

**ASSESSING HALON ALTERNATIVES FOR AIRCRAFT ENGINE
NACELLE FIRE SUPPRESSION**

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Assessing Halon Alternatives for Aircraft Engine Nacelle Fire Suppression

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A coaxial turbulent spray burner was built to evaluate the relative effectiveness of different chemicals for suppressing fires in a jet engine nacelle. The fire suppressant of current choice, halon 1301 (CF_3Br), must be replaced because of its detrimental effect on the ozone layer. The alternatives being considered lack the chemical activity of CF_3Br , so that the ability of the agents to mix into the flame convectively and to absorb heat is critical to their success. An agent delivery system was designed to inject the desired amount of material into the air upstream of a fuel nozzle and to control the agent injection rate through variation of the storage pressure and the duration of time that a solenoid valve remains open. The influence of air velocity, fuel flow, and injection period on the amount of nitrogen required to extinguish a jet fuel spray flame is discussed. The effectiveness of eleven different fluorocarbons, hydrofluorocarbons, and hydrochlorofluorocarbons is compared to that of halon 1301. The alternatives required 1.7 to 2.3 times the amount (on a mass basis) of CF_3Br to extinguish the spray flame, with HCFC-22 being the most efficient and FC-31-10 the least.

Introduction

Chlorinated and brominated hydrocarbons as a class of chemicals have come under close scrutiny because they have been implicated in the depletion of stratospheric ozone (Anderson, 1987). Under the auspices of an international agreement, commonly known as the Montreal Protocol, halon 1301 has been singled out as being particularly effective at scavenging ozone, and its manufacture has been eliminated starting in 1994 (Harrington, 1993).

Halon 1301, or trifluorobromomethane (CF_3Br), is used as a fire extinguishing agent in aircraft engine nacelles (the structure encasing the compressor, combustor and turbine) because of the chemical's many positive attributes; viz., it can be stored in a small volume as a liquid at room temperature and pressures greater than 1.61 MPa; it is a gas at atmospheric conditions, allowing it to be dispersed quickly leaving no residue; it has low toxicity in pure form; it can be produced at a reasonable price in high quantity; and, most important, very little agent is required to extinguish the fire.

A fire resulting from a leaking fuel line in the engine nacelle is often detected with a thermal sensor after the temperature exceeds a threshold value. The agent is released manually by the crew within seconds after confirming that a fire is present. Suppression is normally successful if the flow of fuel can be eliminated and the agent concentration can be maintained above a minimum level (6 percent by volume for halon 1301) throughout the nacelle for a minimum of a half second.

Alternatives to halon 1301 are sought (Grosshandler et al., 1994) that do not create unacceptable safety, environmental, or systems compatibility problems. This article describes the features of a turbulent spray burner used to predict the performance of alternative agents in simulated full-scale engine nacelle fires. A systematic study of the facility using nitrogen as the suppressant, and the measured suppression effectiveness of eleven low-ozone-depleting agents (listed in Table 1) are presented.

Background on Flame Suppression

A flame will be extinguished when the time required for the chemical chain reaction, t_{chem} (estimated from the inverse of a global kinetic rate coefficient), exceeds the time it takes to replenish the necessary heat and reactants, t_{flow} (given by the ratio of a characteristic length scale and convective flow velocity). Liñan (1974) showed that as the maximum flame temperature and the fuel burning rate decrease, a critical value of the Damköhler number ($D_n \equiv t_{flow}/t_{chem}$) is reached where the flame is abruptly extinguished. This suggests two strategies for suppressing fires: (1) decreasing t_{flow} by increasing the flow velocity (or strain rate); and (2) increasing t_{chem} by reactant removal, cooling the flame, or chemical inhibition.

Fundamental studies have shown that the character of the fluid mechanical flow field is a key parameter in controlling flame extinction (Williams, 1974). As the strain rate increases, t_{flow} decreases and a flame becomes weaker and easier to extinguish by agent addition. If the flame is strained at a high enough rate, the flame will self-extinguish. Reactant removal is accomplished by actively eliminating or by simply consuming the fuel and/or air. Under sufficiently rich or lean conditions flame extinction will again occur without the aid of a fire suppressing agent. Cooling the flame reduces the rate of energy release due to the exponential temperature dependence in the Arrhenius rate coefficient. This can be accomplished by reducing the heat feedback from the surroundings, by cooling the fuel and air, or by increasing the heat capacity of the material entering the flame. A gaseous agent with higher specific heat (higher molecular weight and number of atoms) will generally be more effective in this situation.

