Sustainable Fire Protection for Military Vehicle and Aircraft Applications

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Abstract

Next generation Halon alternative fire protection solutions ideally incorporate sustainable technologies that balance performance needs with safety and environmental concerns when used to address fire threats. The fire extinguishing performance of FK-5-1-12 has been demonstrated in military ground vehicle and aircraft applications. In order for clean agents to be effectively used in these types of environments, they must be applied in a manner that quickly disperses the agent so that explosion fire threats can be mitigated and suppressed.

Solid propellants are used for generating large quantities of working gas upon command in applications ranging from automotive airbag inflation to fire extinguishment. The working gas from solid propellant is utilized in Hybrid Fire Extinguisher (HFE) technology to dispense a variety of fire suppression fluids including clean agents.

The combination of HFE technology with FK-5-1-12 creates a fire protection system that is highly effective against explosive-like fires, maintains large safety factors for occupied space applications, and is environmentally sustainable. FK-5-1-12 has several positive features when compared to other Halon alternatives including zero ozone depletion potential, five-day atmospheric lifetime, global warming potential of one, and a low toxicity profile. Furthermore, FK-5-1-12 is a liquid agent at room temperature; as such, combined with the HFE, it remains safely unpressurized until deployed. The HFE uses solid propellant to pressurize the system, which enables consistent operation over a wide temperature range. Since the HFE is not pressurized until activated; it can be operated in any orientation; and chemically active additives can be incorporated into the propellant making the effluent gases more effective at extinguishing fires than inert agents, thus allowing overall system weight and size to be reduced.

Various different test series have been conducted in order to demonstrate the performance of a Hybrid Fire Extinguisher with FK-5-1-12. This includes static discharge and live fire testing. Initial live fire testing was sponsored through the Next Generation Fire Suppression Technology Program (NGP). The NGP sponsored testing validated the principle in a simulated aircraft environment. Since then, third party testing has successfully demonstrated the required performance of a Hybrid Fire Extinguisher with FK-5-1-12 for vehicle crew compartments. The fire protection system is also under consideration for use in US Army applications. The combination of the two technologies creates a system that further enhances the advantages of the individual technologies and effectively addresses the fire threat scenarios observed in military ground vehicles and aircraft.

Introduction

The current challenge in developing long term solutions that replace Halon fire suppression is to strike the right balance of performance and safety while navigating the rapidly changing regulatory landscape. Through critical exemptions, military decision makers and airframe manufacturers have heretofore not been required to make a wholesale conversion from Halon. Many applications have been largely immune to any conversion requirements. But, the accelerated transformation in the environmental regulatory climate in the USA has introduced sustainability as a key factor in deciding what solutions are employed equal to Halon.

Weight, space and extinguishment speed are critically important in the uniquely demanding needs in military vehicles and modern aircraft of all types. Now the combination of proven gas generation technology with novel non-Kyoto 2nd generation clean agent chemistry is being recognized for its effectiveness at reducing risk not only from explosion and fire but from uncertain future regulatory action.

Hybrid Fire Extinguishers

Hybrid Fire Extinguishers (HFEs) consist of two major subsystems: a propellant cartridge (or solid propellant gas generator) and a tank filled with fire suppression fluid. The propellant cartridge is used to pressurize the tank, and thus it is what makes an HFE unique with respect to traditional nitrogen pressurized systems. Figure 1 contains a diagram of a generic HFE.[1]

