SUPPRESSANT PERFORMANCE EVALUATION IN A BAFFLE-STABILIZED POOL FIRE

William Grosshandler and Michelle Donnelly
Building and Fire Research Laboratory
National Institute of Standards and Technology
Gaithersburg, MD 20899 USA

Rao Charagundla and Cary Presser
Chemical Sciences and Technology Laboratory
National Institute of Standards and Technology
Gaithersburg, MD 20899 USA

INTRODUCTION

The amount of a gaseous agent required to extinguish fires in full-scale engine nacelles varies greatly with the geometry of the test fixture and the manner in which the flame is stabilized. It has been observed that if the test is designed to allow fuel to collect behind obstacles in the vicinity of a hot surface, a significantly higher mass of agent is necessary for sustained suppression. The superior performance of chemically acting agents, such as CF_3Br and CF_3I, relative to a hydrofluorocarbon alternative like HFC-125 is also accentuated in some of these tests. Full-scale testing carried out by the Navy using two different fixtures, each meant to simulate fires in the F/A-18 engine nacelle, has led to different conclusions regarding the amount and relative performance of both HFC-125 and solid propellant gas generator (SPGG) fire suppressants.

The complexity and unpredictability of full-scale tests can be traced to two factors: flame stabilization and agent mixing. Flame stability is governed by local geometry, surface temperature, and fuel and air flow patterns. Flame extinction will occur if the agent is entrained into the flame zone in sufficient concentration, if the fuel and air flows are disrupted enough by the agent discharge process, or by a combination of the two effects. Entrainment and localized flame stretch are, in turn, controlled by the way the fire suppression system is designed and by the location of the fire relative to the discharge nozzle.

Hirst and Sutton [1] developed a wind tunnel to explore the impact of step height, air flow, and pressure on the blow-out of a jet fuel pool fire stabilized behind a backward facing step. Hirst et al. [2] studied the suppression of these types of fires using various halons, and concluded that a liquid pool burning in a flow behind an obstacle is the most difficult fire to extinguish. This was born out in full-scale tests done later [3]. Experiments by Hamins et al. [4], in cooperation with Walter-Kidde Aerospace, were conducted in a wind tunnel scaled down from the earlier work by Hirst to examine the performance of HFC-125 and HFC-227ea. Investigations at the Air Force Research Laboratory [5] as part of the Next-Generation Program (NGP) sought to determine the detailed structure, during suppression, of a non-premixed methane/air flame stabilized behind a step. The changing character of the flame with step height and air velocity was examined, along with the amount of Halon 1301 required to suppress the flame as a function of the flow parameters and injection interval.

A turbulent spray burner was designed in earlier work at NIST [6] to simulate an engine nacelle spray fire resulting from a ruptured fuel or hydraulic fluid line. In this apparatus, the agent release and mixing process were well controlled, and the air flow was maintained constant with a sonic orifice. This arrangement allowed the agent to be discharged without disrupting the incoming air. The turbulent spray burner was used with both gaseous and powdered agents. Hamins et al. [4] redesigned the burner to include a heated disk in the center of the flow down-

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stream of the fuel nozzle. They showed that the concentration of nitrogen necessary to extinguish a turbulent propane flame increased substantially with surface temperature. The same trend, but to a lesser degree, was observed with hydrofluorocarbons.

A transient application, recirculating pool fire (TARPF) suppression facility has been developed in the current study to screen different agents and prototype systems, and as an indicator of full-scale performance. The TARPF agent suppression screen is designed to reproduce the most difficult fire situation and to allow control of critical agent discharge parameters, including agent discharge rate and duration, and air flow. The performance of powders, gases, and solid-propellant gas generators (SPGGs) can be examined; relationships between the mass of agent necessary for sustained suppression, and agent injection duration, temperature of a hot surface, and obstacle geometry can be explored.

EXPERIMENTAL FACILITY

The TARPF is a small wind tunnel consisting of a number of sections (Figure1). The main portion is 2.5 m long with a square cross section 92 mm on a side. Air, supplied by a compressor rated for a maximum flow of 180 g/s at 1.0 MPa, can be delivered to the tunnel at nominal speeds up to 17 m/sec. Flow is monitored using a calibrated sonic orifice and a piezoelectric pressure transducer. A heater is available to increase the inlet air temperature to above 200 °C. A honeycomb flow straightener and mixing screens are located a meter upstream of the test section. The burner consists of a sintered bronze plate, 92 mm wide by 190 mm long. Propane is the fuel used in the current study, but plans include the capability to burn JP-8. Stainless steel baffles between 10 and 55 mm high are located upstream of the burner. A ramp can also be inserted to form a backward-facing step (Figure 1). Heat release rates assuming complete combustion are up to 10 kW. The flame is viewed from above and the side through 6 mm thick glass windows.

