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A TURBULENT SPRAY BURNER FOR ASSESSING HALON ALTERNATIVE FIRE SUPPRESSANTS

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ABSTRACT

A research program to characterize candidate compounds for replacing halon 1301 for in-flight aircraft fire protection is described in this paper. The thermodynamical, fluid mechanical, and flame extinction properties are examined, and a number of fuels and flame arrangements are investigated in an attempt to develop a general test protocol which will reliably predict the relative fire suppression efficiency of new agents being considered for a variety of applications. A coaxial turbulent spray burner was built to evaluate the relative effectiveness of agents for suppressing high intensity fuel fires such as one might encounter in a jet engine nacelle. Fuel is injected along the centerline of the 50 mm diameter burner, and air co-flows about the fuel passage at bulk velocities up to 33 m/s, producing an 18 kW flame with an overall equivalence ratio of 0.17. The flame is stabilized in the wake formed behind a 35 mm diameter disc surrounding the fuel nozzle. A key element of the facility is the agent delivery system, which is designed to inject the desired amount of material into the air upstream of the fuel nozzle. The amount of agent is controlled by varying the storage pressure and the duration of time (13 to 910 ms) that the solenoid valves remain open. The influence of air velocity, fuel flow, and injection period on the amount of a N_2 required to extinguish the turbulent spray flame is discussed, and the effectiveness of twelve gaseous agents is compared.

BACKGROUND

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, two compounds, halon 1211 and 1301, have been singled out as being particularly effective at scavenging ozone, and their manufacture is to be

eliminated starting in 1994 (Hartington, 1993).

Halon 1301, or trifluorobromomethane (CF_3Br), is used as a fire extinguishing agent in a multitude of applications because of its positive attributes. CF_3Br is a liquid at room temperature and high pressure, allowing it to be stored in a small volume; it is a gas at atmospheric conditions, allowing it to be dispersed quickly and leave no residue; it has low toxicity; it can be produced at a reasonable price in high quantity; and, most importantly, very little agent is required to extinguish the fire. These characteristics are desirable for protecting the contents of most enclosures against unwanted fire, but the positive attributes of CF_3Br make it extremely attractive for aircraft applications because of the severe weight and volume constraints.

The work described in this paper is part of a larger effort at NIST focused on finding an alternative to halon 1301 for application to aircraft engine nacelle and dry bay in-flight fire protection. The engine nacelle encases the compressor, combustor and turbine. Protection is required to eliminate a possible fire resulting from leaking fuel, hydraulic, or lubrication lines. Dry bays refer to closed spaces in the wings and fuselage, inaccessible in flight, and into which fuel could spray and possibly ignite following an equipment malfunction.

Alternative chemical compounds are sought which perform the same functions as the halon used currently in the above applications, and which do not create unacceptable safety, environmental, or systems compatibility problems. In an earlier study, preliminary screening procedures (Gann *et al.*, 1990) and some criteria for evaluating replacements for both halons 1211 and 1301 (Pitts *et al.*, 1990) were developed. A list of 103 chemicals was compiled from various families of compounds, including halogenated and non-halogenated species, compounds containing sulfur, phosphorous, metals, silicon, or germanium, and inert gases.

This paper summarizes the overall research objectives of the NIST program, and describes the features of one facility, the

Table 1. Gaseous chemicals being evaluated, their boiling point, molecular weight, and critical volume

Compound (Formula)	B.P., K	M.W.	$v_c, m^3/kg$
Nitrogen (N ₂)	77	28	0.00321
FC-116 (C ₂ F ₆)	195	138	0.00161
Halon 1301 (CF ₃ Br)	215	144	0.00136
HFC-32/HFC-125 (CH ₂ F ₂ /C ₂ HF ₅)	220	67	0.00209
HFC-125 (C ₂ HF ₅)	225	120	—
HFC-227 (C ₃ HF ₇)	231	170	—
HFC-22 (CHF ₂ Cl)	232	87	0.00190
FC-218 (C ₃ F ₈)	236	188	0.00159
HFC-134a (C ₂ H ₂ F ₄)	247	102	0.00197
HCFC-124 (C ₂ HF ₄ Cl)	263	137	0.00177
FC-318 (cyclo-C ₄ F ₈)	267	200	0.00162
HFC-236fa (C ₃ H ₂ F ₆)	273	152	—
FC-3110 (C ₄ F ₁₀)	273	238	0.00165

turbulent spray burner, used to evaluate the suppression effectiveness of alternative compounds. Results are presented on the amount of agent necessary to extinguish a jet fuel spray.

OVERALL PROJECT DESCRIPTION

The effectiveness of a fire suppression agent is related to its thermodynamic properties, its behavior during release, its interaction with flame chemistry, the timing of its release, and the nature of the fire. A series of experiments are underway to examine the thermodynamical, fluid mechanical, and flame extinction properties of the gaseous compounds listed in Table 1. In particular, information on those phenomena which control the actual suppression process is sought, be they the chemical reactivity of the agent or the properties associated with the physical mixing of the agent into the fire. The release and delivery of the agent is critical for dry bay protection, where events leading to a threatening over-pressure occur in less than 50 ms.