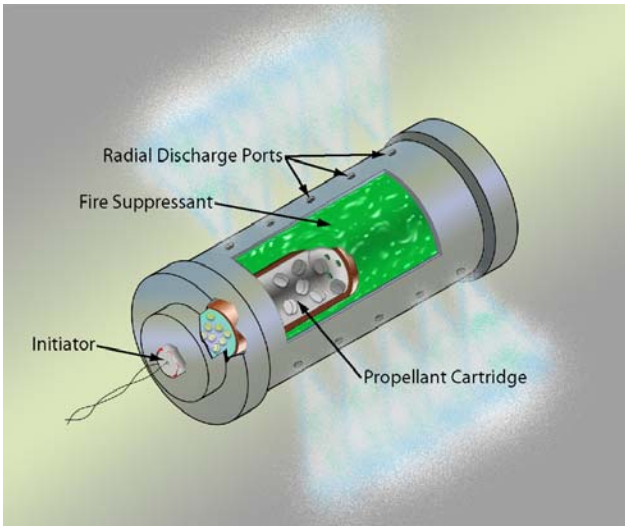

Figure 1 – Hybrid Fire Extinguisher

Solid Propellant Gas Generators (SPGGs) provide a means for efficiently storing gas that can be released upon demand. They are advantageous for many specialized applications since the discharge rate and temperature of the gas can be tailored. One of the most common uses of SPGGs is for the inflation of automobile airbags; therefore, the reliability and consistent performance has been proven through decades of field experience.

The major components of an SPGG include the following[2]:

- Initiator (often called a squib)
- Propellant
- Housing (or pressure vessel)
- Control orifice(s) (or discharge ports)

Figure 2 contains a diagram of a generic SPGG[1].

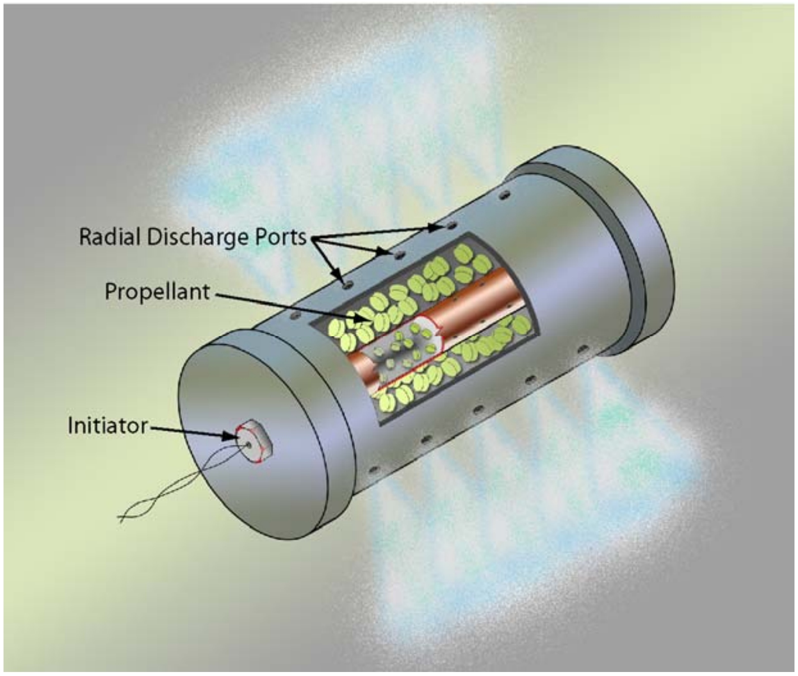

Figure 2 – Solid Propellant Gas Generator

The Initiator receives the firing signal and activates a small pyrotechnic charge that ignites the propellant. One of the most common types of initiator designs is the bridgewire initiator. A low resistance material (the bridgewire) is located between two electrical conductors and surrounded by a pyrotechnic charge. The charge is ignited when the proper high-voltage discharge (firing signal) is used to heat and break the bridgewire.[3]

The propellant portion of the HFE consists of two components; a booster and a main propellant. The booster propellant typically consists of a fast-burning, easily ignitable propellant that receives the initiator charge and quickly generates a significant quantity of hot gas. This increases the pressure within the housing to a level where the main propellant can be efficiently ignited and burned. The slower-burning main propellant generates the majority of the SPGG working gas.

The working pressures of SPGGs range from hundreds to tens of thousands of pounds per square inch depending upon the application. The housing acts as the pressure vessel while the control orifice(s) regulate the gas flow from the SPGG.

The amount and rate of working gas expelled by an SPGG depends upon the properties of the solid propellant and the design of the SPGG components. A number of equations are used to describe the relationships between the various parameters.

