PYROTECHNICALLY AUGMENTED LIQUID AGENT SYSTEM

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ABSTRACT

A new fire extinguishing concept utilizing an alternate agent has been developed under the DARPA Technology Reinvestment Program. Many alternate liquid agent replacements for halon have low volatility at low temperatures, which limits their effectiveness. The Pyrotechnically Augmented Liquid Agent System (PALAS) utilizes a solid gas generator propellant to provide pressure and heat to enhance the vaporization of a low volatility liquid fire extinguishing agent. Development hardware has been made and tested under conditions simulating the dry bay fire threat in the F-22 main landing gear wheel well. HFC-227ea agent has been used in the development hardware and has successfully extinguished fires in the cluttered F-22 dry bay simulator at temperatures as low as -40 "C. A computer model bas been written to describe the pressures and internal dynamics of the system as a function of time during the device discharge. The computer model has been used to predict device performance and has been used to establish the sizes of internal flow-limiting control orifices. A larger PALAS unit is being developed for the military vehicle crew bay environment and will be tested in an M113 armored personnel carrier and the Bradley Fighting Vehicle.

This paper will describe the PALAS concept and the development program, including test results.

INTRODUCTION

Walter Kidde Aerospace is an industry leader in the design and manufacture of fire detection and fire suppression systems for aerospace and defense applications. These applications include aircraft dry bays, aircraft engine nacelles, and military vehicle crew hays. Effective fire suppression for these areas is required throughout all the anticipated environmental conditions. Typical fighter aircraft dry bays, **for** example, may be exposed to temperatures from -65 to 200 "F. Halon 1301 systems were ideal for these applications because of the low mass of Halon 1301 required to extinguish fires throughout the operational environment. Unfortunately, concerns about ozone depletion has led to the ban of further production of Halon 1301.

The search for environmentally friendly and effective replacements for Halon 1301 has been well documented [1,2]. Currently available replacement agents for Halon 1301, which are also environmentally friendly and nontoxic, are typically not as effective at extinguishing fires as halon 1301. There are a number of reasons for the poor performance of the currently available replacement agents including fire extinguishing mechanisms and volatility. Halon 1301 has a low boiling point (-60 °C), and this allows good three-dimensional dispersion of the vaporized agent around "clutter." Some replacement agents may have high boiling points compared to

Halon 1301, and this adversely impacts fire suppression performance in a cluttered bay at low temperature. The agent's Jakob number is a thermodynamic measure of the ability of a liquid agent to vaporize. The higher the Jakob number, the easier it is for the agent to "flash" vaporize, and consequently, the easier it will be for the agent to disperse throughout a volume with clutter [3]. The Jakob number is a dimensionless number mathematically defined as:

$$Ja = \Delta h / \Delta H_{vap}$$

where Ah is the change in enthalpy of the liquid from the ambient temperature to the boiling point of the liquid and ΔH_{vap} is the heat of vaporization for the liquid. Table 1 summarizes the boiling points and Jakob numbers **for** several agents.

Table 1. Boiling Points and Jakob Numbers for Select Alternate Agents.

Agent	Boiling Point, °C [a]	
HFC-227ea	-16.4	0.306
HFC-236fa	-1.5	**0.165**
HFC-125	-48.6	0.520

[a] Reference 4
[b] Reference 5

The Kidde/Atlantic Fire Suppression Consortium, composed of Walter Kidde Aerospace and Atlantic Research Corporation, working under a Technology Reinvestment Program (TRP) contract with the Defense Advanced Research Projects Agency (DARPA) has designed and developed a unique fire suppression technology called PALAS - Pyrotechnically Augmented Liquid Agent System (U.S. Patent 5,660,236). PALAS is a "hybrid" fire extinguisher that uses a solid propellant gas generator to provide heat and pressure to a liquid fire suppression agent. By imparting heat and pressure to the agent, the Jakob number is effectively raised, and therefore, the three-dimensional dispersion performance of the agent is enhanced.

PALAS CONCEPT

Benefits of PALAS

The PALAS technology can allow liquid agents, which **are** environmentally friendly and otherwise desirable, but which are hindered by relatively poor fire suppression performance in cluttered bays- particularly at low temperatures, to have improved performance through enhanced vaporization. This enhanced vaporization can make alternate agents a suitable replacement for halon in some applications. Agents that are toxicologically benign can be used with PALAS in occupied areas. Problems with overpressure in bays, such as that which occurs when only inert gas is used to decrease the percentage of oxygen to extinguish a fire, are mitigated with PALAS because a smaller volume percent of agent can be used to extinguish the same fire threat. Testing of the device has been conducted with **HFCs** at this time, but the device can be used for any low volatility agent in the future.