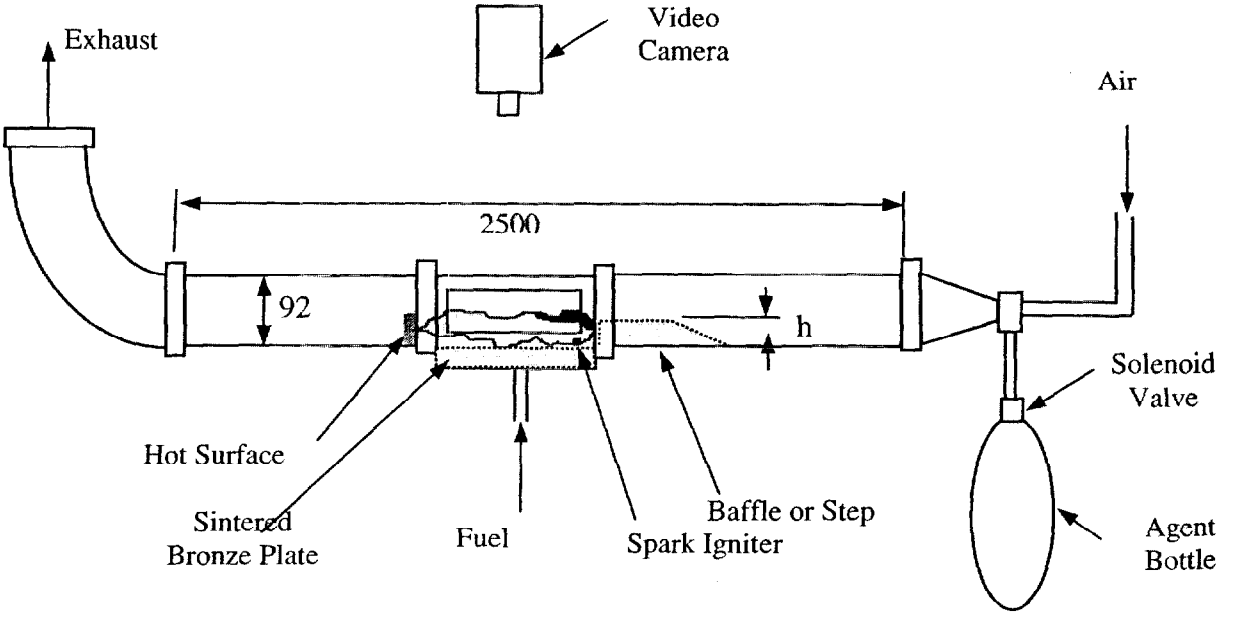

Figure 1. Schematic of TARPF facility.

Ignition is with a spark plug located on the side wall of the test section, about 20 mm above the surface of the burner and downstream of the baffle. An electric strip heater 25 mm by 87 mm in area simulates a hot surface reignition point and produces average surface temperatures up to 500 EC. The strip heater can be placed in the air flow either ahead of or behind the burner. The JP-8 spray nozzle, when it is added, will be positioned to ensure that liquid fuel will impinge on the strip heater.

The fire suppressing agent is injected downstream of the air metering orifice. Since the flow is choked in the metering orifice plate, the introduction of the agent can be accomplished without altering the total air flow. This is particularly critical when trying to distinguish chemical from physical modes of extinction. Mixing of the agent with the air is facilitated by injecting the agent through two opposed radial ports into the reduced diameter entrance region.

One and/or two-liter pressure vessels are used to store the gaseous agent to be screened. The discharge rate and duration are controlled by the initial agent pressure and an electronically actuated solenoid valve. Figure 2 is a pressure trace taken during a typical nitrogen discharge. The initial pressure is set to 960 kPa with an electronically controlled metering valve located between a standard high pressure nitrogen gas bottle and the stainless steel agent bottle. The computer acquires background data on the initial state for 1 sec, at which point the electric solenoid valve is opened to allow nitrogen to enter the wind tunnel. An electronic timer closes the valve after the desired interval. Pressure and temperature in the agent bottle are measured at a frequency of 1000 Hz during the discharge process. The piezoelectric pressure transducer is able to follow the change, but the thermocouple is too slow. To determine the instantaneous mass discharge (dm/dt in Figure 2), the nitrogen is assumed to be an ideal gas with the expansion inside the bottle occurring isentropically. The measured temperature adjusts much more slowly than the theoretical value (T_{ad} in Figure 2) due to the thermal inertia of the thermocouple.

Three observations can be made from the shape of the discharge curve: (i) the discharge data are much noisier than the pressure data, because they rely on the gradient of pressure; (ii) the measured interval (about 180 msec) is longer than the 150 msec interval set in the electronic timer, due to the inertia of the solenoid valve; and (iii) the discharge rate at the start of the process is markedly higher than the average rate.

Powders with physical properties similar to sodium bicarbonate can be injected into the tunnel by pressurizing the vessel with nitrogen or air and entraining a measured amount of the powder placed in a tee at the entrance to the injection port, as was done previously in the turbulent spray burner [6]. The TARPF facility is designed to handle new propellant formulations for SPGG suppressants in quantities of about 1 g. Solid propellant gas generators of considerably higher mass may need special accommodations.

RESULTS AND DISCUSSION

The TARPF facility was operated over a range of propane and air flows to examine qualitatively the behavior of the flame and to determine conditions which lead to blow out. Blow-out can be achieved either by increasing the air flow or decreasing the propane flow. At low air velocities, a fluctuating laminar flame is anchored on the top edge of the baffle or step and extends well downstream of the porous plate. The flame is orange throughout and produces soot that quickly coats the side wall window. As the velocity increases, the flame becomes turbulent and less luminous, and the soot deposition ceases. Upon approach to blow-out, the orange color