Two major equations used to describe the mass flow rate of gas generated by burning solid propellant are as follows:

$$\dot{m} = A_b r \rho_b \qquad \textbf{(1)}$$

$$r = a p_1^n \qquad \textbf{(2)}$$

where $\dot{m}$ is the mass flow rate of gas, A_b is the burning area of the propellant, r is the propellant burn rate, ρ_b is the propellant density, r is the burn rate in units of length/time (typically inches/second), p_1 is the chamber pressure (typically psia), a is the pressure coefficient, and n is the burn rate exponent.[2,3]

Propellant burn rate is affected by temperature, pressure, and the ratio of the burning area-to-orifice area. This allows the system performance to be tailored to meet design factors. Namely, the affect of temperature variation can be minimized through the appropriate design of control orifice(s). This allows SPGGs to exhibit consistent performance over wide temperature ranges.

In the case of an HFE, the propellant cartridge (or SPGG) is used to pressurize the tank that holds the fire suppression agent. This is in contrast to typical nitrogen pressurized systems where the tank is pre-pressurized with nitrogen gas. That being said, the pressurization profile within the tank of a HFE can be tailored by adjusting the SPGG performance parameters.

The unique pressurization profile is not the only benefit from using an SPGG rather than nitrogen to pressurize the HFE tank. In a SPGG, the gas is discharged at an elevated temperature and it flows out of the control orifice(s); therefore it more effectively vaporizes the fire suppression fluid in the tank as it heats and mixes the agent. The ability to vaporize agents makes the use of an HFE especially advantageous in cold temperature situations and when the suppressant is a liquid at typical ambient conditions. The ability of propellant driven discharge devices to improve the effectiveness of fire suppression agents has been previously demonstrated. The FAA conducted a series of tests in the 1960s with several different Halon agents, such as $CBrF_3$ (Halon 1301) and $CBrClF_2$ (Halon 1211). Testing was conducted at ambient and simulated 50,000 foot altitude conditions. Side by side comparisons of agent effectiveness when dispensed from either nitrogen pressurized or propellant pressurized (hybrid) systems were conducted. The results showed that propellant pressurized systems were more effective for all of the agents, and the difference in performance was even more pronounced under the cold 50,000 foot altitude simulated conditions. In the latter environment, the effectiveness (on a weight basis) was increased by over 50 percent. Under ambient conditions, the amount of required weight was decreased by 29 to 37 percent depending upon the agent.[4,5]

The use of propellant to pressurize and dispense fire suppression agents has been shown to offer many advantages. In addition to the advantages noted previously, the chemistry of propellant can be altered in order to change the make-up of the propellant exhaust. Chemical additives can be used to promote catalytic radical termination of the combustion process. Chemically active propellants have been tested and shown to increase the effectiveness of fire suppression systems.[1,6,7]

FK-5-1-12 Use in Hybrid Fire Extinguishers

FK-5-1-12's initial development centered on commercial fire suppression applications as a Halon replacement in streaming and total flooding. FK-5-1-12 has a boiling point of 49.2 °C (120.6 °F) and a freezing point of -108.0 °C (-162.4 °F); therefore, it is a liquid in storage at all anticipated temperatures in end use. The effective use concentration for most applications ranges from 4–6%v/v.

Although the FK-5-1-12's vapor pressure compared with Halon 1301 or other halocarbons is a relatively low 40.4 kPa @ 25°C (5.9 psig @ 77°F), its heat of vaporization is a low 88.0 kJ/kg (37.9 BTU/lb) at its boiling point. So, it doesn't require much energy to convert the material to a gas. FK-5-1-12 effectively vaporizes over a wide temperature range, since its typical use concentration is well below its saturation point in air.[8] This ease of vaporization makes FK-5-1-12 an efficient total flooding agent. The enhanced combination of FK-5-1-12 with the unique Hybrid Fire Extinguisher dispensing technology creates a system that vaporizes the agent more effectively than specialized nozzles alone and enhances the distribution of the agent throughout a protected volume.

The HFE using FK-5-1-12 is not pressurized until system actuation. This is a distinct advantage over conventional super-pressurized systems, because the extinguisher tank can be almost completely filled safely with FK-5-1-12. No ullage space is required to expel FK-5-1-12 as in conventionally super-pressurized systems. This allows for potentially less cylinders required with added potential for weight and space savings.