Halon 1301 contains bromine, which inhibits the combustion reaction by tying up the chain-branching hydrogen radicals in a catalytic cycle involving HBr. Chlorine interacts with the flame in a similar manner but to a much lesser degree. Fluorine also reacts with hydrogen to form HF, but the hydrogen-fluorine bond is so strong that the F atom is not recycled. Hence, the agents investigated in this study rely primarily on a physical cooling mechanism rather than chemical inhibition to suppress a fire. Tucker et al. (1981) and Sheinson et al. (1989) further discuss the chemical and physical aspects of fire suppression.

Pitts et al. (1990) present a comprehensive review of the literature relevant to fire suppression by various gaseous agents, and discuss the role of different suppression mechanisms and

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various test procedures. The conventional method to determine the amount of agent necessary for suppression of a liquid fuel fire is to increase the concentration slowly in a low-velocity air stream flowing concentrically over a small (≈ 25 mm diameter) burning pool. This apparatus, referred to as a cup burner, has been used for evaluating halon 1301 and other flame extinguishants (e.g., Booth et al., 1973). The cup burner cannot simulate the combined droplet evaporation and turbulent mixing that might occur in a realistic engine nacelle fire.

Hamins et al. (1994) looked at suppression mechanisms for the specific application of aircraft protection, and described different facilities used to cover a wide range of possible fire conditions. A description by Bennett (1992) of full-scale engine nacelle fires indicates that the fires of interest are turbulent and characterized by a range of strain rates. The turbulent spray burner, designed for the current study, produces a complicated flame structure in which fuel droplets vaporize and react with an oxidizer that can be composed of either pure air, or air mixed with combustion products and/or fuel vapor. Because of the inherent differences in the structure of the combustion zone between the turbulent spray burner and the more traditional cup burner apparatus, different suppression behavior in the two facilities would not be unexpected.

Experimental Facility

An objective of this investigation was to develop a laboratory apparatus that captures the critical elements that exist within an engine nacelle fire as an alternative to difficult and costly experiments on a full-scale facility. In addition to the flexibility offered by a reduced-scale facility, the turbulent spray burner minimizes the influence of agent transport and vaporization on flame suppression effectiveness, and allows independent control of the rate at which the agent enters the flame.

The spray burner facility, shown in Fig. 1, consists of an air delivery system, a fuel delivery system, and an agent injection system. Air at atmospheric pressure coflows around a 6-mm-dia fuel supply passage within a 0.5-m-long, 50-mm-dia stainless steel pipe. A pyrex tube with a 65 mm ID, supported on a Teflon ring, confines the flame for an additional 75 mm beyond the outer steel casing. This pyrex tube is used to observe the mixing of the agent with the flame front. The fuel is injected along the centerline through a pressure-jet nozzle that forms a 45 deg solid-cone spray. The exit of the nozzle is flush with the open end of the surrounding air passage. The flame is stabilized on a 35-mm-dia steel disk attached to the nozzle body. The air is supplied by a high-capacity compressor at 800 kPa, and the flow is monitored with a sonic orifice. The air temperature varied between 19 and 24°C as measured with a type-K thermocouple that was positioned 1.1 m upstream of the nozzle exit. The average air velocity, measured over the burner cross section, is adjustable to a maximum of 50 m/s. The fuel, JP-8, is stored in an 18 liter tank and delivered to the burner with an electric gear pump at pressures controllable to 1.0 MPa-g. The nozzle is designed to deliver fuel at a rate of 0.5 ml/s when the gage pressure is 687 kPa.

The gaseous agents were injected impulsively into the air stream at a position 0.54 m upstream of the nozzle. Uniform

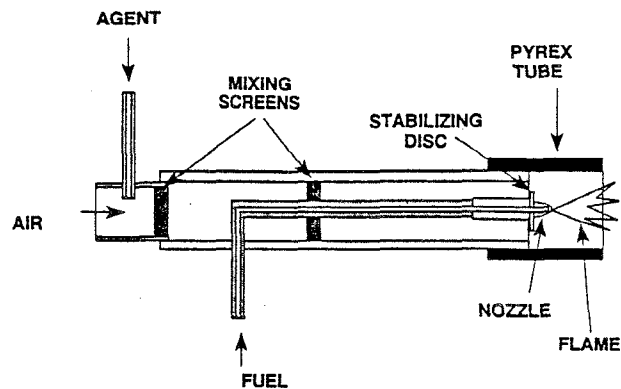


Fig. 1 Cross-sectional view of turbulent spray burner

dispersion across the air stream was enhanced by injecting the gas in a radial direction into a reduced diameter (25 mm) section of the air passage through two 6 mm diameter tubes. Screens with a 50 percent open area were placed 40 and 80 mm downstream of the injection point to ensure complete mixing between the air and agent prior to encountering the flame zone.

