SUPPRESSION CRITERIA IN ENGINE NACELLE FIRES

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ABSTRACT

A series of experimental measurements were conducted and simple models were developed in an effort to provide an improved understanding of the influence of various parameters on the processes controlling flame stability in engine nacelle applications. The model was constructed to predict the quantity of agent required to suppress a generic engine nacelle fire. The model was based on suppression experiments from a bench-scale turbulent jet spray burner and a pool burner, and on agent fluid mixing calculations. The experiments indicate that fire hazard is dependent on a large number of parameters including the air velocity, nacelle temperature, fuel type, and system pressure in the nacelle. The geometry of the fire configuration is critical in defining the ease of fire suppression. The model illustrates the importance of injection duration, air flow, nacelle free volume, fluid mixing, and fire scenario on the minimum agent suppression requirements.

1. Introduction

The engine nacelle encases the jet engine compressor, combustors, and turbine. A nacelle fire is typically a turbulent diffusion flame stabilized behind an obstruction in a moderately high speed air flow. The fuel source for a fire in the nacelle can be leaking pipes carrying jet fuel or hydraulic fluid, that can feed the fire either as a spray or in the form of a puddle or pool. Extinguishment occurs when a critical amount of agent is transported to the fire zone.

Because of its many positive attributes, halon 1301, or trifluorobromomethane (CF_3Br), has been used as a fire extinguishing agent for protecting aircraft engine nacelles. As halon 1301 is replaced with possibly less effective suppressants, continued effective aircraft protection becomes a challenge. Engineering design criteria for the delivery rates of alternative agents must be developed since it is not possible to perform full-scale tests on every aircraft and for every possible fire scenario. In this study, a series of experimental measurements were conducted and simple models were developed in an effort to provide an improved understanding of the influence of various parameters on the processes controlling flame stability in engine nacelles.

In the experimental studies, the effectiveness of candidate replacement agents was tested on the suppression of two baffle stabilized flame configurations, a spray flame and a pool fire. The experimental studies are summarized in a discussion that emphasizes the importance of agent entrainment into the recirculation zone of obstacle stabilized flames. The experimental data are used as input in a simple model that gives guidance on agent concentration requirements for flame suppression in generic nacelle configurations.

2. Experimental Method and Apparatus

The experimental facility used here has been described in detail (Gann, 1995). Figure 1 shows a cross-sectional view of the burner. The apparatus incorporated an air delivery system, a fuel delivery system, an agent injection system, and a combustion zone. Air co-flowed around a fuel tube within a 7.3 cm stainless steel tube. The fuel was injected along the centerline through a pressure-jet nozzle that formed a 45° solid-cone spray, typical of a simple oil furnace fuel nozzle. The flame was stabilized by a steel disk (3.5 cm diameter) attached to the body of the nozzle. A pyrex tube contained the flame beyond the outer steel casing.

The mass of agent delivered to the air stream was determined by measuring the initial temperature and the transient pressure in the vessel and using the Redlich-Kwong equation of state (Van Wylen and Sonntag, 1978). The agent temperature and pressure in the storage vessel were measured with a type-K thermocouple and a pressure transducer located upstream of the solenoid valve. The final temperature was determined by assuming that the gas expansion of agent in the vessel occurred isentropically. The pressure data were collected at a rate of 1000 Hz, with the initial and final conditions found from the average one-half second prior to the release of the agent and one-half second after the solenoid valve closed. Uniform dispersion of agent across the air stream was checked by hot film probe measurements. The amount of injected agent was controlled by varying the initial vessel pressure, the time that the solenoid valve was open and the valve opening diameter. The agent injection system under idealized conditions was designed to deliver a square-wave pulse of agent to the burner for the amount of time programmed by the computer controller.