The temperature of FK-5-1-12 upon discharge from an HFE can be used as one measure for the efficiency of the vaporization from the unit. Static discharge tests were conducted to measure the temperature. A standard HFE was loaded with 2.5 liters (4 kg) of FK-5-1-12, and thermocouples were placed within the HFE discharge manifold, inside the nozzle, and just beyond the nozzle approximately 10 inches within the agent plume. The HFE was mounted to a wall in an open area and the unit was functioned. Figure 3 contains a diagram of the test setup.

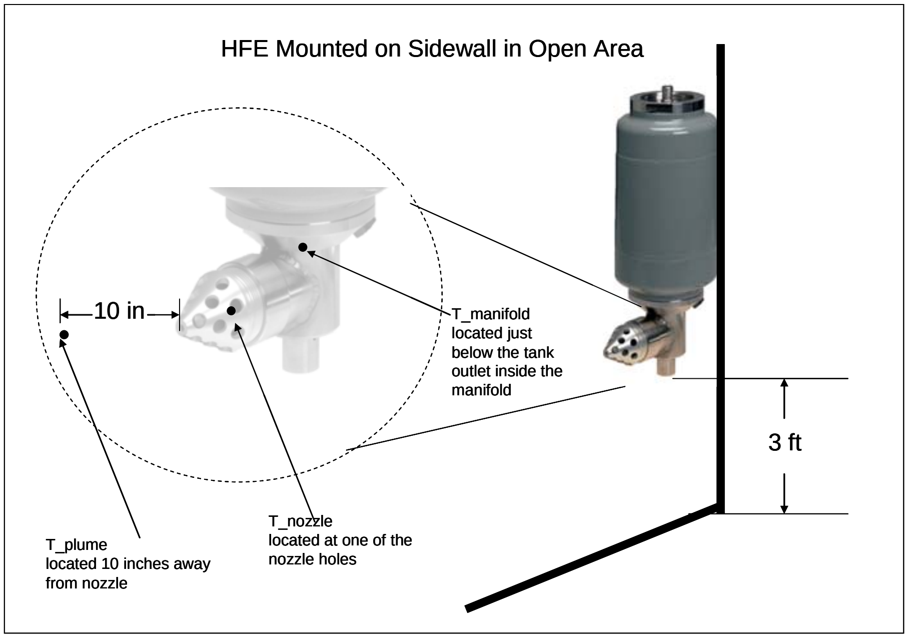

Figure 3 – Static Discharge Test Setup

Static discharge tests were conducted at cold and ambient conditions. The ambient test units were assembled in the test lab under ambient room temperature conditions 21.1± 5.5°C (70± 10°F). Cold temperature test units were conditioned inside of a conditioning chamber that was set to -57.8°C (-72°F). The test chamber is not cold conditioned; therefore, the test unit was removed from the conditioning chamber and functioned within 10 minutes in order to minimize the increase in temperature of the FK-5-1-12 within the tank prior to testing. Figure 4 contains temperature plots from representative cold and ambient tests.

