 1301 with an environmentally acceptable agent. By using a hybrid system as the delivery mechanism instead of a conventional blow-down approach it is possible to enjoy the fire suppression effectiveness of a halon system without weight and volume consequences. In most cases, a hybrid system using a nonhalon agent offers a drop-in replacement for a halon system.

HYBRID EXTINGUISHER DESIGN STUDY

A hybrid fire extinguisher is merely the integration of a solid propellant gas generator and a conventional fire suppression bottle (minus the valve and nitrogen). This integration can be accomplished via several approaches, depending on the needs of the specific application. Several approaches that PAC has evaluated are shown in Figure 6. These approaches are well suited for occupied spaces (crew compartment) and applications where a distribution system or plumbing exists (commercial aircraft engine nacelle).

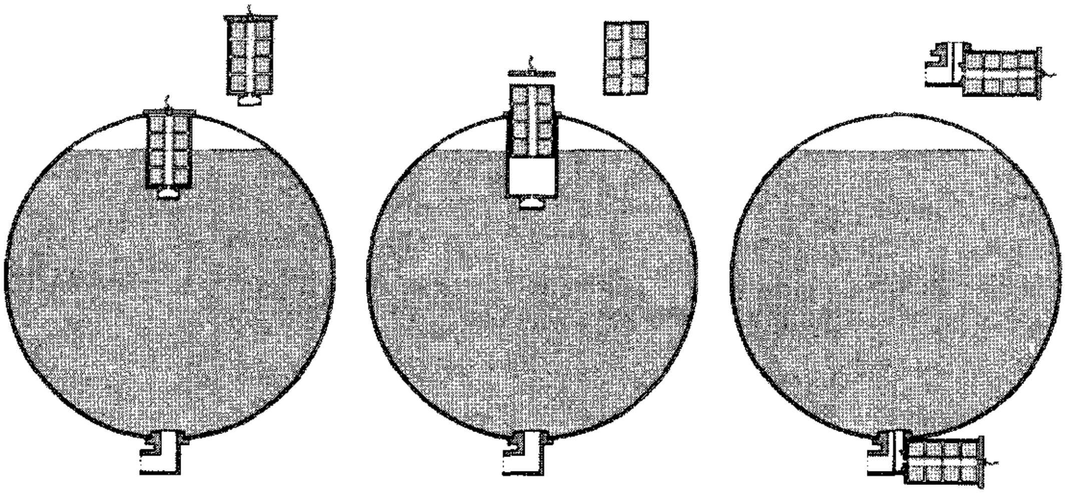

Figure 6. Three functionally equivalent hybrid fire extinguisher configurations.

Concept 1—This approach incorporates a throw-away solid propellant gas generator. Once the hybrid has functioned, the gas generator (which is threaded into the bottle) can be removed and tossed into the trash. A new gas generator is installed. a new hermetic seal is installed, the tank is refilled and the hybrid is ready to be used again.

Concept 2—This approach is similar to Concept 1; however, the solid propellant gas generator contains a solid propellant cartridge and is itself refurbishable. Once the hybrid has functioned, the gas generator breech is opened, the spent solid propellant cartridge is removed (tossed in the trash), a new cartridge is installed, a new hermetic seal is installed in the tank, the tank is re-filled and the hybrid is ready to be used again.

Concept 3—This approach is functionally similar to Concepts 1 and 2. However, the solid propellant gas generator is integrated into the discharge port (manifold). Once the hybrid has functioned, the gas generator/manifold is removed and replaced with a new unit, the tank is refilled and the hybrid is ready to be used again. The advantage of this approach is that it enables the use of **a** pre-existing Halon 1301 bottle to be used as a hybrid. This is a good solution for retrofitting a hybrid fire extinguisher into an existing commercial aircraft engine nacelle application.

While the concept behind the HFE is very simple. optimum fire suppression performance is achieved by balancing several key features of the hybrid extinguisher design, e.g., solid propellant gas generator pressurization profile; solid propellant exhaust gas temperature; solid propellant load vs. fire suppressant agent load; and bottle outlet size. Depending on the fire suppressant agent selected (boiling point, heat capacity, density, etc.), a designer might choose to increase or decrease the propellant to agent weight ratio. Depending on the application. the designer might desire a fast (<50 msec) or a slow (>100 msec) discharge time. The luxury that a hybrid offers is that all of these variables can be changed for the specific fire protection application.