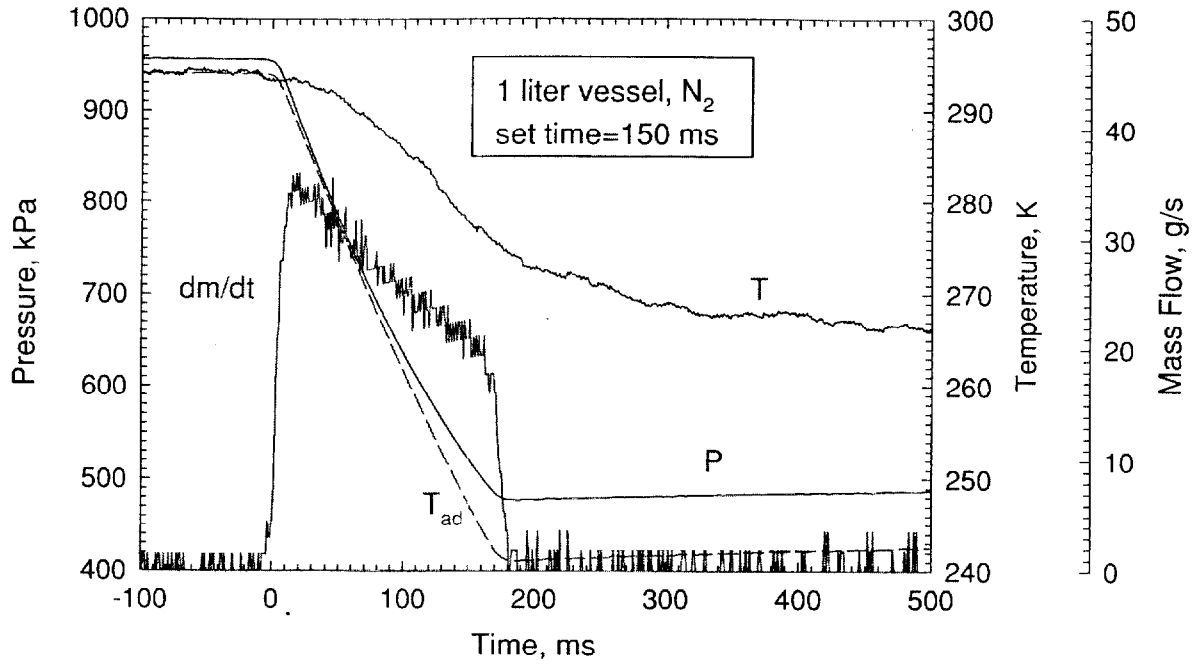

Figure 2. Measured pressure, temperature, and discharge rate of nitrogen from storage vessel. (Dotted line is theoretical agent temperature assuming adiabatic expansion.)

disappears and the visible blue flame shrinks in length to a tight eddy at the base of the obstacle. The fuel injected at the downstream portion of the burner does not fully react near blow-out because it is mixed with air beyond its flammability limit.

An average air velocity of 17 m/sec, found by dividing the volumetric flow (corrected to 101 kPa and 20 °C) by the duct inlet area (92 by 92 mm), is sufficient to blow out the flame stabilized on the 25 mm baffle if the propane flow (corrected to standard conditions) is less than 47 mL/sec. (This corresponds to a wall blowing velocity of 2.7 mm/sec). An average air velocity of 8 m/sec will extinguish a flame when the propane flow is 20 mL/sec, and less than 4 m/sec of air will blow out the flame for propane flows below 12 mL/sec.

The amount of a suppressant necessary to extinguish a baffle stabilized fire in the TARPF depends upon the fuel and air flows chosen to challenge the suppressant. Figures 3 and 4 show how the amount of nitrogen necessary to extinguish the 25 mm baffle-stabilized flame varies with the flow of air and fuel. (The filled circles in the figures indicate extinction and the crosses represent no extinction.) When the air speed is less than 5 m/sec and the fuel flow is fixed at 45 mL/sec, decreasing the speed (Figure 3) reduces the amount of nitrogen necessary to extinguish the flame. No flame extinction occurred between 5 and 15 m/sec because the amount of nitrogen necessary exceeds the maximum amount contained in the storage vessel. Above 16 m/sec, the strain on the flame is sufficient at times to extinguish the flame without the need for any nitrogen. (The dashed lines are included in the figure to assist the eye in identifying the extinction boundaries.) The propane flow does not have much affect on the amount of nitrogen needed to extinguish the flame if the injection interval and air flow are fixed (Figure 4). There is

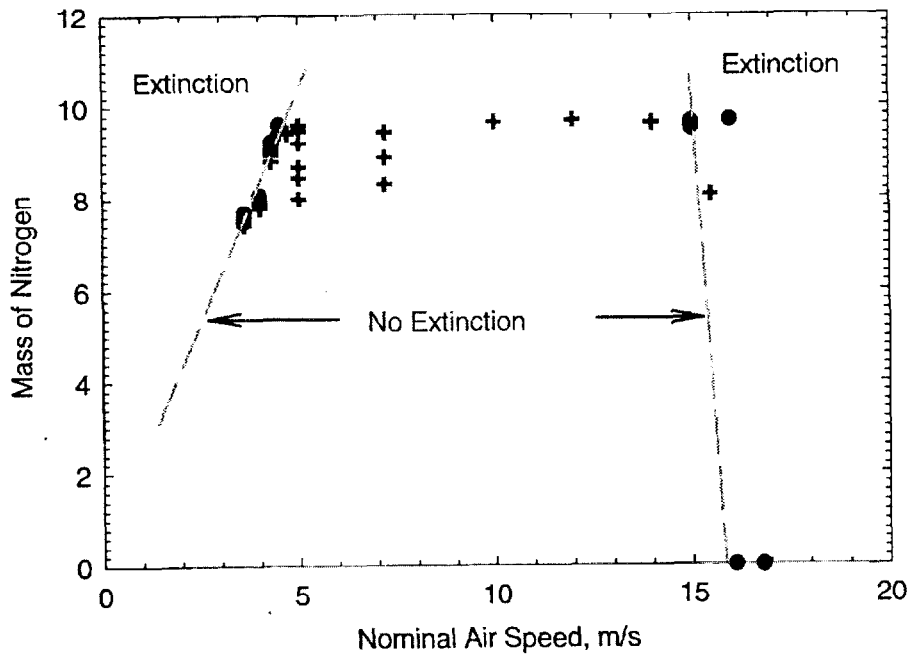

Figure 3. Impact of air speed on extinction of 25 mm baffle-stabilized flame; propane flow is 45 mL/sec, nitrogen injection time is 312 msec: circles imply extinction, crosses imply no extinction.