Knowledge of the thermodynamic and transport properties of agent mixtures under conditions of vessel blow-down and the development of a two-phase turbulent jet are necessary to allow the design of efficient and light weight storage and delivery systems. This information is particularly important for agents with no chemical inhibition properties since the delivery of more material will be necessary to extinguish the fire.

Four different experiments are being conducted to rank the relative combustion suppression effectiveness of the listed agents, using (1) a cup burner, (2) an opposed flow diffusion flame (OFDF) burner, (3) a turbulent spray flame burner, and (4) a deflagration/detonation tube. Table 2 lists the fuels to be used and the experimental variables for each configuration.

The cup burner has been used previously to measure the critical flow of gaseous suppressant needed to extinguish a low

Table 2. Flame Extinction Experiments

1. Cup Burner Diffusion Flame
 - Nominal agent residence time: 100 ms
 - Fuels: heptane, JP5, JP8, hydraulic fluids 5606 and 83282
 - Variable: agent concentration
2. Opposed-flow Diffusion Flame
 - Nominal agent residence time: 5 to 100 ms
 - Fuels: heptane, JP8
 - Variables: strain rate, agent concentration
3. Turbulent spray flame
 - Nominal agent residence time: 2 to 10 ms
 - Fuels: JP8, hydraulic fluid 83282
 - Variables: temperature, velocity, agent concentration, injection period
4. Premixed Deflagration/Detonation wave
 - Nominal agent residence time: 5 to 50 μ s
 - Fuel: ethene
 - Variables: agent concentration, fuel/air ratio, pressure

velocity diffusion flame and has been the basis for ranking the relative effectiveness of various chemicals (*e.g.*, Sheinson *et al.*, 1989; Booth *et al.*, 1973). The agent concentration needed to extinguish a diffusion flame stabilized between counter-flowing streams of oxidizer and a vaporizing liquid fuel is being measured following the technique developed by Seshadri (1977). Unlike the cup burner, the effect of the flow field (strain rate) on the extinction process is an independently controlled parameter in the OFDF.

The speed of an accelerating turbulent flame near the detonation limit can reach magnitudes three orders higher than that of a laminar flame. A detonation tube based upon the design of Peraldi *et al.* (1986) is being used to vary the wave from a high-speed turbulent flame at lean conditions to a quasi-detonation at the stoichiometric point.

In the above three experiments the agent will be in contact with the reacting fuel and air for residence times ranging from 5 μ s for the detonation tube to 100 ms in the OFDF. The turbulent spray flame discussed in this paper is designed to cover intermediate residence times, between 2 and 10 ms.

TURBULENT SPRAY BURNER

An engine nacelle fire is typically a turbulent diffusion flame stabilized behind an obstruction in a high speed air flow. Jet fuel, either as a spray or pre-vaporized, is the most likely source for the fire. Extinguishment occurs when a critical level of agent is mixed with the air upstream, and is transported to the flame where it can be entrained into the primary reaction zone. The process is affected by the turbulence intensity, velocity of the