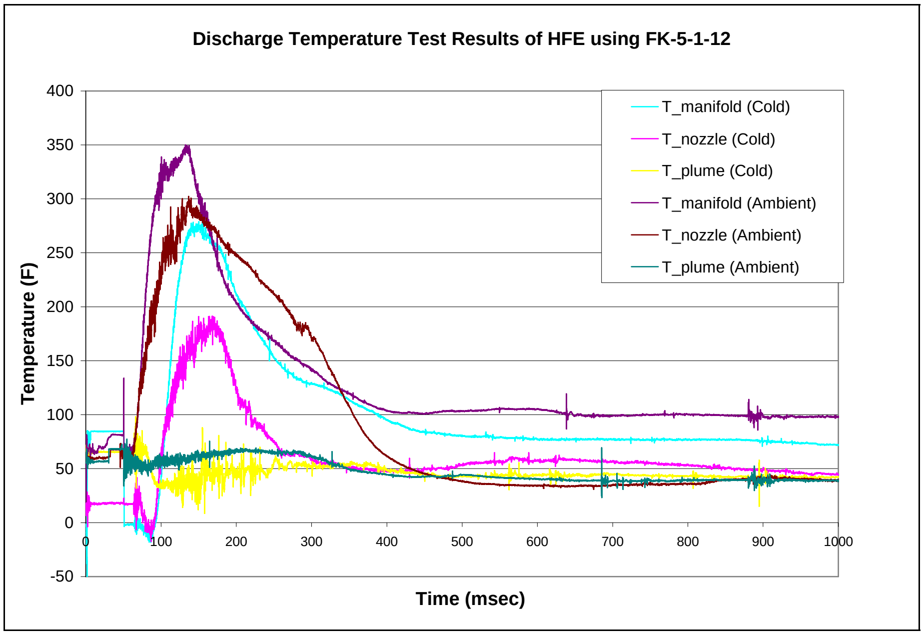

Figure 4 - Discharge Temperature Test Results of HFE using FK-5-1-12

The plots in Figure 4 show that the peak temperatures of the agent in the manifold (just after tank exit but before the nozzle) were 139°C (282°F) and 177°C (350°F) for the cold and ambient tests respectively. The temperature of the fluid at the exit of the nozzle were cooler at 88.3°C (191°F) and 150°C (302°F) respectively for the cold and ambient tests. The average plume temperatures over the first 400 milliseconds were 10.6° (51°F) and 15°C (59°F) for the cold and ambient tests respectively. The fluid temperature(s) in the nozzle and manifold are above the boiling point of FK-5-1-12 for both the ambient and cold test conditions.

In addition to static discharge testing, live fire testing with HFEs using FK-5-1-12 has been conducted. Multiple demanding test scenarios representative of aircraft dry bays, engine nacelles and vehicle crew compartments have been demonstrating the extinguishing effectiveness of Hybrid Fire Extinguishers using FK-5-1-12. Examples follow of testing conducted in fixtures representative of aircraft dry bays and engine nacelles.

In 2006 and 2007, approval and validation testing was conducted to qualify FK-5-1-12 for the protection of engine nacelles with hybrid systems using gas generators similar to that of the HFE. At the request of Airbus France, FAA conducted and completed FK-5-1-12 Halon equivalency testing in the minimum performance standard (MPS) full-scale engine nacelle fire simulator at the FAA Technical Center, Atlantic City, New Jersey, USA.

FAA uses a “FireEx”, a specially arranged delivery system designed to accommodate varying volumes from which a candidate clean agent alternative super-pressurized with nitrogen in solution is discharged into the MPS test fixture. This was done to assure a specified fill density was achieved. For the non-super-pressurized FK-5-1-12, however, the fill procedure was modified in order that testing would more closely resemble the same manner in which a hybrid gas generator-driven system would deliver FK-5-1-12 into an engine. Using a piston flow arrangement, FAA pressurized the FireEx head space with nitrogen immediately prior to the test discharge. FK-5-1-12 was then expelled through nozzles completely volatizing within the MPS test fixture. An example of such a discharge is shown in Figure 5.[9]

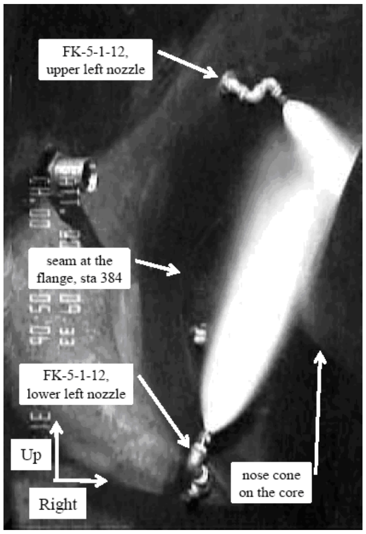

Figure 5 – Typical FK-5-1-12 Nozzle Spray Pattern in the FAA Full-scale Engine Nacelle Fire Simulator

The result of the testing in accordance with the FAA protocol was an FK-5-1-12 Halon 1301 equivalency of 6.1%v/v. In application, this equivalency concentration is required to be held for a minimum of 0.5 seconds in full-scale engine tests.