Theory of Operation

A schematic representation of a PALAS unit is shown in Figure 1. There are two chambers separated by a piston. The chamber to the left is a gas generator chamber; the agent is contained in the chamber on the other side of the piston. The gas generator section of PALAS contains a solid propellant grain. As the propellant combustion takes place, pressure builds up in the propellant chamber. This pressure acts on the piston, pushing it into the agent chamber, compressing the agent. As propellant chamber pressure continues to increase from sustained propellant combustion, the rupture pressure of the propellant release disk is reached, and the propellant chamber gas is allowed to flow through the propellant gas bypass tube. Nearly simultaneously, the agent pressure reaches the rupture pressure of the agent release disk, and agent flow commences through the agent orifice. Both the agent flow and propellant gas flow are allowed to mix before being expelled through the discharge ports. The agent flow rate and hot gas flow rate are sized to control the temperature to enhance vaporization. The propellant choke in the propellant chamber maintains the propellant chamber pressure at a nearly constant level for a long enough period of time to achieve agent discharge in less than 100 ms.

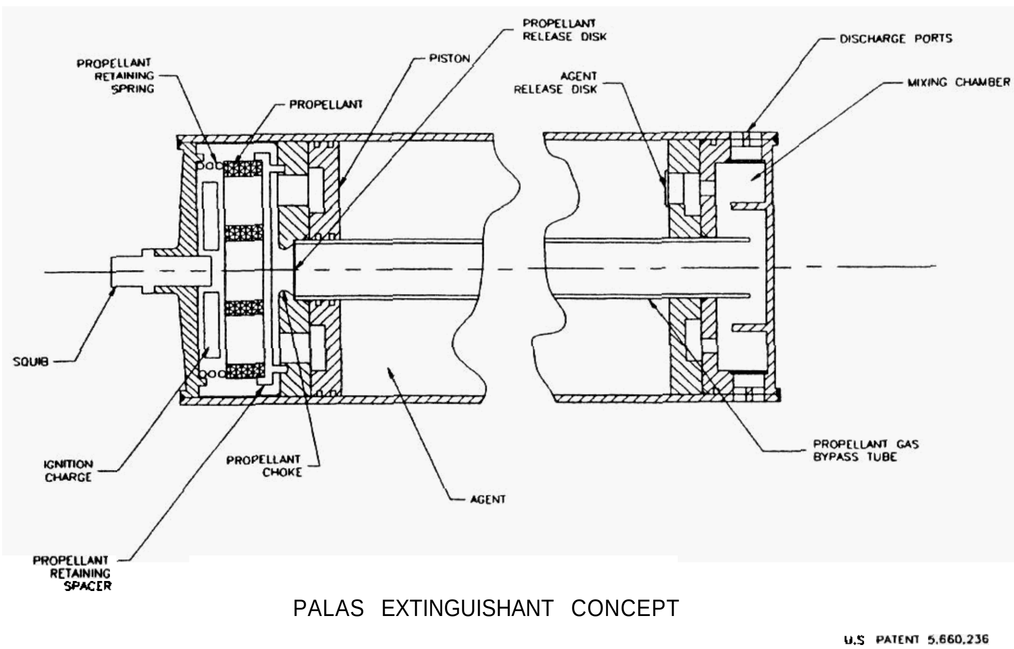


Figure 1. Schematic Representation of PALAS Unit.

PALAS DEVELOPMENT

PALAS development can be considered in these phases: design of development hardware and hardware manufacture, propellant development, test, analysis, and mathematical model predictions. The develop-ment hardware was designed to be reusable and sturdy enough to withstand repeated discharges and potential overpressure conditions. The unit was designed to be replaceable so that different size units could be made out of interchangeable parts. As shown in Table 2, the propellant development activity had the goal of producing a propellant with low particulates **in** the exhaust, stable burning throughout the temperature range for a dry bay, and enough heat to vaporize the agent. At the same time, the propellant should not provide so much

Table 2. PALAS Propellant Goals.