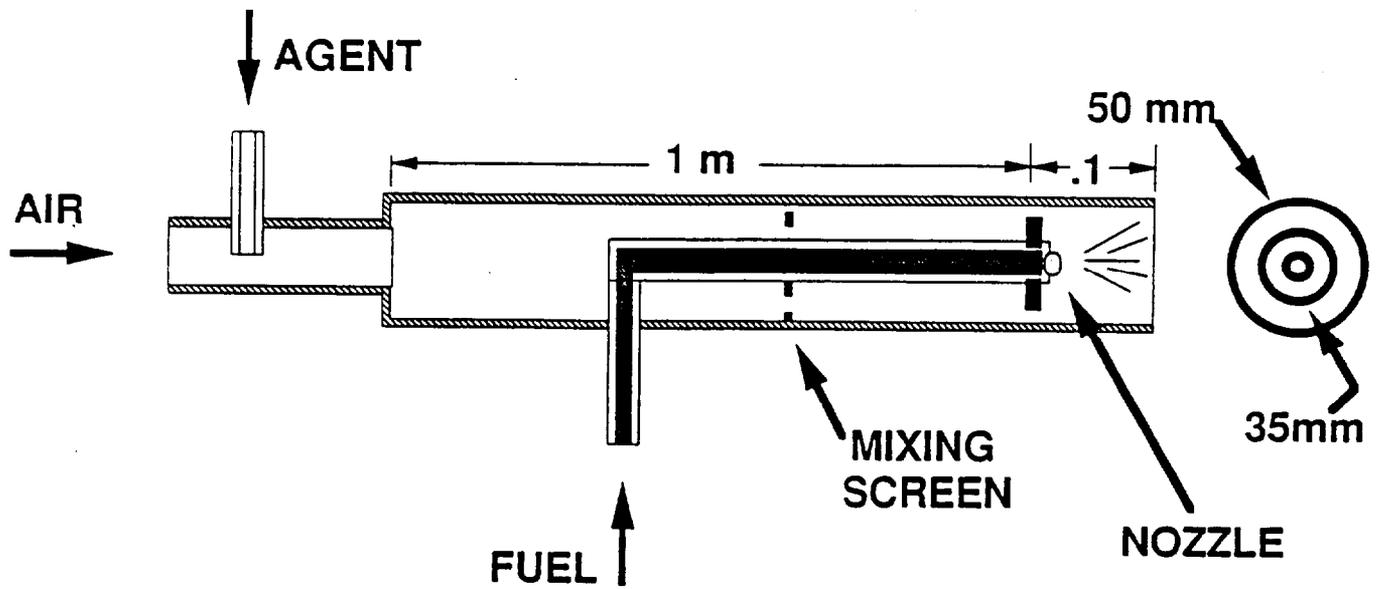


FIGURE 1. CROSS-SECTIONAL VIEW OF TURBULENT SPRAY BURNER

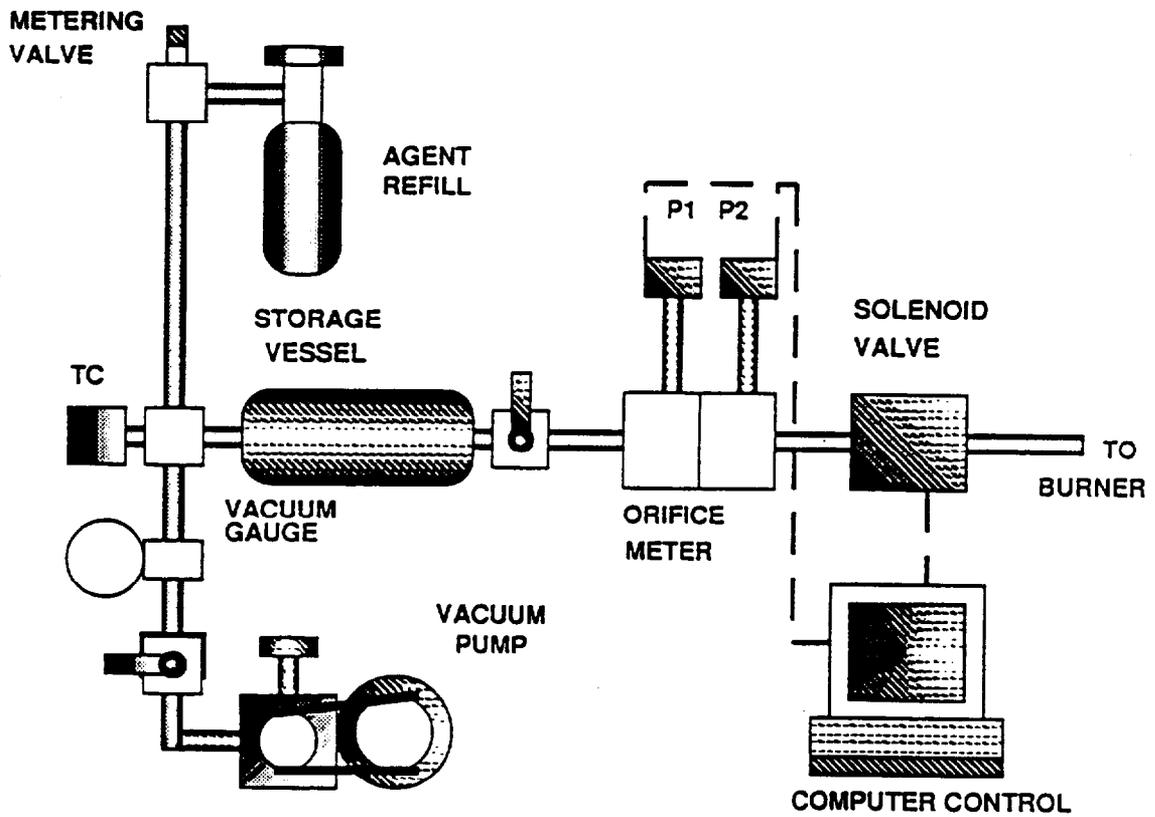


FIGURE 2. SCHEMATIC OF GASEOUS AGENT INJECTION SYSTEM

flow, and system temperature, as well as the agent concentration and properties.