Given the success of the HFC-227ea and H_2O hybrids during the TACOM ground vehicle crew compartment fire protection test program, PAC has further optimized designs of these hybrids for production, while maintaining the functionality demonstrated during the test program. The following design parameters were used for one of the family of hybrids PAC has developed:

- 5-lbm FM-200 in each bottle
- 0.3-lbm $NaHCO_3$
- 250-gm propellant
- Bottle OD: 5.5 in
- Bottle operating pressure: approximately 1200 psig
- FM-200 loading density in bottle: 70 lbm/ft^3
- FM-200 discharge time: approximately 100 msec

HFC-227ea HYBRID TESTING AT PAC

HFE system level tests have been conducted at PAC to verify bottle pressure, plume characteristics (size, temperature, and quality), and discharge time duration. Typical instrumentation includes pressure transducers in the gas generator and bottle; thermocouples are used to measure fluid temperature in the discharge passage. A digital high-speed video camera is used to record plume characteristics.

Figures 7 and 8 show the pressure and temperature traces of a typical HFC-227ea hybrid test, respectively. Peak tank pressure is around 1200 psig and 90% of the discharge occurs in less than 80 msec. Peak temperature measured outside the nozzle approaches 350 ºF in some conditions. It should be noted that the time at temperature is very short, and the temperature drops off very dramatically within inches of the discharge nozzle. Additionally, decreasing the solid propellant to the agent weight ratio can reduce this temperature. Test results for nozzle up and down positions were compared to examine the effect of bottle orientation. No performance difference was observed, demonstrating that gravitational effect is negligible with a hybrid system.

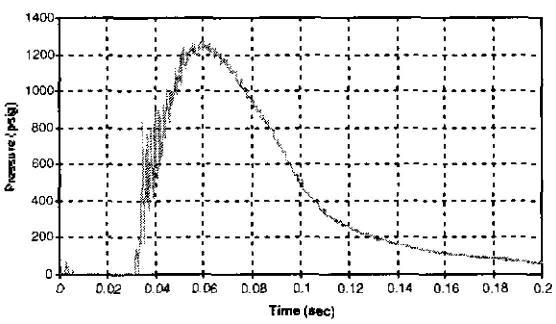

Figure 7. FM200 hybrid bottle pressure.

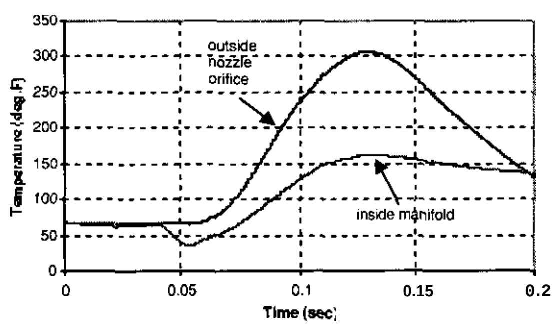

Figure 8. FM200 hybrid exhaust temps.

Figure 9 shows a series of snapshots of the discharge plume. The time interval between consecutive frames is 20 msec. The majority of the discharge correlates with the main pressure duration in the gas generator and tank. The plume appears to change phases during the discharge event.

There is an initial burst (<10 msec) of agent with a higher liquid content. The remaining discharge clearly has a high vapor quality. This transient *is* expected since the heat transfer required to vaporize the liquid agent inside the bottle with the gas generator exhaust is not instantaneous. Figure 10 shows a series of snapshots of the plume of a hybrid that had been soaked to -40 "C. While the transient from liquid to vapor in the plume takes a few milliseconds longer, the perfor-

Figure 9. **A** series of FM-200 HFE discharge snapshots at ambient.