The injection mechanism, shown in Fig. 2, consists of the agent supply bottle connected to a stainless steel storage vessel through a metering valve, and to the burner through a computer-controlled solenoid valve. The storage volume, including the one liter pressure vessel and associated plumbing, is 1040 ± 10 ml and the agent pressure is adjustable up to 687 kPa-g. The agent temperature and pressure in the storage vessel are monitored with a type-K thermocouple and a pressure transducer, respectively, located upstream of the solenoid valve. The amount of agent injected is controlled by varying the initial pressure, the time that the solenoid valve is open, and the size of a metering orifice located just upstream of the solenoid valve. The actual mass delivered is computed from the difference between the initial and final pressures in the storage vessel. The rate of injection is determined primarily by the initial pressure and the size of the metering orifice (4.8 and 6.4-mm-dia orifices were used in the reported investigation).

Experimental Methodology

The flow of air and JP-8 was varied to ascertain how flame stability was affected by these parameters. The fuel pressure was first fixed at 687 ± 10 kPa-g (corresponding to a mass flow rate of around 0.42 g/s). The spray is ignited with a relatively low air flow using a propane torch. The flame extends well beyond the exit of the pyrex tube and is highly luminous under these conditions. As the air flow is increased, the flame attaches itself to the stabilizing disk and the plume length decreases until the flame is stationed within the pyrex tube. At high air flows, little soot radiation is observed beyond the exit plane, although the flame itself maintains some luminosity. A moderate amount of

Nomenclature

a = Redlich-Kwong interaction constant
 b = Redlich-Kwong covolume
 C_p = constant pressure specific heat
 D_n = Damköhler number
 FSN = flame suppression number
 m = mass
 \dot{m} = rate of mass flow
 P = pressure

R = universal gas constant
 T = temperature
 t_{chem} = characteristic chemical reaction time
 t_{flow} = characteristic flow time
 V = volume
 VF = volume factor
 β = mass fraction of agent in air stream

γ = specific heat ratio
 ρ_L = saturated liquid density

Subscripts

air = pertaining to air
 halon = pertaining to halon
 f = final state
 i = pertaining to agent i , or initial state

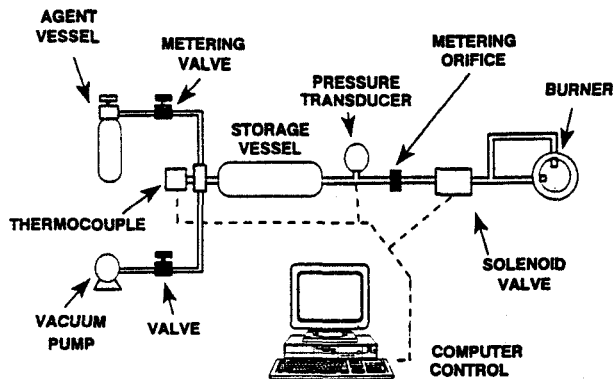


Fig. 2 Schematic of gaseous agent injection system

soot forms on the nozzle face in a matter of minutes. A stable flame is sustainable until the air flow rate exceeds 73 g/s, at which point the flame blows out. The average gas velocity across the air duct is about 33 m/s at the above-mentioned mass flow rate, which translates to an estimated residence time in the recirculation zone downstream of the stabilizing disk of 5 ms. Blow-out experiments were repeated for fuel nozzle pressures of 515 and 858 kPa-g. At the reduced pressure, the fuel flow rate decreases by about 14 percent, which results in an equivalent decrease in the amount of air necessary to extinguish the flame. The higher fuel line pressure has no appreciable effect on the blowout limit. The operating conditions chosen as the baseline measurements were a mass flow rate of JP-8 of 0.42 g/s and an air flow rate of 33 g/s at atmospheric pressure (resulting in an average inlet air velocity of 14 m/s). This produced an 18 kW flame with an overall equivalence ratio of about 0.17. The temperatures of the fuel and air, and the initial temperature of the agent, were ambient (19–24°C).