The independent parameters which were controlled in the spray burner facility were the air flow, the agent delivery interval or injection duration, the air temperature, the system pressure, the fuel flow, and the agent temperature. The primary dependent experimental parameters were the agent mass and the rate of injection required for suppression. Extinction measurements were performed with three gaseous agents for all conditions. They were CF_3I, C_2HF_5 (HFC-125), and C_3HF_7 (HFC-227). Extinction measurements were also performed using CF_3Br (halon 1301) to establish a performance reference.

3. Experimental Results

Figure 2 shows the critical mass fraction (β) of CF_3Br and the three alternative agents at extinction as a function of air velocity for a constant injection interval equal to 700 ms. For conditions below the data points, the flames were not extinguished, whereas for conditions above the data points, the flames were extinguished. CF_3Br required the smallest mass fraction to extinguish the flames, followed by CF_3I, and the other two agents, HFC-125 and HFC-227, which were measured to have nearly identical effectiveness. As the air velocity increased from 3 m/s, ß decreased. At high air velocities, the flames were less stable and easier to extinguish, i.e. less agent was required to extinguish them. At V= 33 m/s, air with no agent addition caused flame extinction. For very low air velocities (2 m/s), ß decreased or remained nearly the same as the results for V= 3 m/s. For all agents, the values of ß for the low air velocity spray flame results are very similar to agent extinction concentrations measured in cup burner flames and in opposed flow diffusion flames (OFDF) at low (25 s^{-1}) strain rates (Hamins *et al.*, 1994). Table 1 documents the correspondence between the flame extinction measurements in the three burners. All tests were conducted with JP-8 fuel. Table 1 shows that a correspondence also exists between the critical agent mass fractions for moderate (80 s^{-1}) strain rates in the OFDF burner (Hamins *et al.*, 1994) and moderate air velocities (15 m/s) in the spray burner. The same correspondence holds for high (22.5 m/s) air velocities in the spray burner and high (175 s^{-1}) strain rates in the OFDF burner. This suggests that the same processes that control flame extinction in simple diffusion flames govern flame extinction in the baffle stabilized spray flame. The practical implication of the results shown in Table 1 is that it is not necessary to rank the suppression effectiveness of agents in every possible configuration, a single test apparatus is sufficient.

Other experiments showed that more agent mass was required to extinguish flames when the air was heated. This trend was