A coaxial turbulent burner is used to simulate an idealized engine nacelle fire. The fuel, JP-8, is injected along the centerline of the stainless steel burner through a pressure-jet nozzle that forms a 45° solid-cone spray. The nozzle delivers 0.5 ml/s when the gauge pressure is 687 kPa. Air at atmospheric pressure co-flows around the nozzle passage within an annular region which has an outer diameter of 50 mm. The exit of the nozzle is flush with the open end of the surrounding steel casing. A pyrex tube with a 52 mm inner diameter contains the flame for 75 mm beyond the nozzle. The horizontal flame is stabilized on a 35 mm diameter steel disk attached to the nozzle body. Figure 1 presents a cross-sectional view of the burner. The air flow is monitored with a critical orifice meter, yielding mean air velocities from 5 to 33 m/s. The inlet temperature can be varied between ambient and 150 °C by electrically heating the air from the compressor. The temperature is monitored one meter upstream of the burner exit.

The gaseous agents are injected impulsively into the air stream and dispersed uniformly across the tube before they reach the flame. Prior to an experiment, the agent is transferred as a gas to an evacuated one liter chamber and pressurized to between 39 and 687 kPa(g). At the desired moment, a computer controlled solenoid valve is opened and the agent flows into the air stream through two separate passages to reduce the pressure drop and increase mixing. The flow is determined by measuring the instantaneous pressure drop through an orifice (4.8 or 6.4 mm diameter). This flow can be compared to the mass computed from the Redlich-Kwong equation of state (Van Wylen and Sonntag, 1978) and the change in pressure inside the storage vessel. A schematic of the injection system is shown in Fig. 2. The amount of agent to be injected is controlled by varying the initial gauge pressure and the period of time (13 to 910 ms) that the solenoid valve remains open. Uniform dispersion across the combustion chamber is achieved by passing the agent/air mixture through mixing screens before it encounters the stabilized spray flame.

CHARACTERIZATION OF FACILITY

The air and fuel flows were varied to ascertain how the flame stability was affected by the operating conditions. The fuel pressure was fixed at 687 ± 10 kPa (corresponding to a mass flow rate of around 0.42 g/s). The spray was ignited with a propane torch at a minimum air flow. The flame extended well beyond the exit of the pyrex tube and was highly luminous under these conditions. As the air flow increased, the flame attached itself to the stabilizing disk and the plume length decreased until the flame was stationed mostly within the tube passage. At high air flows little soot radiation was observed beyond the exit plane, although the flame itself maintained some luminosity. A moderate amount of soot formed on the nozzle face in a matter of minutes. A stable flame was sustainable until the air flow rate exceeded 73 g/s. The average velocity across the air duct was about 33 m/s at this mass flow, which translates to an estimated residence time in the recirculation zone of 5 ms.

The blowout experiment was repeated for fuel nozzle pressures

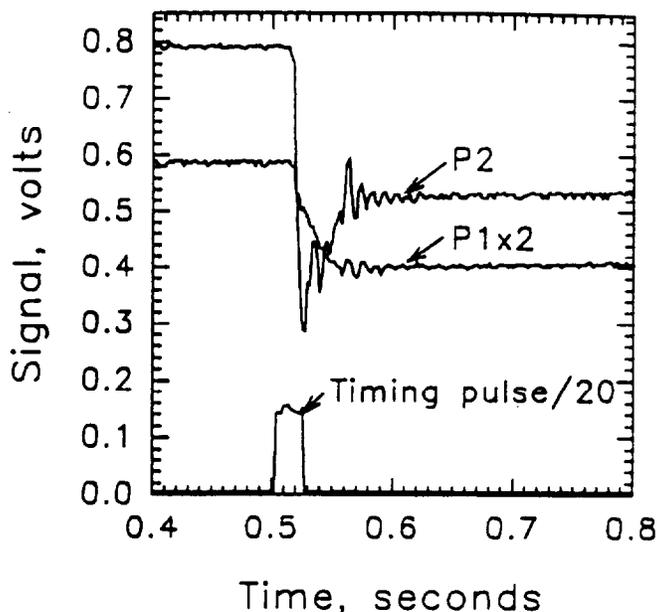


FIGURE 3. TYPICAL PRESSURE RESPONSE DURING INJECTION. TIME IS SET TO 18 MS

of 515 and 858 kPa. At the reduced pressure the fuel flow rate decreased by about 14%, which resulted in an equivalent decrease in the amount of air necessary to extinguish the flame. The higher nozzle pressure had no appreciable effect on the blowout limit.

The operating conditions chosen for baseline measurements were a fuel line pressure of 687 kPa (0.42 g/s) and an air flow of 33 g/s, resulting in an average inlet velocity of 14 m/s. This produced an 18 kW flame with an overall equivalence ratio of about 0.17.

The injection system, under idealized conditions (incompressible flow, massless valves, no pressure losses), was designed to deliver a square-wave pulse of agent to the burner for the amount of time programmed by the computer control. The actual flow deviated substantially from this scenario. There was about a 15 ms delay between when the solenoid was triggered and the flow of the agent actually began. When the valve started to close, pressure waves were created which reverberated in the injection system at the acoustic velocity, causing the flow rate to modulate.