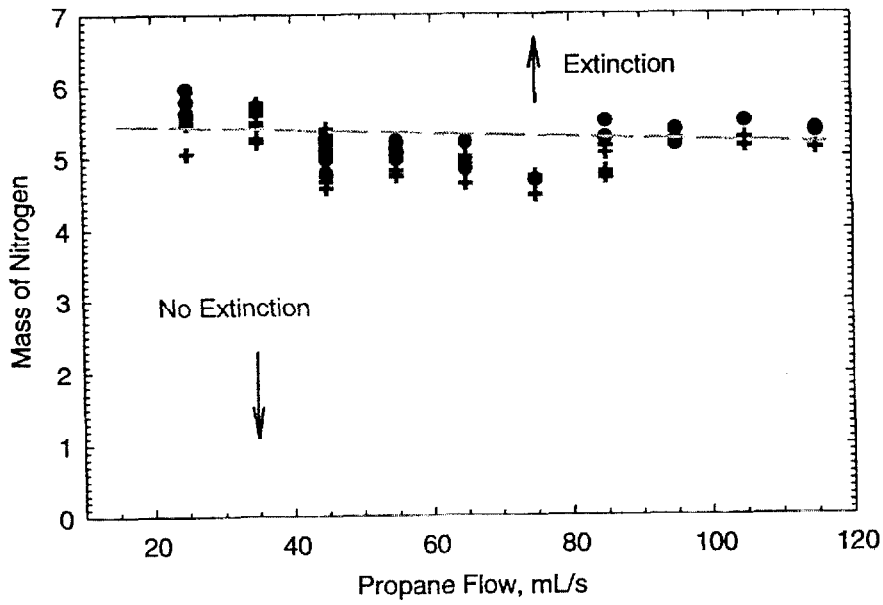

Figure 4. Impact of propane flow on N_2 required for suppression of 25 mm baffle-stabilized flame; air flow is 3.88 m/sec, injection time is 185 msec: circles imply extinction, crosses imply no extinction.

a lower limit for the propane (<12 mL/sec) that leads to extinction due to heat loss to the burner, even with no nitrogen dilution. The upper limit of propane (120 mL/sec) is dictated by the maximum safe operating temperature of the burner; however, since the mass of nitrogen needed to suppress the flame does not appear to increase, there is no need to operate the burner at higher fuel flows. (Note: The dip in mass required for propane flows around 75 mL/sec is attributed to the low number of experiments conducted in this region.)

The relationship between the total mass of nitrogen required for suppression and the injection interval is plotted in Figure 5 for a 3.88 m/sec air flow, 45 mL/sec propane flow flame stabilized on a 25 mm baffle. The open symbols are experiments that did not extinguish the flame; the closed symbols are experiments that led to extinction. (The total number of experiments conducted exceeds by a factor of 10 the number of data points plotted in this and the following curves; for clarity, only those conditions close to the extinction boundary are included.) As the interval increases from 100 to 500 msec, the minimum mass required increases over three-fold. The rate of mass addition (calculated by dividing the total mass by the estimated injection interval) decreases with increasing injection interval, as shown in the right-hand figure.

The effect of adding a ramp in front of the baffle to form a backward-facing step is examined in Figure 6. The data plotted with squares were taken at the same air flow (Figure 5); however, with a higher propane flow, 85 mL/sec. The addition of the ramp and increase in propane flow do not have much influence on the mass of nitrogen required for suppression (compare squares in Figure 6 to data in Figure 5). For both the baffle and backward step, just under 6 g of N_2 are required when the injection interval is 200 msec. The data plotted as circles in Figure 6 were taken with the nominal air speed reduced to 1.5 m/sec and the propane flow reduced a proportionate amount to 33 mL/sec. Less than 4 g of N_2 are needed to extinguish this flame if injected over a 200 msec interval. The differences in rates of mass addition to suppress the high flow (squares) and low flow (circles) flames can also be seen at the right (Figure 6). The low flow condition corresponds to what Takahashi et al. [5] describe as Regime I suppression (rim-stabilized flame), and the high flow is transitional between Regimes I and II (intermittent turbulent flame).

Figures 7 and 8 show what happens to the required nitrogen mass and addition rate if the baffle height is decreased to 10 mm or increased to 55 mm (blockage from 11 to 60%). The symbols have the same meaning as in Figure 6: squares represent experiments conducted at the high air and propane flows, and circles represent experiments conducted at the lower flows. Open symbols indicate that the flame was not extinguished, and filled symbols indicate flame extinction. The short baffle produces a fire that is the easiest to extinguish, and the high baffle the most difficult in terms of the amount and rate of N_2 addition.