No solid particulates in exhaust	Low burning rate exponent
Non-toxic exhaust	Low temperature exhaust
Stoichiometrically balanced exhaust	Low cost
High gas yield	Completely insensitive

heat that hydrogen fluoride is formed from decomposition of the agent. Initial testing was conducted with a readily available propellant formulation used in an automotive airbag inflator. The special requirements for the PALAS unit, however, necessitated the development of a proprietary propellant formulation. This new propellant was used in all of the tests against a fire challenge.

F-22 DRY BAY SIMULATOR TEST PROGRAM

Refurbishable development hardware has been designed and built for the purpose of testing the PALAS concept against the fire threat posed by a dry bay fire in a simulated F-22 main landing gear wheel well. A test article, simulating the F-22 dry bay, has been built in the WKA dry bay fire simulator (DBFS) test facility. The test article, shown in Figure 2, contains aluminum structures to simulate the clutter in the dry bay, such as the tire, landing gear, and assorted component boxes. The DBFS facility is capable of providing a fuel spray fire in a simulated bay with representative clutter. Placement of the device in the test article did not allow a direct line of sight between the fire and the device. Therefore, genuine three-dimensional dispersion is needed, especially at low temperatures, to extinguish the fire.

External air flow can be provided across a simulated wound in the skin of the test article. The test article can be conditioned to a low temperature by recirculating internal air through a chilling system prior to a test. Table 3 summarizes the capabilities of the DBFS facility.

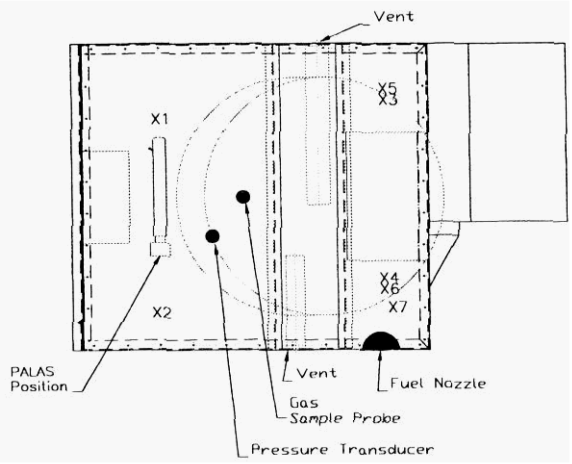


Figure 2a. F-22 Wheel Well Dry Bay Simulator: Plan View.

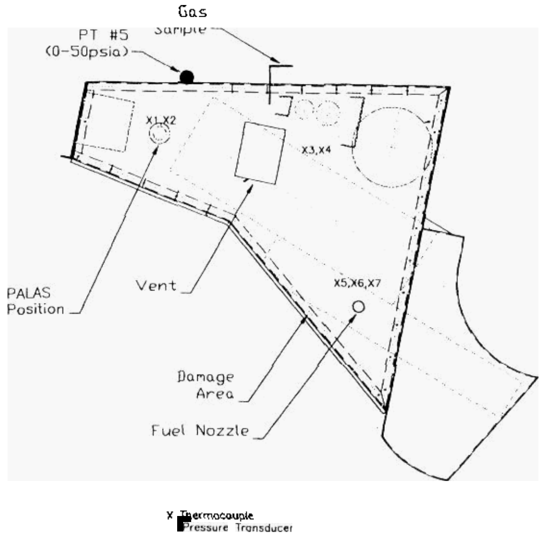


Figure 2b. F-22 Wheel Well Dry Bay Simulator: Side View.

Table 3. Walter Kidde Aerospace Dry Bay Fire Simulator (DBFS) Capabilities.

Characteristic	DBFS Capability
External airflow	300 knots
Low temperature	-40 °C
Internal airflow	350 cfm
Fuel spray	4 MW/5 sec, 10kJ incendiary ignition

The PALAS hardware was designed to accommodate different masses of HFC-227ea agent through the use of interchangeable cylinders and pistons of different lengths. Different combinations of cylinders and pistons make different volumes for the agent chamber. A fill density of 75-lb. agent per cubic foot of extinguisher volume was used in the design of the PALAS unit. Published thermodynamic properties of HFC-227ea agent and the PROFISSY computer program from **NIST** were used to predict the properties of the agent at the different volumes and temperatures for the units [6,7]. Extinguisher sizes from 3% agent volume concentration to 18% agent volume concentration (in 3% increments) were designed and fabricated for the F-22 dry bay volume of 24.6 ft^3. Table 4 shows the corresponding mass of agent for each of the six agent volume concentrations.