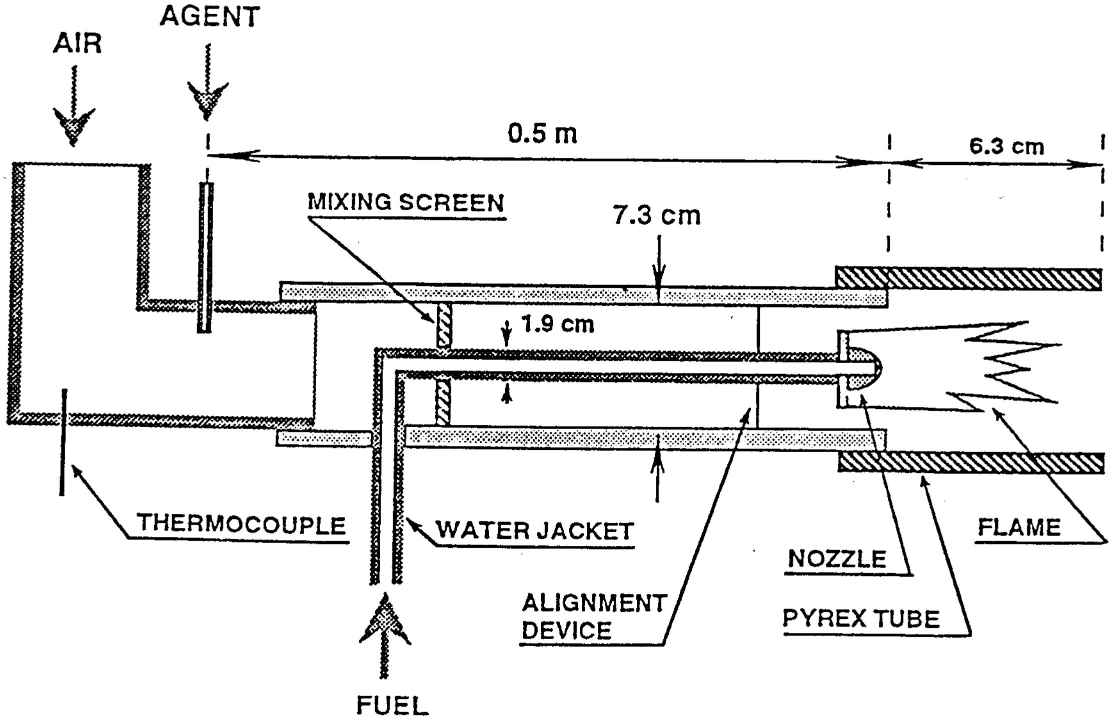

Figure 1. Schematic diagram of the baffle stabilized spray burner used for suppression testing.

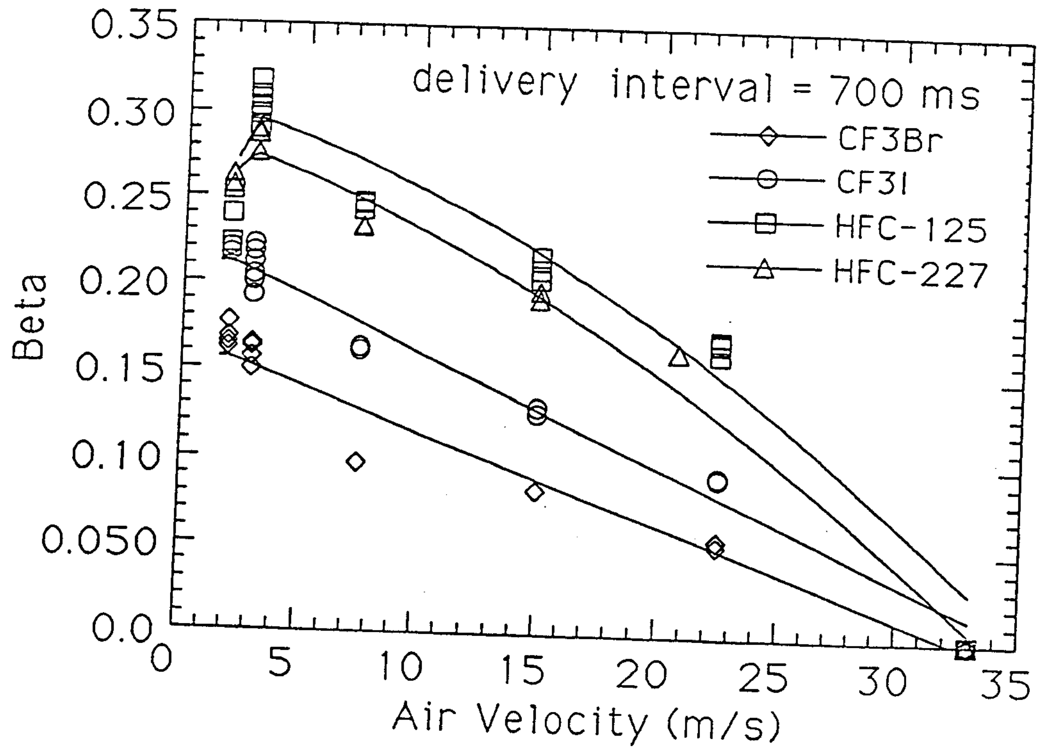

Figure 2. The critical agent mass fraction at extinction as a function of air velocity.