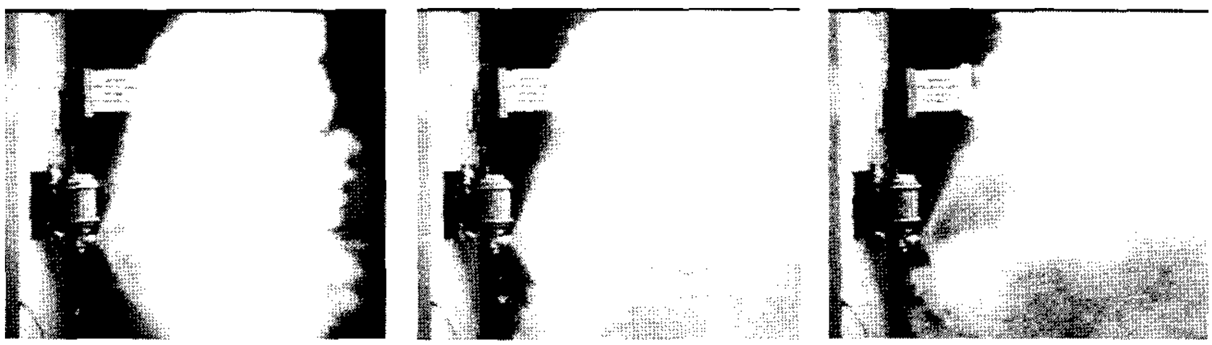

Figure 10. **A** series of FM-200 HFE discharge snapshots after 40 °C soak.

mance is principally identical to the ambient discharge. The pressure traces verified similar discharge performance between the ambient and cold soak test conditions.

For the purpose of comparison. a FM-200 blow-down system was also tested at ambient and –40 °C soak conditions. The bottle, a standard ground vehicle crew compartment (solenoid valve actuated) fire extinguisher, has an internal volume of 144 in^3. It was loaded with 4.25 lbm of FM-200, and then supercharged to 750 psig using nitrogen gas. Figures 11 and 12 show the pressure and temperature traces for a test at ambient conditions. Figure 13 shows a series of snapshots of the test at room temperature, illustrating the high liquid quality of the plume during the entire discharge event. Figure 14 shows the pressure trace for a test at –40 °C. The pressure traces show the longer discharge time associated with the blow-down system versus the hybrid system. This effect is exacerbated at the cold soak condition. The exhaust temperature trace demonstrates the extreme cold temperatures in the plume. It was observed that a layer of frost covered everything within this plume area post-test (this poses frost-bite potential in occupied applications). This was not the case with the hybrid system. Additionally, the hybrid demonstrated much further 'throw' distances for the HFC-227ea agent. This improved distribution (agent 'throw') demonstrated by the hybrid system accounts for the more effective fire suppression performance observed during the FAA and TACOM live fire test programs. The testing demonstrates the performance of the HFC-227ea hybrid system and highlights its advantages versus a conventional nitrogen pressurized blow-down system.

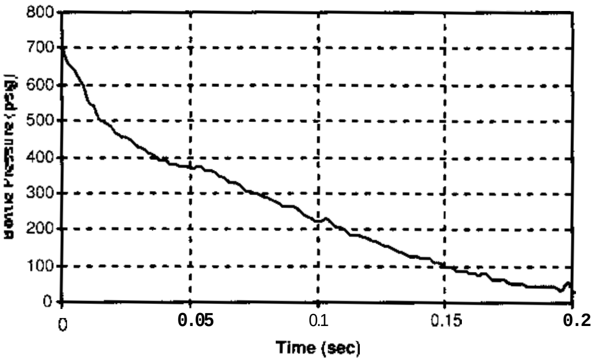

Figure 11. FM200 blow-down system bottle pressure.

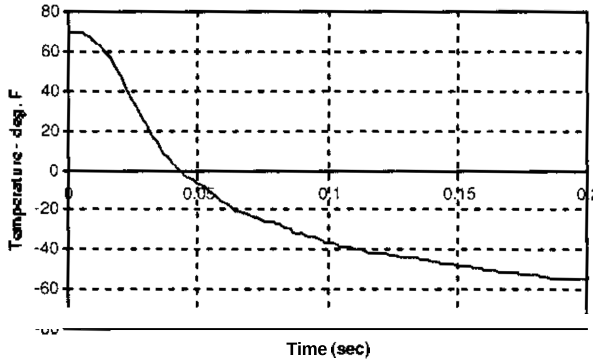

Figure 12. FM200 blow-down system exhaust temperature.