The effect of baffle height is not large if the injection interval is at least 150 msec, as can be seen more clearly in Figure 9. (Note that 6 mm have been added to the height of each obstacle to account for the distance between the floor of the tunnel and the recessed top surface of the burner.) The bottom curve delineates the minimum amount of nitrogen for suppression when the air flow is fixed at its high value and the agent injection interval is maintained at 175 msec. The open circles represent the largest mass of N_2 that did not result in extinction for flames stabilized on the different sized baffles; the filled circles are the minimum mass of agent that successfully extinguished the flames. The diamonds are the results for the 25 mm baffle with the ramp in place (backward-facing step).

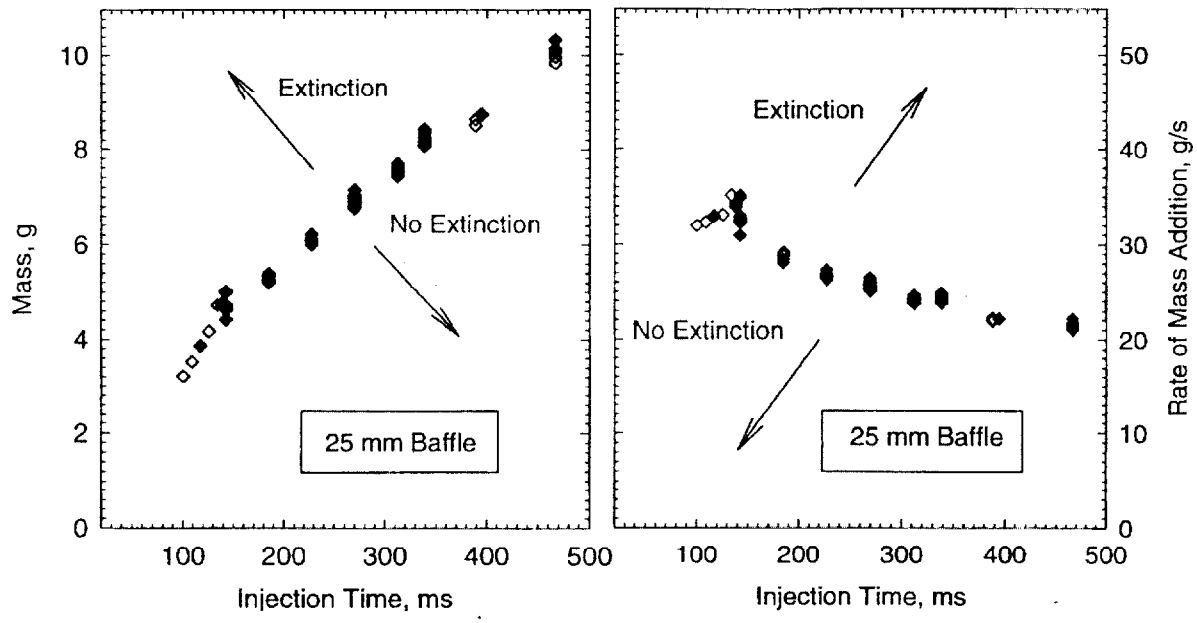

Figure 5. Mass and rate of nitrogen addition required to extinguish 3.88 m/sec air flow, 45 mL/sec propane flame: filled diamonds, extinction; open diamonds, no extinction.

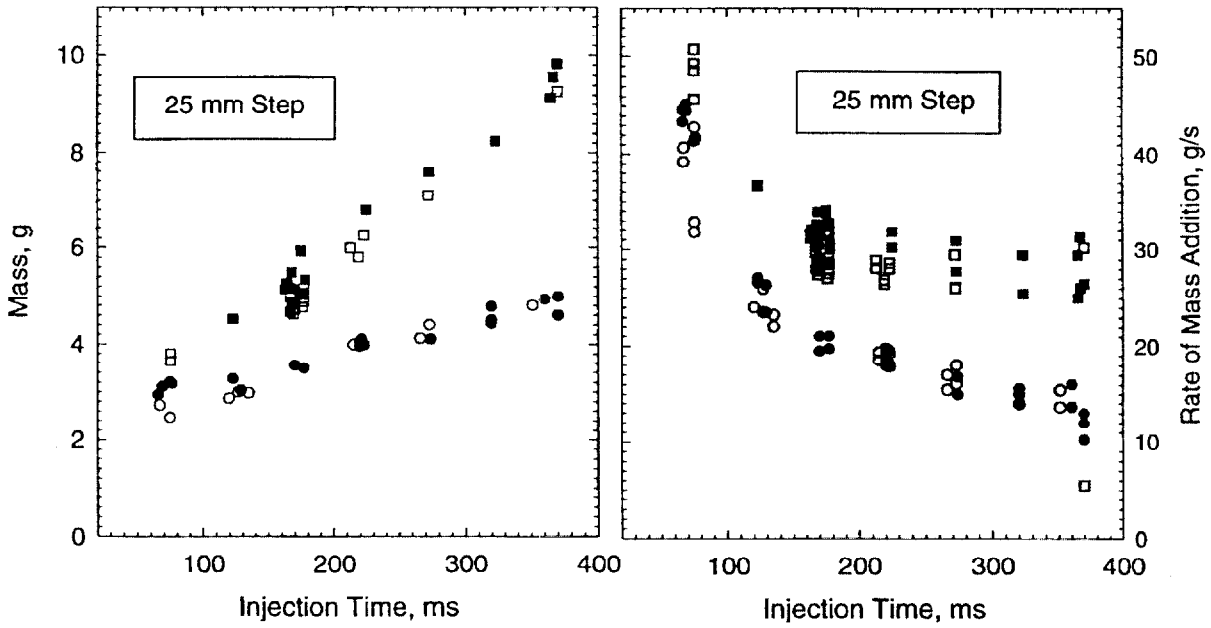

Figure 6. Mass and rate of nitrogen addition required to extinguish high flow (squares) and low flow (circles) air/propane flames: filled symbols, extinction; open symbols, no extinction.