Table 1 Comparison of the critical agent mass fraction at extinction measured in different burners

Agent	Cup Burner	Air Velocity (m/s) in Spray Burner			Strain Rate (s^{-1}) in OFDF burner		
		3.0	15	22	25	80	175
CF_3Br	0.14	0.16	0.085	0.05	0.13	0.080	0.050
CF_3I	0.18[b]	0.21	0.13	0.09	a	a	a
HFC-125	0.28	0.30	0.21	0.17	0.28	0.22	0.16
HFC-227	0.27	0.28	0.20	0.15	0.26	0.20	0.14

a Not measured
b Measured with heptane as fuel. The agent concentration required to extinguish heptane and JP-8 cup burner flames has been measured to be within 4% of each other for many agents (Grosshandler *et al.*, 1994).

anticipated, since heating the air adds enthalpy to a flame, and a flame with a higher enthalpy is expected to be more stable. However, increasing the air temperature altered the agent ranking.

For temperatures below 150 °C, CF_3I was the most effective agent. For temperatures above 150 °C, the three agents, CF_3I, HFC-125 and HFC-227 were approximately equally effective.

Experiments using a butterfly valve placed on the downstream end of the burner showed that the system pressure did not impact the agent concentration required to obtain extinction over the pressure range tested (101-135 kPa). Suppression measurements also showed that the fuel flow had little effect on the agent concentration required to achieve flame extinction. Of the three candidate replacement agents evaluated in the turbulent spray burner, CF_3I was consistently the most effective compound. CF_3I required the least amount of gaseous agent to extinguish the flames on both a mass and volume basis. The other two alternative agents tested, HFC-125 and HFC-227, were measured to have nearly identical suppression effectiveness, and were significantly less efficient than CF_3I in extinguishing the flames. On a mass basis, none of the agents performed as well as halon 1301.

Using the results from experiments testing the effect of agent injection duration on flame stability, a model was developed that treats the recirculation zone in baffle stabilized flames as a perfectly stirred reactor and allows prediction of the agent concentration required for flame extinction as a function of the agent injection duration. The key parameter in this model is the characteristic mixing time (τ) for reactants to entrain from the free stream into the recirculation zone. The concentration in the recirculation zone will approach the free stream agent concentration for long entrainment times ($\approx 3\tau$). For the spray flames with a free stream air velocity of 3 m/s, $\tau \approx 100$ ms. According to many studies, this value is proportional to d/V, the ratio of the baffle diameter to the air velocity (Gann, 1995).

To extinguish a flame, the agent concentration in the recirculation zone must obtain a critical value. This concentration depends on the agent type and the free stream air velocity as shown in Figure 1. Agent type does not significantly impact mixing rates behind an obstacle in combusting or non-combusting conditions, but Winterfeld (1965) showed that entrainment times under non-combusting conditions (such as during agent certification) are approximately a factor of two larger than entrainment times under combusting conditions.

Measurements on the suppression of baffle stabilized pool fires were conducted at Walter Kidde Aerospace (WKA) of Wilson, North Carolina under our direction. WKA delivered the test data to NIST for further analysis. The results indicated that the mixing time was relatively large in baffle stabilized pool fires. The characteristic mixing times from the data fits were 0.5 s for HFC-125 (with the air velocity approximately equal to 3 m/s) and 0.7 s HFC-227 (with the air velocity approximately equal to 1.5 m/s). The minimum critical agent concentration required to achieve flame extinction was significantly larger than the concentration required to suppress cup burner flames under similar conditions, consistent with the results of Hirst *et al.* (1976) and Dyer *et al.* (1977). The minimum critical agent concentrations approximately corresponded to the amount of agent required to suppress hydrocarbon flames at their peak flammability limits. A detailed discussion of the work can be found in Gann (1995).

A comparison of flame stability in pool fires and spray flames showed that for similar air flows and baffle sizes, baffle stabilized pool fires were more difficult to extinguish than the baffle stabilized spray fires. Larger agent concentrations and longer characteristic agent mixing times were required to achieve suppression in the pool fires due to the structure of the recirculation zone.