This success led to full testing in July, 2007 at the Airbus test facility in Toulouse France. The Toulouse testing included a gas generator/FK-5-1-12 "ECOLOG" hybrid system fixed to a full-scale engine assembly; in this case, a Rolls Royce Trent 500 jet engine typically used on the Airbus A340 aircraft. Concentrations in the engine upon system discharge were measured at 24 points, double the number required for Halon, using the Pacific Scientific "Halonyzer" while simulating in-flight conditions with a functioning engine. Cylinders were conditioned to the low temperature extreme (-55°C) as well as ambient conditions. A schematic of the system is shown in Figure 6.[10]

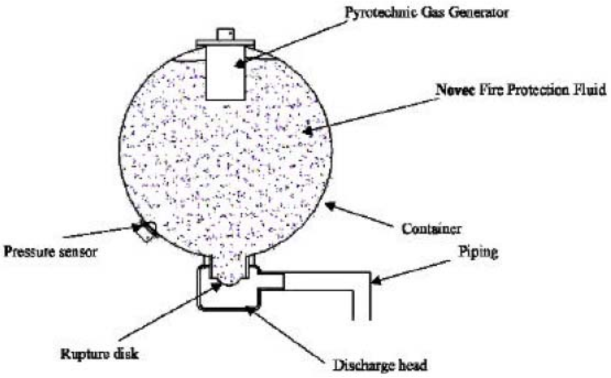

Figure 6 – "ECOLOG" Propellant Driven System using FK-5-1-12 in Airbus Testing

The test results exceeded the minimum FAA MPS requirements for both the full engine as well as the APU compartment and indicates the robustness of the technology in demanding applications. System optimization is ongoing with deployment expected on Airbus's new A350.

A series of tests were conducted in a Fire Test Fixture that has been developed to conduct comparison testing of a variety of different propellant and fire suppression agents. The Fire Test Fixture houses a baffled JP-8 fire and a blower is used to adjust the airflow. The fire is a spray fire and the fixture's main compartment is a rectangular structure that measures 2 feet wide by 2 feet tall with a length of 6 feet. For the FK-5-1-12 Hybrid Fire Extinguisher testing, the Fire Test Fixture was used to represent a generic aircraft dry bay fire. Figure 7 contains a diagram of the Fire Test Fixture, and Table 1 contains a summary of the Fire Test Fixture's main parameters.[1,6]