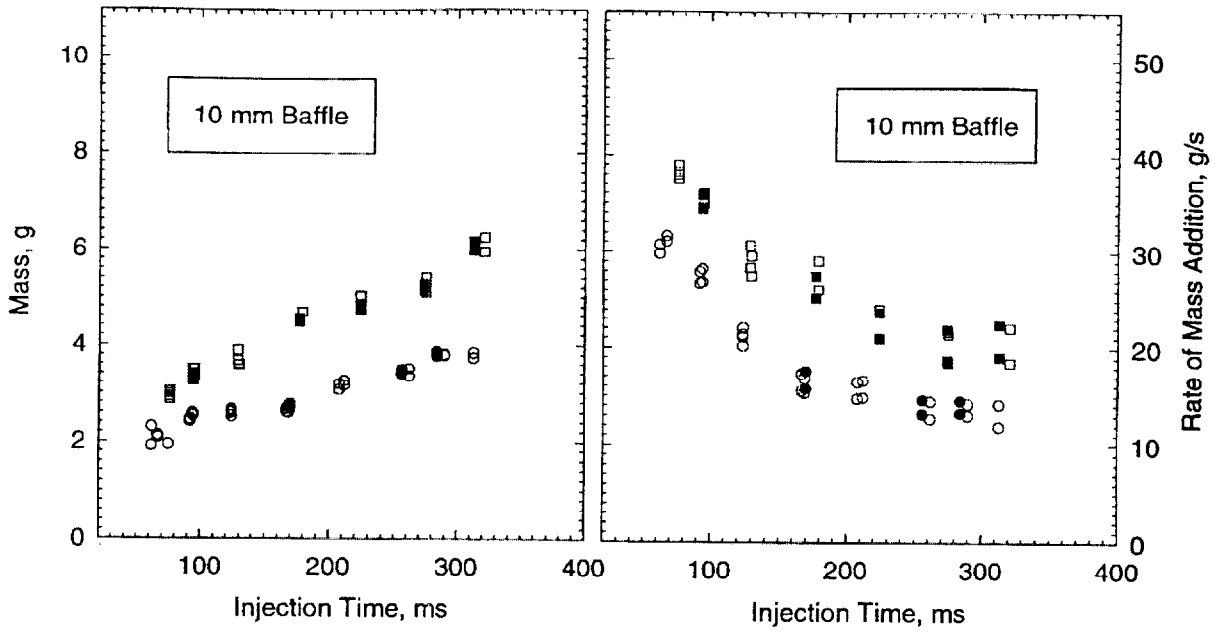

Figure 7. Mass and rate of nitrogen addition required to extinguish high flow (squares) and low flow (circles) air/propane flames: filled symbols, extinction; open symbols, no extinction.

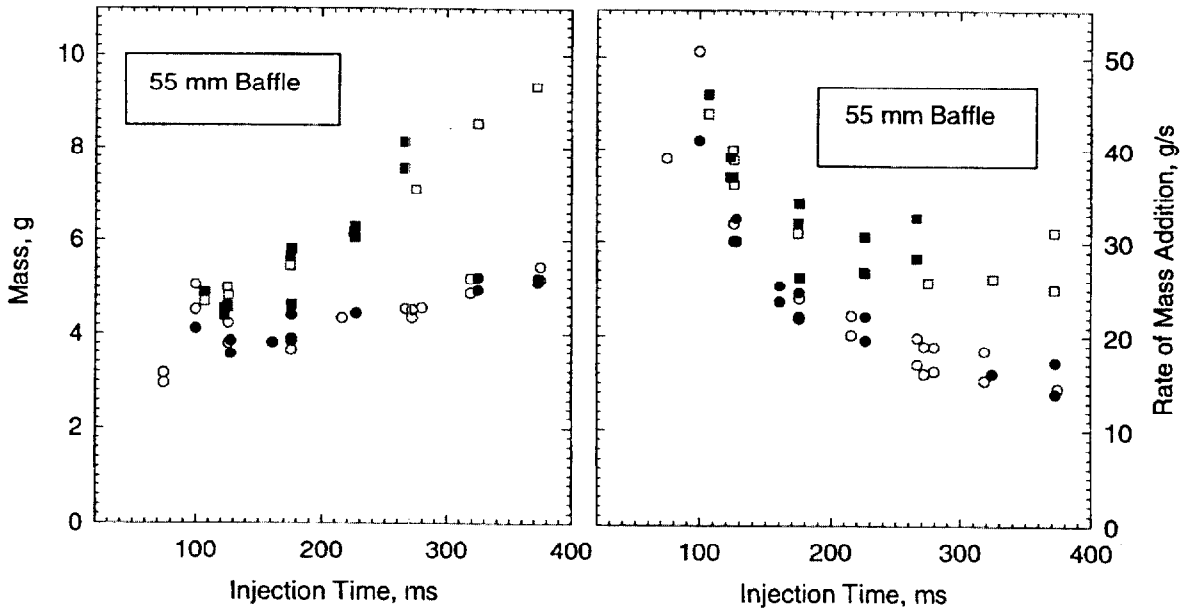

Figure 8. Mass and rate of nitrogen addition required to extinguish high flow (squares) and low flow (circles) air/propane flames: filled symbols, extinction; open symbols, no extinction.