4. A Simple Mixing Model Applied to Engine Nacelle Fires

A simple model to predict the quantity of agent required to suppress a generic engine nacelle fire was developed as a complement to full-scale nacelle fire testing. The model is based on idealized global mixing models describing agent dispersion and dilution for the bulk temporal concentration, and a local mixing model for flame extinction or concentration build-up at specified locations. The local mixing phenomena were inferred from the small-scale experiments described above in Section 3. The model yields guidelines for actual fire suppression system performance. The model is described in detail in Gann (1995).

In principle, computational fluid dynamics (CFD) could provide the answers pertaining to dispersion and the concentration profiles for every single configuration, but at this point, it is impractical to do such calculations for all nacelle configurations, although CFD may prove to be a useful tool in specific applications and future designs. The focus here was to provide simple guidelines on alternative agent delivery rates for engine nacelle fire protection system design. It is highly likely that discharge testing with concentration measurements for certification will remain relevant to document system performance when an alternative agent is used.

The model was used to explore the impact of air flow, mixing modes, nacelle volume, agent injection duration, and fire scenario on the agent requirements for suppression. All of the details of mixing are not simulated, nor are they known for a generic nacelle geometry, but limiting cases were covered which suggest what the values of the minimum agent mass delivery rates should be to achieve flame suppression. Allowances for un-modeled phenomena such as imperfect mixing, inadequate description of the fire scenario and additional safety factors need to be considered for a conservative design methodology.

The mixing models presented here for the bulk flow are well known, and have been used for decades to describe industrial mixing in blending operations and concentration profiles in chemical reactors. The mixing extremes that are covered are the plug flow "segregated" case and the perfectly stirred "homogenous" case. The plug flow model assumes either no mixing of the components (the extreme) or mixing with the incoming air flow only. The perfectly stirred scenario implies intense, chaotic motion leading to a spatially homogenous system. A definition of a perfectly stirred system is that any given particle after being introduced into the volume has an equal probability of being anywhere in the mixing volume, and as a consequence, the concentration is uniform throughout the mixing volume. Such a model was successfully employed to treat flame extinction in the recirculation zone. In chemical reactors, plug flow is typically assumed for tubular reactors, where the mean velocity profile is unidirectional.

In the bulk flow models, deviations from the idealized cases were not considered. The description of a particular nacelle is given by any number of perfectly stirred or plug flow regions in series and/or parallel. The transfer of agent from one region to another was taken into account by solving the transient mass balance equations for each region. The agent is assumed to be introduced as a gas, which then mixes isothermally with air.

The agent concentration for any given location as a function of time is required to assess the suppression system performance. One case is where the agent mixes perfectly with the incoming air stream, and flows downstream as a plug. The bulk "free stream" concentration is equal to the agent volumetric flow ($\dot{Q}_{agent}$) divided by the total (agent and air) volumetric flow ($\dot{Q}_{total}$). The duration at any location is equal to the nacelle volume (V) divided by the volumetric flow ($V/\dot{Q}_{total}$).

For a perfectly stirred region (PSR), the steady-state bulk concentration is equal to the agent volumetric flow divided by the total flow of agent and air ($\dot{Q}_{agent}/\dot{Q}_{total}$). Assuming isothermal, constant volume conditions, the solution to the mass balance equation for a step change in agent flow entering the nacelle is:

$$X(t) = X_f + (X_0 - X_f)\,(e^{-t/\tau_1}) \qquad (1)$$

where X(t) is the volumetric concentration in the nacelle, X_f is the volumetric agent concentration entering the nacelle normalized by the total flow of air and agent ($\dot{Q}_{agent}/\dot{Q}_{total}$), X_0 is the initial concentration, and τ_1 is the characteristic mixing time given by the mixing volume divided by the total volumetric flow ($V/\dot{Q}_{total}$). A step change from a fixed volumetric flow of agent, to zero agent flow gives

$$X(t) = X_p\,(e^{-t/\tau_2}) \qquad (2)$$

where X_p is the concentration in the PSR when the agent flow is stopped (at time t=0) and τ_2 is the characteristic time given by the total volume divided by the air flow ($V/\dot{Q}_{air}$).