The injection system, under idealized conditions (incompressible flow, massless valves, no pressure losses), is designed to deliver a square-wave pulse of agent to the burner for the amount of time programmed by the computer controller. The actual flow deviates substantially from this scenario. There is a 15 ms delay from when the solenoid is triggered to the actual initiation of

agent flow. When the valve starts to close, pressure waves are created which reverberate in the injection system at the acoustic velocity, causing the flow to modulate (Grosshandler et al., 1993).

The critical temperatures of the agents listed in Table 1 vary from a low of 19.7°C for FC-116 to a high of 130.6°C for HFC-236fa. To account for possible nonideal gas behavior in the storage vessel, the Redlich-Kwong equation of state (Van Wylene and Sonntag, 1978) was used to determine the mass of agent, m , contained in the vessel of volume V , at pressure P and temperature T ; i.e.,

$$m = \frac{PVM}{RT} \left[\frac{1}{1 - bm/V} - \frac{am/(VRT^{3/2})}{1 + bm/V} \right]^{-1} \quad (1)$$

where M is the molecular weight of the gaseous agent, a and b are constants dependent upon the critical properties of the agent, and R is the universal gas constant (8.314 kJ/kmol·°C). The maximum difference in mass calculated by the ideal gas equation of state and Eq. (1) was 7 percent. The initial temperature is measured, and the final temperature is determined by assuming that the expansion occurs isentropically; i.e.,

$$\frac{T_f}{T_i} = \left(\frac{P_f}{P_i} \right)^{\gamma-1/\gamma} \quad (2)$$

Gamma is the specific heat ratio for the gas, defined as $(M \cdot C_p + R)/M \cdot C_p$, using the values for M and C_p from Table 1. By measuring the change in pressure, Eq. (1) can be used to determine the total amount of mass injected into the burner. The uncertainty in mass created by using Eq. (2) for temperature is small since the temperature changes less than 20°C during injection. The vessel pressure was recorded at a rate of 700 Hz, with the initial and final conditions obtained from the average of at least 100 points measured one-half second prior to the release of the agent, and for one second after the solenoid valve closes, respectively. The uncertainty in the total mass calculated is estimated to be less than ±8 percent.

The mass fraction of agent required to extinguish the flame, β , is defined in terms of the mass flow of agent, \dot{m}_i , and air, \dot{m}_{air} :

$$\beta = \frac{\dot{m}_i}{\dot{m}_i + \dot{m}_{air}} \quad (3)$$

Table 1 Thermodynamic properties of chemicals being evaluated (based on references in Yang and Breuel, 1994)

Formula	Compound	Boiling Point @ 101 kPa, °C	Critical Temp., °C	Molec. Wt., kg/kmol	C_p (gas) @ 25°C & 101 kPa, kJ/kg-K	ρ_L (sat.) @ 25°C, kg/m ³
N ₂	Nitrogen	-196	-147.0	28	1.042	52 ¹
C ₂ F ₆	FC-116	-78.2	19.7	138	0.772	608 ¹
CF ₃ Br	Halon 1301	-57.8	67.0	149	0.466	1551
CH ₂ F ₂ /C ₂ HF ₃	HFC-32/125	-52.5	73.2	67	0.830	1040
C ₂ HF ₃	HFC-125	-48.6	66.3	120	0.798	1190
CHF ₂ Cl	HCFC-22	-40.9	96.2	87	0.795	1192
C ₃ F ₈	FC-218	-36.8	72.0	188	0.781	1321
C ₂ H ₂ F ₆	HFC-134a	-26.2	101.2	102	0.852	1209
C ₃ HF ₇	HFC-227ea	-16.4	101.7	170	0.769	1395
C ₂ HF ₂ Cl	HCFC-124	-13.2	122.5	137	0.714	1357
cyclo-C ₄ F ₈	FC-318	-7.0	115.2	200	0.776	1499
C ₃ H ₂ F ₆	HFC-236fa	-1.5	130.6	152	0.804	1356
C ₄ F ₁₀	FC-31-10	-2.0	113.2	238	0.755	1497