Figure 3 presents the voltage from the pressure transducers obtained during the discharge of nitrogen. The trace marked P1 is the pressure (343 kPa/volt) measured in the storage vessel; P2 is the pressure (137 kPa/volt) measured just before the solenoid valve and downstream of the metering orifice (see Fig. 2). The timing pulse for controlling the solenoid, which was set to open at 0.5 s and to close 18 ms later, is also plotted in the figure. Pressure P2 begins to drop at 0.515 ms; P1 responds a few milliseconds later and records a gradual, monotonic decrease in voltage with time. The pressure (P2) measured downstream of the 6.4 mm orifice drops quickly and then fluctuates through a

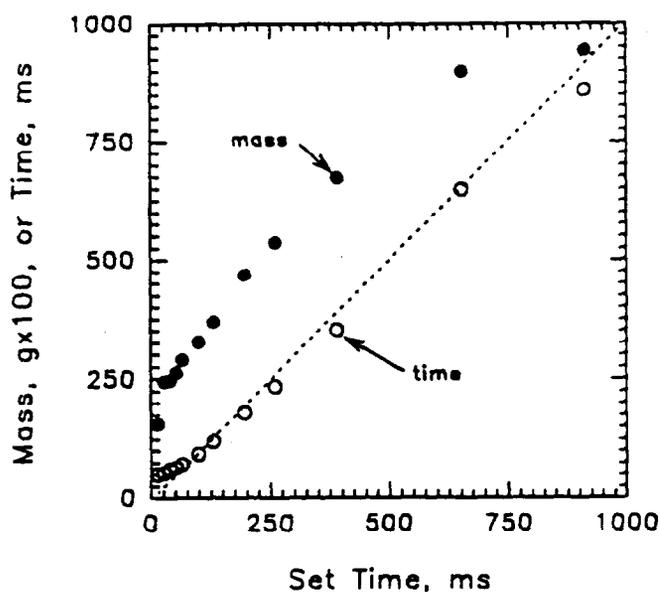


FIGURE 4. TIME OF PRESSURE TRANSIENT (OPEN CIRCLES) AND MASS OF AIR DELIVERED BY INJECTION SYSTEM (SOLID CIRCLES) AS A FUNCTION OF SET TIME. INITIAL PRESSURE IS 687 KPA-G.

number of acoustic oscillations. The precise point where the flow stops is difficult to discern, but by extrapolating backwards in time from the final pressure measured by P1 it is possible to estimate when the mass flow becomes negligibly small.

The mass of agent, m , in the storage vessel of volume V , pressure P , and temperature T is determined from the Redlich-Kwong equation of state,

$$m = \frac{PVM}{RT} \left[\frac{1}{1-b/v} - \frac{a/(vRT^{3/2})}{1+b/v} \right]^{-1} \quad (1)$$

M is the molecular weight of the gaseous agent, R is the gas constant, v is the volume (1040 ml) per unit mass of the agent, and a and b are constants dependent upon the critical properties of the agent (Van Wylen and Sonntag, 1978). The initial temperature is measured, and the final temperature is determined by assuming the expansion occurs isentropically following the relation

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

Gamma is the specific heat ratio for the gas. Thus, by measuring the change in pressure, equation (1) can be used in an iterative fashion to determine the total amount of mass injected into the burner. Equation (2) assumes the gas is ideal. (From equation (1) the deviation from ideal behavior is found to be a maximum of 7% for the agents in Table 1.) The pressure data are collected

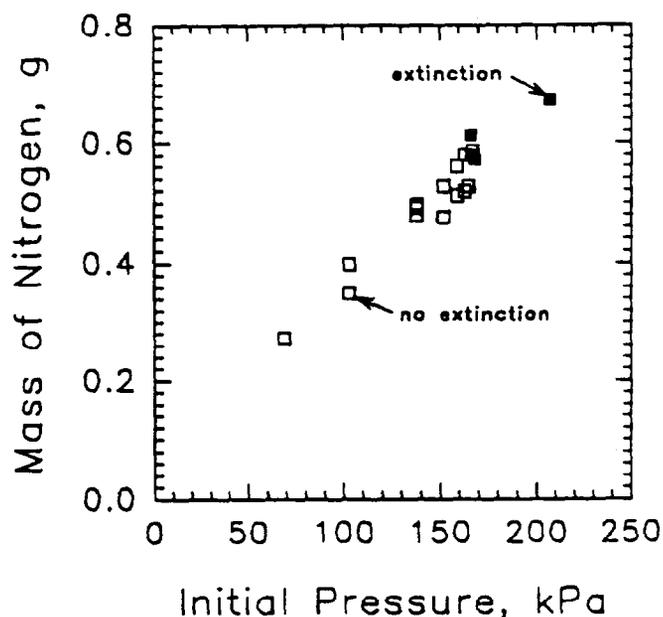


FIGURE 5. EFFECT OF VESSEL PRESSURE ON EXTINGUISHMENT OF JP-8 SPRAY FLAME BY NITROGEN. SOLID SYMBOLS INDICATE EXTINGUISHMENT; OPEN CIRCLES INDICATE NO EXTINGUISHMENT.

at a rate of 500 to 700 Hz, with the initial and final conditions found from the average of at least 100 points measured one-half second prior to the release of the agent, and one second after the solenoid valve closes, respectively. The uncertainty in the total mass calculated is estimated to be less than $\pm 8\%$.