Table 4. HFC-227ea Agent Mass at Different Agent Volume Concentrations (24.6 ft^3 vol.).[a]

% v/v @ 70 °F	**3**	**6**	9	12	15	18
% v/v @ -40 °F	2.3	4.7	7.1	9.5	12.0	14.5
agent mass, Ih.	.34	.71	1.10	1.52	1.97	2.45

[a] Reference 8

Development testing in the DBFS test facility was conducted at both ambient outdoor temperature and at -40 °C. The low temperature condition was established by pre-conditioning the PALAS unit in a temperature chamber and by recirculating the air in the simulated dry bay test article through a heat exchanger in a dry ice-alcohol chilling unit. Liquid CO_2 was also used to decrease the time to cool the test article, taking care to purge the volume of CO_2 prior to test by opening a side panel in the test article. Gas concentrations of CO_2 and O_2 were monitored prior to test to assure the atmosphere in the test article was essentially composed of air and able to sustain a flame. Thermocouples mounted throughout the test article and on the PALAS unit verified the temperature at the time of the test.

The fire challenge was a mass of 600 grams of Jet A fuel, heated to 100°F and pressurized to 10 psig upstream of a multiorifice spray nozzle. Electronic timers were used to control the sequence of events for each test. Ignition of the fuel spray was performed by detonation of a 10kJ incendiary "squib" after 100 ms of fuel spray. **After** a pre-burn time of 70 ms, the PALAS extinguisher was activated by voltage applied to a "squib" to start the PALAS propellant combustion. The fire was observed through clear lexan side panels on the test article with video cameras and was recorded on high-speed videotape equipment at a speed of 500 frames/second.

A bracketing procedure (Figure 3) was used to find the smallest size unit that would extinguish the fire repeatedly.

At ambient temperature, the 9% unit (1.10 lbs HFC-227ea agent) consistently extinguished the fire in 3 out of 3 trials. In the -40 °C cold fire tests, 12% v/v (1.97 lbs) was required to extinguish the fire 3 out of 3 times, but the next size smaller (9.5% v/v [1.52 lbs]) was successful 2 out of 3 times.

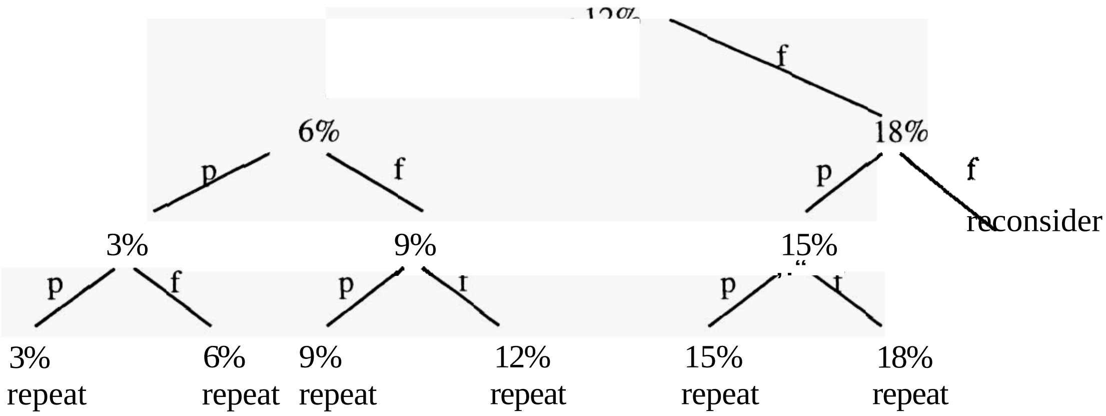


Figure 3. Fire Test Bracketing Procedure: p = pass, f = fail.

As a *means* of comparison, the same incremental masses of HFC-227ea agent were discharged by conventional nitrogen pressurization through a radially discharging suppressor. The radial suppressor relied on conventional nitrogen pressure of 600 psig in the agent bottle to expel the agent, without the addition of heat. The radial suppressor contained agent at a fill density of 58 lbs/ft^3. At ambient temperature, 9% v/v (1.10 lbs) was sufficient to extinguish the fire three out of three times. At -40 °C, however, not even the 14.5% v/v (2.45 lbs) suppressor extinguished the fire. Combining two radial suppressors for 3.55 lhs total agent mass (19.7% v/v) also did not extinguish the fire. The next largest size attempted was two units, each with 2.45 lhs. This total mass of 4.9 lbs (25.3% v/v) HFC-227ea was successful at extinguishing the fire.