¹ gas density computed at storage bottle conditions, 25 °C and 4.1 MPa

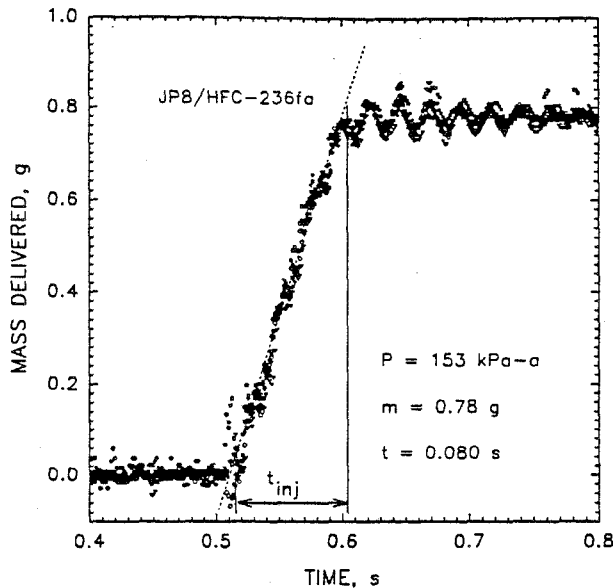


Fig. 3 Mass-time trace for injection of HFC-236fa. The different symbols correspond to six successive runs in which amount of agent is just enough to extinguish JP-8 spray flame.

The mass flow rate of air is measured directly. The parameter m_i is the ratio of the mass of agent added to the flame, as determined from Eq. (1), and the actual time interval of agent injection into the burner. The variation of mass of agent with time for a typical discharge is shown in Fig. 3, with each symbol representing a different injection event for the same initial conditions. The injection time interval is estimated from where the line drawn tangent to the rapidly increasing portion of the pressure trace intersects zero and the final value of mass in the vessel. The pressure oscillations shown in Fig. 3 at the end of the event were present in all cases and are due to the impulsive operation of the solenoid valve. The frequency is determined by the acoustic velocity and the size of the storage tank.

The mass of nitrogen delivered from the storage vessel to the burner as a function of injection time interval was measured for a fixed initial vessel pressure of 687 kPa-g (Grosshandler et al., 1993). The results indicate that the delivered mass of nitrogen increases almost linearly with time in the range between about 25 and 250 ms. Deviations from linear behavior occur for shorter periods because the valve does not have enough time to open fully, and for longer periods due to the finite amount of agent (≈ 10 g for N_2) initially contained in the storage vessel.

A number of experiments were carried out with the burner operating at baseline conditions and with air as the extinguishing agent to ensure that the flame could not be suppressed simply by blowing it out. When air was injected into the burner, the flame fluctuated momentarily, but was never extinguished even when the storage pressure and injection period were at their maximum values (viz., 687 kPa-g and 910 ms).

The protocol used in the experiments was first to ignite the fuel spray and set the air and fuel flows to the desired level. The flame was allowed to burn for several minutes to ensure steady operation. The storage vessel was pumped down and then flushed several times with the agent being tested to purge contaminating gases from the system. The pressure in the vessel was adjusted with the solenoid valve closed using the inlet metering valve. Initially, a pressure was chosen that was expected to be insufficient to extinguish the flame. The computer-controlled data acquisition system was initiated, and the response of the flame to the injection process was observed. If the flame was not extinguished, the pressure in the agent vessel was increased and the

experiment was repeated immediately. Eventually, a pressure was found that was sufficient to suppress the flame. This procedure was normally repeated four times for each agent.

Characterization With Nitrogen

The influence of air velocity, injection period, and injection pressure on the amount of N_2 required to extinguish the JP-8 spray flame and on the value of β was investigated to characterize the operation of the experimental facility. The turbulent burner was set to deliver air at 33 g/s and fuel at 0.42 g/s, and the storage vessel was pressurized with nitrogen to 113 kPa-g. The injection interval was then increased one millisecond at a time until the flame was suppressed. Flame extinguishment occurred between 23 and 26 ms for five different runs, delivering an average of 0.33 ± 0.03 g nitrogen at a mean flow rate of 11.2 ± 0.5 g/s. The extinguishing mass fraction (β) varied between 0.24 and 0.26. This value compares to a mass fraction for nitrogen of 0.28 measured in the cup burner apparatus with JP-8 as the fuel (Hamins et al., 1994).