The storage vessel was pressurized with air to 687 kPa (g), and the solenoid valve was opened for successively longer periods of time, up to a maximum of 910 ms. Figure 4 presents the cumulative increase in mass with the set time. The results indicate that the mass of air (solid symbols) increases close to linearly with time in the range between about 25 and 250 ms. For short time settings, much less mass is delivered because the valve does not have sufficient time to fully open. The deviation from linear behavior when the valve is open for a long period results from the entire mass (10 g) contained in the injector storage vessel becoming depleted. Figure 4 also presents the time over which the pressure decreases in the vessel. There is a minimum time for the solenoid valve to respond due to inertia, which explains the greater measured time for settings below 25 ms.

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

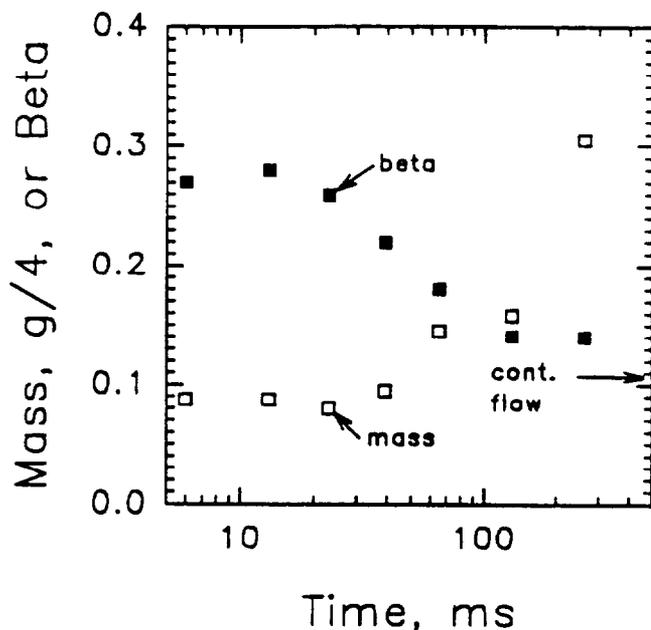


FIGURE 6. EFFECT OF INJECTION TIME INTERVAL ON MASS OF NITROGEN (OPEN SQUARES) REQUIRED TO EXTINGUISH JP-8 SPRAY FLAME. SOLID SQUARES: β .

EXPERIMENTAL RESULTS

A figure of merit for extinguishing the flame, β , can be defined in terms of the agent and air flows:

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

where the i subscript refers to the mass flow of the agent. A small value for β is desirable. The mass of agent added to the flame is determined from equation (1), and the actual time interval of agent injection into the burner is estimated from the aforementioned pressure trace. The influence of air velocity, injection period, and injection pressure on the amount of N_2 required to extinguish a JP-8 spray flame and on the value of β was investigated as a means to validate the operation of the experimental facility.

Effect of air velocity

The storage vessel was pressurized with nitrogen to 113 kPa and the turbulent burner set to baseline conditions (mass flow of air equal to 33 g/s, nominal air velocity of 14 m/s). The fuel flow rate was kept constant at 0.42 g/s. The injection interval was increased one millisecond at a time until the flame was extinguished. Flame extinguishment occurred between 23 and 26 ms for five different runs, delivering 0.33 ± 0.03 g of nitrogen at an average rate of 11.2 ± 0.5 g/s. From equation (3), the figure of merit is calculated to vary between 0.24 and 0.26. This compares to a figure of merit for nitrogen of 0.28 as measured by Hamins (1992) in the NIST cup burner apparatus with JP-8 as the fuel.

Additional experiments were carried out for air flows of 44 g/s (19 m/s) and 22 g/s (10 m/s). The high velocity required an average total mass and flow of 0.29 g and 11.5 g/s, respectively. The amount of nitrogen required to extinguish the lower air velocity flame was 0.32 g, with an average flow of 10.7 g/s. In this case, doubling the air flow reduced the mass of nitrogen required by 10%. If one calculates a figure of merit using equation (3), the high air flow condition yields $\beta = 0.21$ and the low air flow yields $\beta = 0.33$.