As can be seen from Figure **4,** the PALAS is effective at using less agent mass (in the range of 50 to 60% less agent) than a conventional pressurized extinguisher of the same type of agent at cold temperatures. This result shows that the concept of adding heat to the discharging agent does work and is effective.

How does PALAS compare to a conventional system with Halon 1301? Although Halon 1301 was not used in this test program, a Halon 1301 system sized for 9% v/v concentration could be assumed to be adequate **for** a dry bay application, based on the volume concentration that consistently extinguished dry

Table 5. Agent Mass and Volume Comparison for F-22 Dry Bay Extinguisher (estimates for –65 °F).

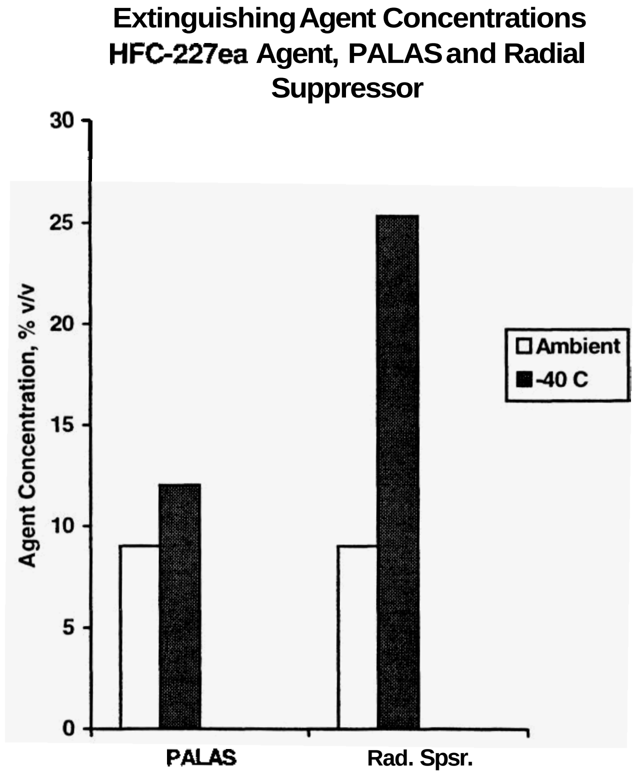
Extinguisher Type	Agent Conc., % v/v	Fill Density, lb/ft^3	Agent Mass, lb.	Agent Volume, in'
Halon 1301	9	60	1.3	37.4
PALAS HFC-227ea	12	75	2.1	48.4
Radial **Suppressor** HFC-227ea	25.3	58	5.3	158

A concern with using HFC agents is the generation of hydrogen fluoride (HF) as agent pyrolysis occurs at high temperature. PALAS uses hot gas to raise the temperature of the agent for enhanced vaporization. Should a false discharge of PALAS take place, that is, an accidental discharge without a fire present, then it would be desirable for the device not to generate HF. During discharge testing, the HF concentration in the dry bay simulator was measured by drawing sample gas from the dry bay into distilled water to trap the acid gas. Fluoride ion concentration in the water was then measured to determine the concentration of HF in the sample gas [9]. Two samples were taken during the discharge tests. The HF measurements in Table 6 can be considered as peak values because the gas samples were taken when the PALAS unit was discharging. The technique is accurate to within +/- 50 ppm. Notice that the values in Table 6 are within the threshold of detection for the measurement technique. These very low values are not considered a problem.

Table 6. HF Concentration of PALAS Discharge Without Fire Threat.

Temperature Condition	Agent Concentration, % v/v	HF Concentration, average of 2 samples, ppm
180 °F	14.4	78
65 °F	12.0	27
-40 °F	12.0	32

Further testing of PALAS is planned to take place at Wright-Patterson **Air** Force Base during live-fire testing on a simulated F-22 main landing gear wheel well dry bay at the Wright Laboratory Aircraft Survivability Research Facility. The Wright-Patterson testing is expected to include a variety of combustible fluids (JP-8 fuel, hydraulic fluid, and polyalphaolefin [PAO] coolant) and a variety of ballistic projectile threats.