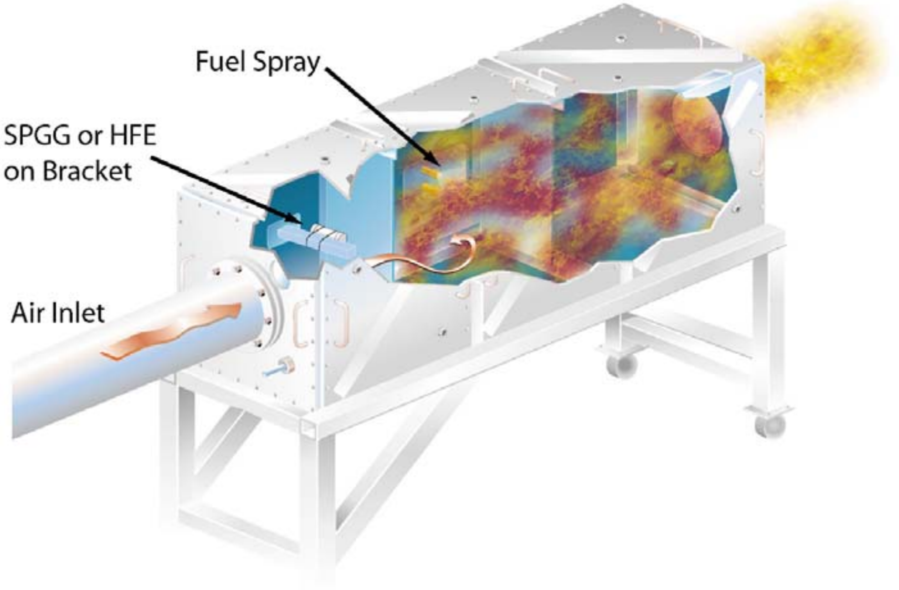

Figure 7 – Fire Test Fixture

Table 1 – Fire Test Fixture Parameters

Airflow		
Mass flow rate	454 g/s	1.0 lb$_m$/s
Volumetric Flow Rate	385 L/s	13.6 ft^3/s
Linear Flow Rate (in pipe)	762 cm/s	25 ft/s
Fuel Flow		
Fuel	JP-8	
Mass flow Rate	15 g/s	0.033 lb$_m$/s
Volumetric flow rate	19 ml/s	0.005 gal/s
Stoichiometry		
Air-fuel ratio (m•$_{air}$/m•$_{fuel}$)	31	
Equivalence Ratio	0.50	
Fire Zone Dimensions		
Flame Temperature	1000 K	1300 °F
Intensity	700 kW	700 kW
Length	122 cm	4 ft
Cross-Sectional Area	3700 cm^2	4 ft^2
Volume	450 L	16 ft^3
Residence Time	1.2 s	1.2 s
Injection Interval	~100-200 ms	~100-200 ms

A number of standardized measures of agent effectiveness have been used throughout several reports with regards to Fire Test Fixture test results. These measures are as follows:

- Total Agent Mass
    - In the case of a Hybrid Fire Extinguisher, this is the total mass of the propellant contained in the SPGG plus the total amount of fire suppression agent contained in the tank
- Normalized Fire Suppression Number (FSN)
    - Value that is used to compare the performance of an agent to a baseline agent tested in the Fire Test Fixture. In the case of the Hybrid Fire Extinguisher, the baseline configuration is defined as FS01-40 propellant in the SPGG and HFC-227ea fire suppression fluid.
- β or flowrate adjusted mass flow of agent[11]
    - $\beta = \dot{m}_{agent}/(\dot{m}_{agent} + \dot{m}_{air})$ **(3)**
    - where $\dot{m}_{agent}$ is the mass flow rate of the total agent and $\dot{m}_{air}$ is the mass flow rate of air
- Xc or critical mole fraction[11]
    - $Xc = (\beta/MW_{agent})/[(\beta/MW_{agent}) + ((1-\beta)/MW_{air})]$ **(4)**
    - where MW_{agent} and MW_{air} are the molecular weights of the agent and air respectively

The threshold amount of agent is defined as the agent configuration that is able to extinguish the fire in the Fire Test Fixture two out of three times in repeated tests. Table 2 summarizes the threshold results for the Hybrid Fire Extinguisher.[1,6]

Table 2 – Hybrid Fire Extinguisher Fire Test Fixture Threshold Results

	Hybrid Fire Extinguisher FS01-40 Propellant in SPGG FK-5-1-12 Fire Suppression Fluid in Tank
MW, g/mol	316
HFE Load (g)	358
Discharge mass, g	340
FSN (FS01-40/HFC-227)	1
β	0.789
Xc	0.255

The results indicate that the Hybrid Fire Extinguisher using FK-5-1-12 has equivalent performance to the baseline configuration.

A recent test series of Hybrid Fire Extinguishers using FK-5-1-12 has been sponsored and completed at third party facilities against fire threats representative of military vehicle crew compartment fire threats. An independent report containing the results of the third party sponsored testing is expected to be released by the end of first quarter 2008.

Conclusions

In testing against a variety of fire scenarios characteristic of threats encountered in military vehicle and aircraft applications, a system comprised of FK-5-1-12 in Hybrid Fire Extinguishers has been demonstrated to be at least as effective (on a total agent mass basis) as a comparable system with a more volatile agent such as HFC-227ea. FK-5-1-12 effectively negates end user risks associated with environmental regulatory activity restricting the use of ozone-depleting and global warming alternatives. The Hybrid Fire Extinguisher efficiently vaporizes the fluid, allowing it to more efficiently fill the open volume upon discharge. These Extinguishers are pressurized by Solid Propellant Gas Generators, whose working gases can be used to mix with and heat the FK-5-1-12 agent prior to discharge from the tank. This system results in a safer Fire Extinguisher that does not require high pressure storage, and also yields uniform discharge rates over a broad temperature range. Furthermore, unlike static-pressurized fire bottles, discharge times in this system can be tailored to meet longer or shorter fire protection requirements.

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