Effect of injection time and nitrogen pressure

A series of experiments were carried out with the air and fuel flow rates at baseline conditions, and the time interval was fixed as the nitrogen pressure was increased. Figure 5 is a plot of the mass of nitrogen delivered to the burner as a function of initial vessel pressure for an injection interval set to 65 ms. The open squares indicate that the flame remained lit; the solid squares correspond to successful extinguishments. The minimum vessel pressure necessary to extinguish the flame 100% of the time can be seen to occur at 167 kPa. The amount of nitrogen resulting from this pressure and time interval is 0.58 ± 0.03 g.

The injection time interval has an effect on the minimum amount of nitrogen required to extinguish the flame. The open squares plotted in Figure 6 show this effect. For these experiments, the pressure was fixed 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, as can be seen in Fig. 4, the actual period of injection does not change appreciably. Injection times longer than 23 ms lead to greater amounts of N_2 , with more than three times as much required when the injection time is set to 260 ms. A limit is reached at long time intervals where the transient mass addition is insufficient to extinguish the flame.

Nitrogen was allowed to flow continuously in one experiment, with the rate increasing until the flame was extinguished. The figure of merit was found from equation (3) to be 0.11, and is indicated by the continuous flow line in Fig. 6. This compares to a value of 0.28 found in the NIST cup burner with the same fuel/agent combination. The lesser amount of nitrogen required for the spray flame is the result of the much higher turbulence level and reduced time available for the combustion to occur. The solid squares also plotted in the figure are the values of β corresponding to the different injection time intervals. As the time is shortened, β increases, reaching a limiting value of about 0.28. (It is a coincidence that this is identical to the value of β measured in the cup burner.)

If the value of β were the sole criteria for evaluating an extinguishing strategy, one would choose to inject the agent over an extended period of time. However, as seen in Fig. 6 this will have the undesirable effect of greatly increasing the amount of agent required to put out the flame. For an agent which is to be used in a transient manner, then, 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 for a total flooding agent.

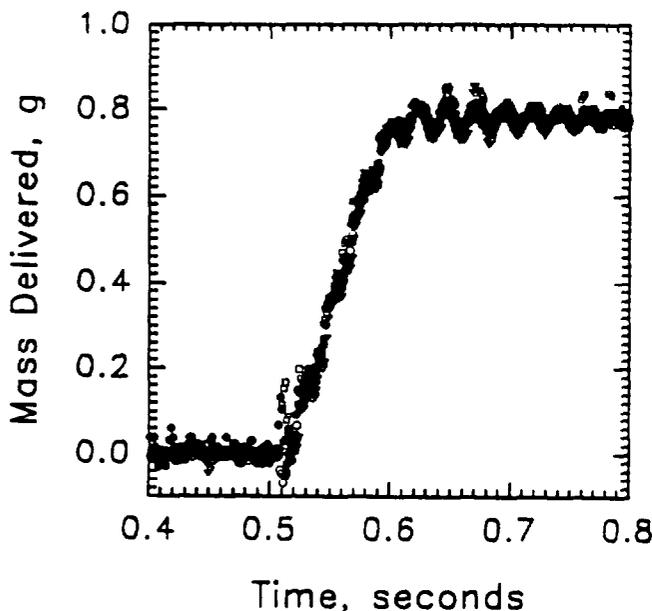


FIGURE 7. REPEATABILITY OF MASS DELIVERY SYSTEM FOR SIX SUCCESSFUL EXTINCTIONS OF JP-8 SPRAY FLAME WITH HFC-236FA.

Effect of agent

Table 1 lists eleven different hydro-chloro-fluorocarbons which were evaluated. Initial tests with the HCFCs indicated that a much lower vessel pressure was needed to extinguish the flame than had been the case with nitrogen. As a result, the 6.4 mm orifice was replaced with a 4.8 mm orifice so that the percent uncertainty in the pressure change measurement could be reduced. Figure 7 is a plot of the mass delivered to the burner as a function of time for six different experiments where the mass of the agent, HFC-236fa, was just above the extinction threshold. The average mass injected was 0.78 g with a range of ± 0.02 g. The initial pressure needed to cause extinction was 153 ± 2 kPa-a, and the calculated injection interval was 80 ± 8 ms, as compared to the set time of 65 ms.

The performance of nitrogen, a substance which is considered chemically inert during suppression, and CF_3Br , a chemically active agent, was compared using the smaller orifice and a nominal injection time of 65 ms. This value is intermediate between the estimated residence time in the flame (5 ms) and a typical time interval for injection in an actual engine nacelle (500 ms). Under these conditions, 0.58 ± 0.03 g nitrogen is needed to extinguish the flame. A mass of 0.44 g of halon 1301 is sufficient to extinguish the flame under the identical conditions.

The results from all of the chemicals examined are summarized in Table 3. As expected, none of the HCFCs are as effective as halon 1301. On a mass basis, HCFC-22 requires the least amount (0.65 g) and FC-31-10 requires the greatest (1.00 g). The nitrogen required is 32% more than halon 1301, and 11% less than HCFC-22.