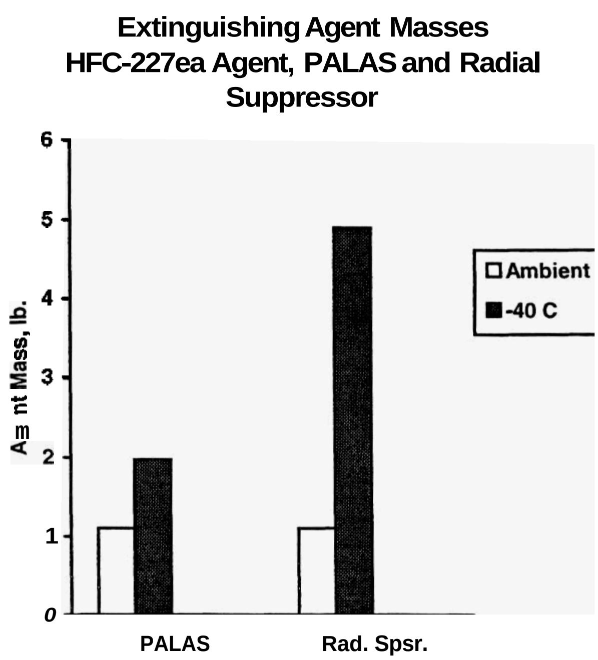


Figure 4. Comparison of **PALAS** and Conventional Suppressor in DBFS Tests (24.6 ft^3 volume).

bay fires during previous live-fire tests [10]. **A** conventional Halon 1301 bottle for the 24.6 ft^3 volume dry bay would contain 1.3 lbs of agent, based on a 9% v/v concentration at the lowest expected temperature of –65 °F [11]. Estimated values of agent mass and volume are presented in Table ***5*** for a Halon 1301 system, PALAS, and the radial suppressor.

MATHEMATICAL MODEL

PALAS operation can he described mathematically by a set of differential equations. Motion of the piston can be expressed as a force balance [12]:

$$mx'' + cx' + kx = F(t) \qquad \text{(equation 1)}$$

where m = mass

x'' = acceleration, second derivative of position with respect to time

c = damping coefficient

x' = velocity, first derivative of position with respect to time

k = spring coefficient

x = position

$F(t)$ = forcing function that varies with time, t

In this case, the agent is compressible, acts as a spring, and has a spring coefficient that varies with agent density. The PROFISSY program was used to generate a relationship between agent chamber volume and agent pressure for a given mass of agent [13]. Knowing the volume and the mass of agent means that the agent fill density is also known. Because of the cylindrical shape of the PALAS agent chamber, the volume (and therefore density) relationship to pressure is also a relationship between piston position and agent chamber pressure. The force, **kx,** increases as the agent is compressed and the value of k increases as the agent compresses to a single-phase liquid state. The forcing function, F(t), is the pressure acting on the piston area from the propellant gas. To define F(t), we need to define the propellant chamber pressure. The propellant chamber pressure can he determined by a mass balance of gas in the propellant chamber [14]:

$$m'_{generated} - m'_{discharged} = d(\rho_g V_c)/dt \qquad \text{(equation 2)}$$

where ρ_g is the density of the gas and V_c is the propellant gas chamber volume

$$m'_{generated} = \rho\, A_b\, r \qquad \text{(equation 3)}$$

where p is the solid propellant density, A_b is the burning surface area of the propellant, and r is the burn rate,

$r = a\, p^n$, where a and n are characteristics of the propellant

After the propellant rupture disc has burst, there will be gas flow through the propellant restricting orifice:

$$m'_{discharged} = C_d\, A_t\, p \qquad \text{(equation 4)}$$

C_d = discharge coefficient of the restricting orifice

A, = throat area of the restricting orifice

p = propellant chamber pressure, which is a function of time, t

$d(\rho_g V_c)/dt$ = change in mass of gas in the chamber with respect to time

$= (\rho_g\, dV_c/dt) + (V_c\, d\rho_g/dt)$

(equation 5)

$\rho_g = p\ mw / (R\ T)$, simplifying by assuming a perfect gas (equation 6)

mw = molecular weight of gas
R = universal gas constant
T = temperature
$V_c/dt = A_p\ x'$ (equation 7)
A_p = piston area
$V_c = V_o + A_p\ x$ (equation 8)

Notice that as the piston moves, the propellant chamber volume increases, and the change in density will contain a term with p' (change in pressure with time).

$$d\rho_g/dt = d(p\ mw / (R\ T))/dt \qquad \text{(equation 9)}$$

By rearranging, and simplifying by assuming a constant temperature once the propellant combustion is taking place, we can get an expression for p'.

$$p' = dp/dt = (R\ T / mw)\ d\rho_g/dt \qquad \text{(equation 10)}$$

The equation of motion (equation 1) can be expressed as

$$x'' = (1/m)(pA_p - cx' - kx) \qquad \text{(equation 11)}$$

where F(t) has been replaced by pA_p.