Additional experiments were carried out with the fuel flow fixed and with air flows of 22 and 44 g/s. The amount of nitrogen required to extinguish the lower air velocity flame was 0.32 g, or $\beta = 0.33$. The higher air flow rate required an average total nitrogen mass of 0.29 g and $\beta = 0.21$ to suppress the flame. In this case, doubling the air flow (which increased the amount of excess air) reduced the mass of nitrogen required by 10 percent. This observation is consistent with Liñan's (1974) explanation for extinction because increasing the air flow both decreases t_{flow} (through higher strain rate) and increases t_{chem} (through dilution), driving the Damköhler down toward its critical value.

A series of experiments was carried out with the air and fuel flow rates at baseline conditions, and with the time interval fixed at 79 ms (± 5 ms) as the nitrogen pressure was increased. Figure 4 presents the variation of the mass of nitrogen delivered to the burner as a function of initial vessel pressure. The open squares indicate that the flame remained lit after agent delivery; the solid squares correspond to successful extinguishment. The minimum vessel pressure necessary to extinguish the flame was 167 kPa-g. The amount of nitrogen injected at this pressure and time interval was 0.58 ± 0.03 g. The variations in mass delivered for a

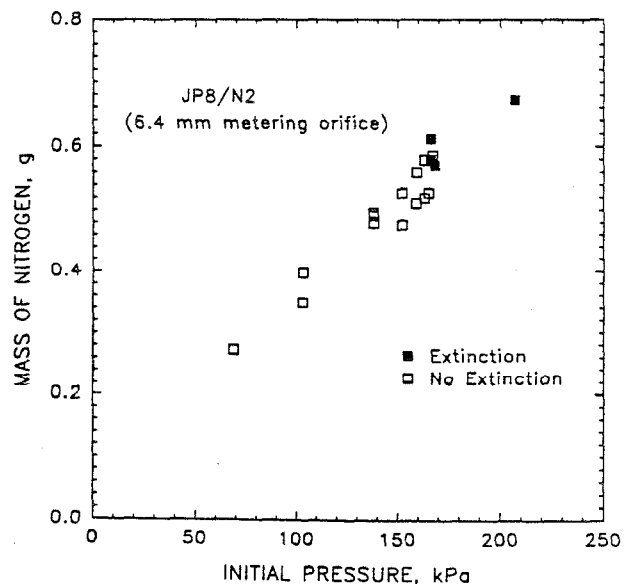


Fig. 4 Effect of vessel pressure on extinguishment of JP-8 spray flame by nitrogen. Solid symbols indicate extinction; open squares indicate no extinction.

fixed pressure are caused by run-to-run variations in the rate of injection.

The injection time interval has an effect on the minimum mass of nitrogen required to extinguish the flame. The open squares presented in Fig. 5 illustrate this effect. For these experiments, the initial pressure was fixed at 167 kPa-g and the injection time interval was gradually increased until extinction occurred. The minimum mass of nitrogen is about 0.32 g, for a set injection period of 23 ms. Reducing the set time to 6-ms has no impact on the amount of nitrogen required to quench the flame because the actual period of injection does not change appreciably (being a function of the time required to open the solenoid valve). Injection times longer than 23 ms resulted in the delivery of greater amounts of N_2 , with more than three times as much N_2 required when the injection time is set to 260 ms.

At long injection time intervals, a limit for β is reached below which the flame cannot be extinguished no matter how long the nitrogen is allowed to flow (even if the nitrogen reservoir were not finite). Nitrogen flowed continuously in one experiment, and the concentration was increased until the flame was suppressed. The extinguishing mass fraction was found to be 0.11, and is indicated by the arrow (labeled "continuous flow limit") in Fig. 5. This compares to a β of 0.28 found in the cup burner with the same fuel/agent combination. Less nitrogen may be required to extinguish the spray flame because regions of greater strain rate exist (i.e., f_{flow} is reduced). The solid squares also shown in the figure are values of β that correspond to the different injection time intervals. As the time is shortened, β increases, reaching a limiting mass fraction of 0.28.

If the value of β were the sole criterion for evaluating an extinguishing strategy, one would chose to inject the agent over an extended period of time. However, as seen in Fig. 5, this has the undesirable effect of greatly increasing the amount of agent required to put out the flame. For an agent that is to be used in a transient manner, the total mass must also be considered. This is distinct from the quasi-steady state measurements taken with the cup burner apparatus, for which β is a reasonable measure of performance.