In an airplane, the storage volume is as important as the mass

Table 3. Summary of JP-8 spray flame results

Agent	Mass (g)	Volume (ml)	β (spray)	β (cup)
Halon 1301	0.44	0.60	0.15	0.14
Nitrogen	0.58	1.86	0.18	0.28
HCFC-22	0.65	1.24	0.20	0.28
HFC-32/125	0.71	1.48	0.22	0.30
HFC-125	0.73	—	0.22	0.28
HCFC-124	0.74	1.31	0.22	0.26
FC-116	0.75	1.21	0.22	0.28
HFC-134A	0.76	1.50	0.24	0.28
HFC-236FA	0.78	—	0.23	—
HFC-227	0.80	—	0.24	0.27
FC-218	0.89	1.42	0.24	0.29
FC-318	0.97	1.57	0.25	0.31
FC-31-10	1.00	1.65	0.27	0.30

of the agent. Based upon the mass required and the critical specific volumes (listed in Table 1), the volume of halon 1301 needed to extinguish the JP-8 spray flame is 0.60 ml; the volume of nitrogen is more than three times larger. The volume of the alternative agents varies from twice that of halon 1301 for the FC-116 to 2.75 times the volume of halon 1301 for FC-31-10. (Critical specific volume data could not be located for HFC-125, HFC-227, or HFC-236fa.)

A figure of merit based upon the mass fraction at extinction, β (± 0.01), is listed for each compound in the same table. The ranking based upon β is similar to the ranking based upon mass. Results from the NIST cup burner are included for comparison. Except for halon 1301, β measured in the spray burner is less than β measured in the cup burner, with the performance of nitrogen improving to a much greater extent than that of the HCFCs. The relatively poorer behavior of halon 1301 in the jet burner is thought to be due to the decreased residence time in the flame, such that the bromine has less opportunity to scavenge the chain carrying radicals.

CONCLUSION

It is concluded that the turbulent spray burner is suitable for comparing the performance of gaseous extinguishing agents in transient operation. The facility is not overly sensitive to the air or fuel flows, and the agent delivery system is able to control accurately the injection period between 25 and 910 ms.

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 eleven alternative compounds evaluated in the turbulent spray burner, HCFC-22 required the least mass to extinguish the flame

and FC-31-10 required the most. None of the HCFCs performed as well as nitrogen on this basis. On a volume basis, however, nitrogen was the poorest performer. Of the alternatives being considered for near term replacement of halon 1301, FC-31-10 required the largest volume; FC-116 required the least.

The alternative agents all performed better in the turbulent spray burner relative to halon 1301 than would be predicted from cup burner measurements. None of them stand out so much better than the rest on both a volume and mass basis to suggest an obvious choice. The information gained from the turbulent burner measurements must be integrated with the results of the other bench scale experiments before the best alternatives for full scale testing can be identified.

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REFERENCES

- Anderson, S.G., 1987, "Halons and the Stratospheric Ozone Issue," *Fire Journal*, 81, pp. 56-62, 118-125, May/June.
- Booth, K., Melia, B.J., and Hirst, R., 1973, "Critical Concentration Measurements for Flame Extinguishment Using a Laboratory 'Cup Burner' Apparatus," ICI Mond Division, Wilmington Laboratory, August 31.
- Gann, R.G., Barnes, J.D., Davis, S., Harris, J.S., Harris, R.H., Herron, J.T., Levin, B.C., Mopsik, F.I., Notarianni, K.A., Nyden, M.R., Paabo, M., and Ricker, R.E., 1990, "Preliminary Screening Procedures and Criteria for Replacements for Halon 1211 and 1301," NIST Technical Note 1278, August.
- Hamins, A., 1992, personal communication, November.
- Harrington, J.L., 1993, "The Halon Phaseout Speeds Up," *NFPA Journal*, 87, no. 2, pp. 38-42, March/April.
- Peraldi, O., Knystautus, R., and Lee, J.H., 1986, "Criteria for Transition to Detonation in Tubes," *Twenty-first Symposium (International) on Combustion*, The Combustion Institute, pp. 1629-1637.
- Pitts, W.M., Nyden, M.R., Gann, R.G., Mallard, W.G., and Tsang, W., 1990, "Construction of an Exploratory List of Chemicals to Initiate the Search for Halon Alternatives," NIST Technical Note 1279, August.
- Seshadri, K., 1977, "Studies of Flame Extinction," Ph.D. Dissertation, University of California at San Diego.
- Sheinson, R.S., Penner-Hahn, J.E., and Indritz, D., 1989, "The Physical and Chemical Action of Fire Suppressants," *Fire Safety Journal* 15, 437-450.
- Van Wylen, G.J., and Sonntag, R.E., 1978, *Fundamentals of Classical Thermodynamics*, Second Edition, John Wiley and Sons, p. 400.