The rate of mass addition is plotted in the upper curve (the triangles are the backward-facing step and squares are the baffles). The data are plotted two ways: the higher value is the rate of nitrogen addition computed during the first 50 msec that the solenoid valve is open (refer to the shape of the dm/dt curve in Figure 2); the lower value is the average over the entire open interval measured from the pressure trace.

Hamins et al. [4] found that for an injection duration, t, it is possible to relate β, the mass fraction of agent in the incoming stream at the extinction conditions, to τ, a characteristic time that depends upon the geometry and velocity of the flow. For premixed flames stabilized by a baffle in the middle of the flow field, the rate of agent entrainment from the free stream into the recirculation zone was suggested by Winterfeld [7] to be proportional to the ratio of the baffle size to the free stream velocity. In the current work, τ is defined as the distance from the fuel surface to the top of the obstacle (including the obstacle height, h, and the depth of recess, δ), divided by the average velocity over the obstacle while the agent is being discharged:

$$\tau = (h + \delta)/\{(V'_{air} + V'_{N2})/[(L - h)L]\} \qquad (1)$$

The velocity is written in terms of the volume flow of air and nitrogen, $V'_{air} + V'_{N2}$, divided by the area above the obstacle, (L - h)L, where L is the length of the side of the square duct. Inserting into equation (1) the range of values for flow rate and baffle height examined in the current study, τ is found to vary between about 1 msec and 10 msec. Figure 10 is a plot of agent mass fraction versus the injection time normalized by τ. The data represent air velocities from 1.5 to 3.88 m/sec, propane flows from 33 to 85 mL/sec, baffle heights between 10 and 55 mm, and a backward step geometry.

A two parameter mixing model [4] is used to correlate all of the experimental data in terms of β_∞, the minimum mass fraction of agent required for suppressing the flame at long injection intervals, and α, a parameter that relates the entrainment time to τ; namely,

$$\beta = \beta_\infty / [1 - \exp(-\alpha t/\tau)]. \qquad (2)$$

β_∞ can be found experimentally by flowing nitrogen continuously into the air stream at increasing rates until extinction occurs. If the air flow is low enough, one would expect to see a value for β_∞ close to that measured in the cup burner for propane, which was found by Hamins et al. [6] to be 0.32. When the flow of air is increased sufficiently, the flame becomes strained to the point that no additional nitrogen is needed for extinguishment (i.e., $\beta_\infty = 0$). For laminar diffusion flames strained at intermediate rates, Trees et al. [8] showed that the minimum extinction mass fraction of nitrogen in a counter-flow flame above a heptane pool drops from the cup-burner value when the strain rate is 50 sec^{-1} to about 0.10 for a strain rate of 400 sec^{-1}. While the flow in the recirculating region behind the baffle is much more complicated than in the counter-flow flame of Trees et al., the scale of the strain rate in the TARPF can be estimated from the range of $1/\tau$ to lie between 100 and 1000 sec^{-1}.

Takahashi et al. [5] used a similar approach to correlate the critical mole fraction of Halon 1301 required to suppress a methane flame behind baffles in a rectangular duct. For an air speed of 7.1 m/sec, their measurements taken with baffle heights of 32 and 64 mm collapsed to a single curve when plotted against an injection time normalized by the step height divided by the air velocity. They did not account for the velocity increase due to the agent flow, but were still able to get good results because the fraction of Halon 1301 is much smaller when compared to the

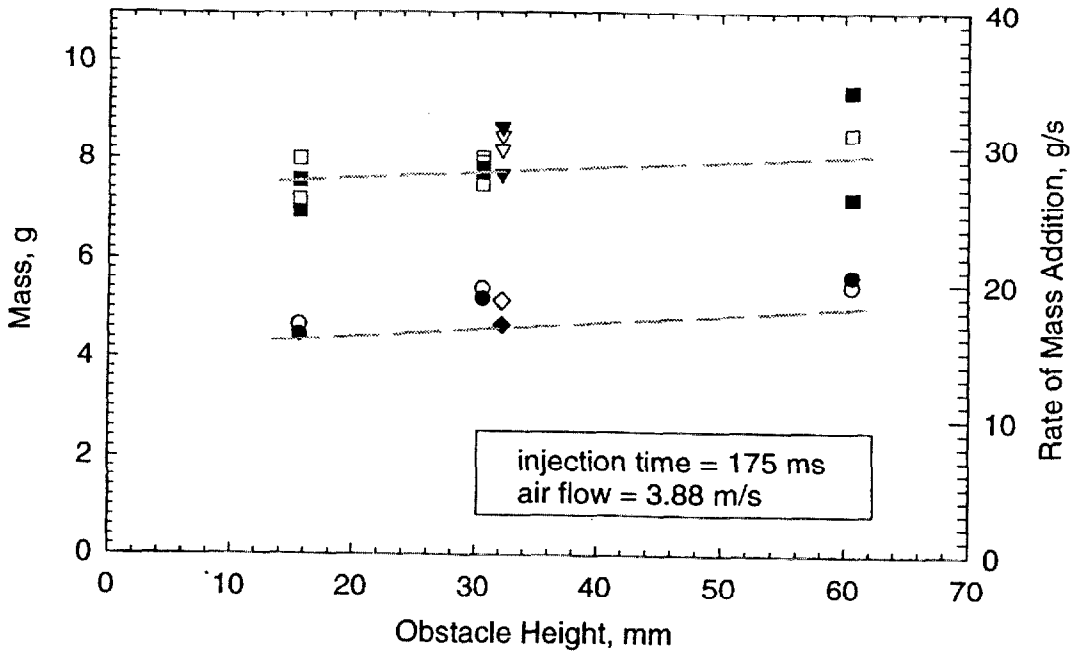

Figure 9. Impact of obstacle geometry on mass and rate of nitrogen required to extinguish propane flame. Open symbols, no extinction; filled symbols, extinction.