Performance of the Alternative Agents

A fixed injection time of 65 ms was chosen to compare the performance of the alternative agents. This value is intermediate between the estimated residence time in the spray flame and a typical time interval for injection in an actual engine nacelle. At this setting, an initial pressure of 167 kPa-g is necessary to extinguish the flame with nitrogen. Nitrogen is considered chemically inert during suppression, and has a much lower molecular weight than halon 1301 and the alternative gaseous agents that were evaluated. As a result, a lower pressure is required in the vessel to deliver the equivalent mass of the heavier molecular weight compounds. The 6.4-mm-dia flow-metering orifice (see Fig. 2) was replaced with a 4.8 mm orifice to increase the pressure drop. The flow remained unchoked for all gases other than N_2 . Extinguishment experiments were performed using halon 1301 to establish a performance reference (Hamins et al., 1994). An average over five experiments led to a required initial CF_3Br pressure of 24 kPa-g to suppress the flame, which translates to a mass of $0.44 \pm .04$ g and a mass fraction, β , of 0.15.

The repeatability of the experimental technique is demonstrated in Fig. 3, for one typical case where the mass of the agent, HFC-236fa, is just above the extinction threshold. This figure presents the mass of agent delivered to the burner with respect to time for six different trials (each represented with a different symbol). The average mass injected is 0.78 g with a range of ± 0.02 g. The initial pressure needed to cause extinction is 52 ± 2 kPa-g, and the calculated injection interval is 80 ± 8 ms.

Expressing the results in terms of the flame suppression number (FSN) is a convenient way to compare the performance of the different agents. The FSN is defined as the mass of agent

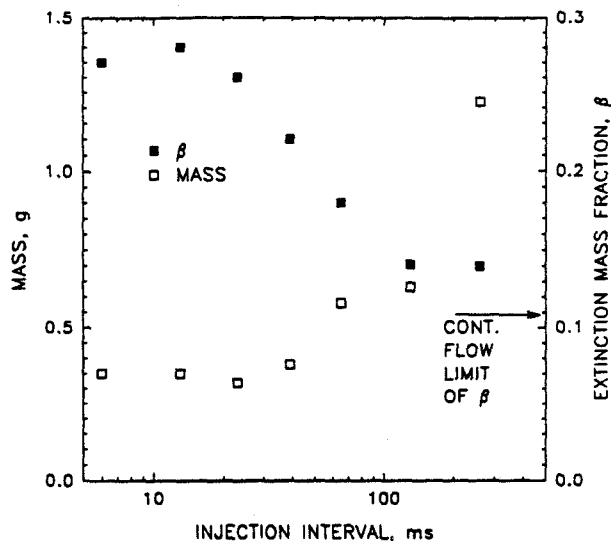


Fig. 5 Effect of injection time interval on mass of nitrogen (open squares) required to extinguish JP-8 spray flame. Solid squares are the corresponding mass fractions, β . The arrow indicates the limiting value for β when nitrogen flows continuously.

relative to the mass of halon 1301 used to suppress an identical flame; i.e.,

$$FSN = \frac{m_i}{m_{halon}} \quad (4)$$

The volume factor (VF) accounts for the differences in saturated liquid densities of the agents, and is defined as follows:

$$VF = \frac{m_i}{m_{halon}} \frac{\rho_{L,halon}}{\rho_{L,i}} = \frac{\beta_i}{(1-\beta_i)} \frac{(1-\beta_{halon}) \rho_{L,halon}}{\beta_{halon} \rho_{L,i}} \quad (5)$$

The volume factor provides a logical conversion from the mass fraction required to the storage volume because the saturated liquid condition at ambient temperature is close to the condition maintained when the storage vessel is filled (assuming negligible solubility of the pressurizing gas).

Figure 6 compares the mass fractions of thirteen different agents required to suppress the spray flame, and their respective flame suppression numbers and volume factors. The agents are arranged according to increasing boiling point, so as to provide a gross indication of their ability to quickly flood a unit volume. (Pitts et al., 1994, discuss in detail the important role of agent dispersion on suppression effectiveness.) Nitrogen requires a mass fraction of 0.18 to extinguish the flame, compared to 0.15 for CF_3Br . The mass fractions of the alternatives increase approximately in the order of HCFCs, HFCs, and FCs, with the least effective agent, FC-31-10, requiring a β of 0.27 for suppression. The FSN rankings are in the same order, with HCFC-22 the best alternative on a mass basis (other than N_2) requiring 50 percent more mass than halon 1301. Of the alternatives examined, nitrogen has the highest specific heat at 25°C (see Table 1) and the highest effectiveness on a mass basis. The differences among the fluorinated alternatives are not large, and all have similar values for C_p . These results suggest that the suppression mechanism for the fluorinated compounds is primarily physical.