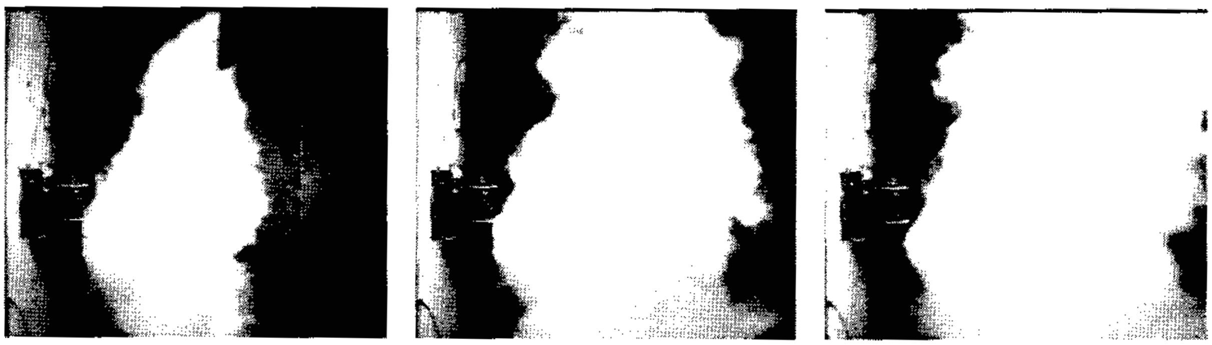

Figure 13. A series of FM-200 blow-down system discharge snapshots at ambient.

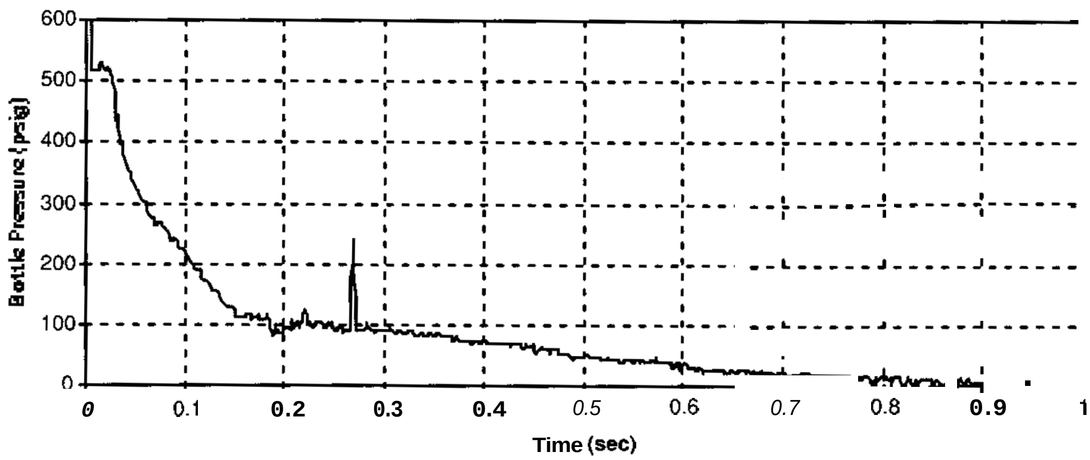

Figure 14. FM200 Blow-down system bottle pressure after –40 ºC soak.

CONCLUSION

Hybrid fire extinguishers use a small quantity of solid propellant to produce inert gases. These exhaust gases are used to pressurize, vaporize, and expel a liquid or gaseous agent from a conventional bottle. Full-scale fire testing conducted by TACOM and the FAA have demonstrated the benefits of hybrid fire extinguishers for ground vehicle crew compartment fire protection and commercial aircraft engine nacelle fire protection. Sizing analysis conducted by PAC have shown that a hybrid fire extinguisher incorporating a halon replacement agent can be used to replace an existing halon system without performance or size penalties.

A hybrid fire extinguisher is merely the integration of a solid propellant gas generator and a conventional fire suppression bottle (minus the valve and nitrogen). This integration can be accomplished via several approaches, depending on the needs of the specific application. These approaches are well suited for occupied spaces (crew compartment) and applications where a distribution system or plumbing exists (commercial aircraft engine nacelle). They offer the viability of an environmentally friendly drop-in replacement for retrofit applications

HFE system level tests have been conducted at PAC to verify bottle pressure, plume characteristics (size, temperature, and quality), and discharge time duration. Similar tests have been conducted with a conventional nitrogen pressurized HFC-227ea (FM200) blow-down system. The testing verified the performance advantages associated with a hybrid system. These include increased agent flow rate control, improved agent distribution, reduced discharge time. higher fill density, improved cold temperature performance, reduction in two-phase effects, insensitivity to orientation, increased safety. and elimination of a fast-actuating solenoid valve.

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