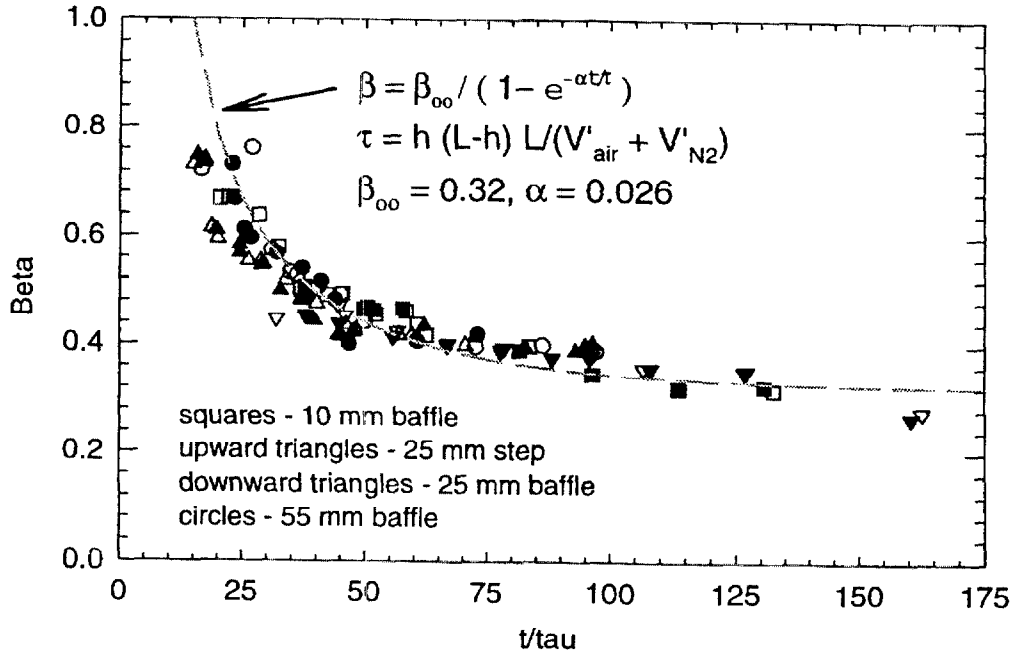

Figure 10. Unified extinguishment nitrogen mass fraction as function of nondimensional injection time. Open symbols, no extinction; filled symbols, extinction.

nitrogen flows needed in the present study. The value of β_∞ with Halon 1301 was found to be slightly less than the heptane cup-burner value. The work done by Hamins et al. [4] using HFC-125 and HFC-227ea suggests that β_∞ may be greater than the cup-burner value for low air flows and strain rates. This is consistent with the results of Dyer et al. [9] in their study using nitrogen to suppress kerosene pool fires in air streams at speeds below 0.2 m/sec.

The dashed line in Figure 10 is equation (2) with β_∞ set to 0.32 and α chosen, by inspection, to be 0.026. While the data for any particular geometry and air flow may be better fit by selecting corresponding values for β_∞ and α, the bulk of the data are well represented by the single curve. The run-to-run variation and uncertainty in the data may not warrant finer analysis, especially when one considers how ill-defined the flow and geometry are in an actual engine nacelle.

SUMMARY AND CONCLUSIONS

A transient application, recirculating pool fire (TARPF) facility has been built for screening the suppression effectiveness of Halon 1301 replacements. Initial characterization experiments were conducted with nitrogen as the suppressant. Nominal air velocities between 1 and 17 m/sec flowing over baffles that are 16 to 61 mm above the surface of a propane pool fire were examined. Two to 10 g of nitrogen injected over intervals between 50 and 700 msec are required to extinguish flames of up to 10 kW. Because the air is metered with a sonic orifice, the injection of agent does not modulate the air flow. For moderate flows of air and fuel, the amount of nitrogen for flame extinguishment is substantially and directly affected by the air velocity and the interval of injection. The height of the obstacle, whether it is a baffle or a backward facing step, and the propane blowing velocity have only a minor influence on the mass of nitrogen needed for suppression.

Halon 1301, additional gaseous agents, powders, and solid propellant gas generators will be examined in the future. The impact of spraying JP-8 onto a controlled hot surface during the suppression process also will be determined.

The ability to measure the relative effectiveness of alternative agents is key to the development of new fire suppression systems. The Next-Generation Program has the goal of identifying agents that are as effective as CF_3Br in suppressing fires in spaces currently protected with halon. The physical and chemical properties, and the manner of storage and release, of these next generation suppression systems may be quite unlike halon, but their effectiveness must be benchmarked against CF_3Br. The TARPF facility will provide the means to screen new concepts in the laboratory for applications in engine nacelles and other spaces involving baffle-stabilized pool fires with adjacent hot surfaces.

ACKNOWLEDGMENTS

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