Nitrogen and FC-116 are not liquids at 25°C and 4.1 MPa (the conditions used to define VF). Neither are viable candidates when ranked according to volume factor (see Fig. 6) unless a very high pressure storage container is available. The HFC-32/125 mixture has the next highest volume factor, with a value of 2.7. The remaining agents have values of VF between 1.8 and 2.3, with HCFC-124 requiring the least storage volume as defined here.

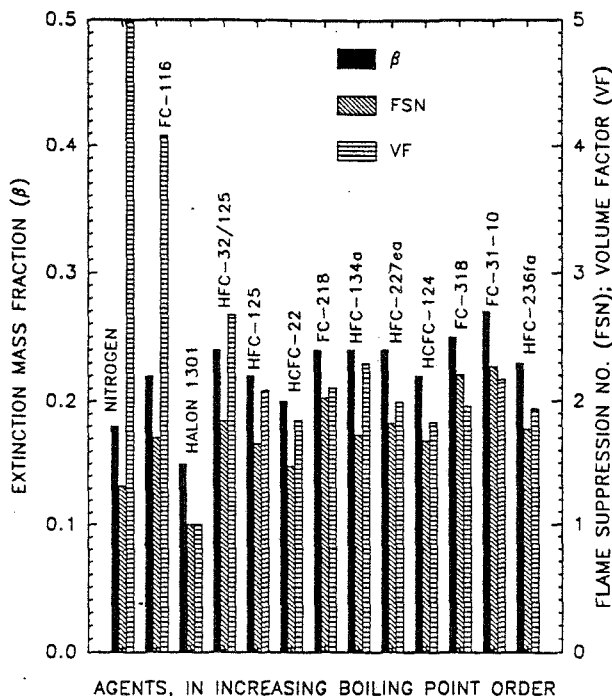


Fig. 6 Comparison of mass fraction (β), flame suppression number (FSN), and volume factor (VF) for gaseous agents evaluated in this study.

Experimental Uncertainty

The data assembled during this investigation provide a quantitative measure of the effectiveness of different compounds for suppressing a laboratory scale, fuel lean, JP-8 turbulent spray flame. The injection time interval for a fixed set of conditions varied by as much as 8.3 ms (1/120 s) because the solenoid valve operates on 60 Hz AC power. This does not add to the uncertainty in the mass nor rate of injection since both of these parameters are determined from the actual pressure trace independent of the initial time interval setting. The reported values of mass and β vary less than ± 8 percent between experiments taken on different days for the same actual injection interval. Undiscovered systematic errors increase the uncertainty in the absolute values of pressure, injection times and flow rates of the fuel and air. The uncertainty in relative values, however, remains less than ± 10 percent since the systematic errors are greatly reduced by the normalization procedure. This level of certainty in β , FSN, and VF is sufficient to rank the agents and to identify the best choices for full-scale testing.

Conclusions

It is concluded that the turbulent spray burner facility produces a stable flame over a range of air and fuel flows, and that the agent delivery system is able to control accurately the injection period between about 20 and 900 ms. The bench-scale spray burner is suitable for comparing the performance of gaseous extinguishing agents in transient operation, but full-scale engine nacelle trials are required to verify if the results can be reliably scaled up by the needed factor of 100.

The mass fraction, total mass, and minimum volume of agent required to extinguish a given flame must all be considered when

ranking the performance of different fire fighting agents. Of the twelve alternatives to halon 1301 evaluated in the turbulent spray burner, nitrogen required the least mass to extinguish the flame, followed by HCFC-22; FC-31-10 required the most. The spread between the most and least effective fluorinated alternatives (on a mass basis) is not large, but is greater than the uncertainty of the results (± 10 percent).

On a volume basis, the two HCFCs were the best and nitrogen the poorest performer. The mixture of HFC-32 and HFC-125 had the largest volume factor of the chemicals with critical temperatures greater than 25°C.

The alternative agents performed better in the turbulent spray burner relative to halon 1301 than was predicted from cup burner measurements. It is suspected that this is due to the higher strain rates present in the spray burner and the reduced amount of time for the bromine atom in halon 1301 to chemically inhibit the combustion process. The chlorine containing compounds, overall, appeared to be the most effective alternatives. Generally speaking, about twice as much mass and volume were needed to suppress the spray flame using these alternative agents when compared to halon 1301.

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