A dummy variable can be substituted, so that x" = y', where

$$y = x' \qquad \text{(equation 12)}$$
$$y' = (1/m)(pA_p - cy - kx) \qquad \text{(equation 13)}$$

The derivative of propellant pressure with time can be found by substituting equations 2 through 8 into equation 10

$$p' = (R\ T / mw)\ (p\ A_b\ r - C_d\ A_o\ p - \rho_g\ A_p\ x')/(V_o + A_p\ x) \qquad \text{(equation 14)}$$

These last three first-order differential equations (equations 12, 13, and 14) can be solved simultaneously in increments of time with the Runge-Kutta numerical method [15]. Using this method, once the initial conditions are defined, the method is self-starting in that the time increment, h, is used to estimate the new values of x, y, and p at time t + h. The new values are used as the next set of initial conditions, time is incremented again, and new estimates of x, y, and p are made for this next time increment. At each time increment, the mass flow of agent through the agent orifice can be calculated by knowing the agent chamber pressure (from the pressure vs. density relationship of the agent) and the agent orifice area. The mass of agent leaving the agent chamber in each time increment is subtracted from the mass of agent in the chamber for calculating the next iteration of chamber properties. The process is repeated for the duration of the time period of interest, resulting in descriptions of piston position and chamber pressures with time.

This mathematical model has been used to predict the performance of development hardware during discharge tests. The effect of orifice sizes, amount of propellant or other variables of interest can be modeled on a computer prior to conducting a test. Additionally, the computer model has been used to design a scaled-up PALAS for the military vehicle crew bay application.

CREW BAY TESTING

PALAS is also being investigated for explosion suppression in military ground vehicle applications. In the case of an armored personnel carrier, for example, rapid extinguishment is essential if the crew and vehicle are to be saved. Additionally, the importance of crew safety means that the fire suppressant must (1) be non-toxic, (2) not cause excessive crew exposure temperature, (3) not cause excessive overpressure in the bay, (4) have low acid gas by-products, and (5) not overly deplete the oxygen level in the crew bay [16]. The suppressant should also be environmentally friendly with no ozone depleting chemicals, low global warming potential, and low atmospheric lifetimes.

A scaled-up development PALAS unit has been designed and built for the crew bay fire threat. The crew bay volume is approximately 450 ft^3. For HFC-227ea agent at a temperature of 70 °F, a 9% volume concentration in this bay corresponds to 20.17 Ibs. If HFC-236fa agent is used, a 9% volume concentration means 18.18 lbs of agent are required. Three PALAS units could provide this agent concentration if each unit contained 6.72 lbs of HFC-227ea or if each unit contained 6.06 lbs of HFC-236fa.

Development of the crew bay PALAS unit is underway. After performing discharge characteristics tests, the unit will be used to suppress a fuel spray fire in a MI 13 armored personnel carrier (APC) hull located at Walter Kidde Aerospace. The APC will be instrumented with thermocouples, pressure transducers, and high-speed video to characterize the effectiveness of PALAS fire suppression against the fuel spray fire.

Under a contract with TACOM, testing will continue against a ballistic impact through a JP-8 fuel tank on a Bradley Fighting Vehicle hull. This testing will be conducted at the Army Research Laboratory, Aberdeen, Maryland. The fire threat in the TACOM testing at Aberdeen will consist of a fast fire or explosion caused by penetration of the crew compartment and fuel tank by a shaped charge projectile.

SUMMARY

Pyrotechnically Augmented Liquid Agent System (PALAS) technology can extend the temperature range in which environmentally safe liquid agents can be effectively used. PALAS accomplishes this by the addition of heat to the liquid agent so that vaporization of the agent is enhanced. The PALAS concept has been demonstrated by building development hardware and conducting simulated aircraft dry bay fire suppression tests with the hardware. This testing has shown that PALAS can use less mass of agent *to* suppress a fire under cold temperature conditions than a conventional pressurized bottle containing the same agent. Development is underway for testing PALAS in a larger volume for a military ground vehicle crew bay fire application, such as an armored personnel carrier.

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