The solutions above for step changes in the incoming stream concentration and flow are indicative of cases where the initial agent injection takes place in a perfectly stirred region, or a constant concentration plug flow feeds a perfectly stirred region. Analytical solutions are obtainable for other cases where the concentration of the incoming flow is a known function of time. A relevant case is when one perfectly stirred region provides the feed to another perfectly stirred region (PSRs in series). This situation is a reasonable model for certain nacelles.

So far the bulk or "free stream" concentration has been described. A description of agent mixing from the free stream into eddies behind bluff bodies in the case of certification and fires is needed in order to relate certification concentration and duration to agent requirements sufficient to extinguish various types of fires. The local mixing phenomena is described in terms of a characteristic mixing time, analogous to the characteristic mixing time described for the PSR bulk mixing.

Two different nacelle mixing models were examined, a plug flow model (model #1) and a PSR model (model #2). A real engine nacelle may behave closer to one of these generic descriptions than the other. The geometry, air entrance location, air and wall temperatures, agent injection location, and flow exit will impact the mixing and dispersion. The specific nacelle geometry was handled by the characteristic mixing times chosen as input. It was assumed that in smooth nacelles, the worst case fire for the smooth nacelle geometry was taken as a baffle stabilized spray flame. For rough nacelles (defined as those nacelles with ribs or other obstructions that can stabilize pool fires), the worst case fire was taken as a baffle stabilized pool fire.

Extinction times for both scenarios were fit to the same first order equation:

$$X_{\infty} = X_c \left(1 - e^{-\Delta t/\tau_f}\right) \tag{3}$$

where X_{∞} is the critical free stream agent concentration at extinction for long injection durations ($\Delta t>3\tau_f$), X_c is the critical free stream agent concentration for short agent injection intervals, and τ_f is the characteristic mixing time associated with the given fire scenario.

A parametric study was employed to determine the required agent amount for a range of discharge durations for the two nacelle models. The variables were nacelle type (smooth or rough which fixes the characteristic mixing times), free volume, air flow, agent density, discharge duration, and critical extinguishing concentration. The temperature and pressure were fixed at 20 °C and 101 kPa respectively. The nacelle volume range was from 0.25 to 8 m^3 in increments that double from the previous value and the air flow range was from 0.25 to 8 kg/s, also in increments that double from the previous value. These values cover the range of possible air flows and volumes in actual nacelles. The injection duration or discharge times examined were 0.25, 0.5, 1.0, 1.5, and 2.0 s, covering a reasonable range of times currently in use.

The baffle stabilized spray fire and pool fire were assumed to have characteristic mixing times (τ_f) equal to 0.1 and 1.0 s, respectively, consistent with the experimental measurements described in Section 3 above. The critical or maximum long injection time concentrations (X_{∞}) were taken as the cup burner extinction concentrations for the spray fire scenario. For the pool fire scenario, the results described in Section 3 and Gann (1995) served as input or in lieu of this data, the peak flammability limit of n-heptane flames was utilized (Malcolm, 1950; Gann, 1995).

For nacelle model #1, an analytical expression for the minimum agent mass is given by

$$W_{ag} = \frac{\Delta t \rho_{ag} X_\infty \dot{W}_{air}}{(1 - \frac{X_\infty}{1-e^{-\Delta t/\tau_f}})(1-e^{-\Delta t/\tau_f})\rho_{air}} \tag{4}$$

where W_{ag} is the minimum agent mass, Δt is the injection duration, $\dot{W}_{air}$ is the mass flow of air, ρ_{ag} and ρ_{air} are the densities of agent and air at ambient conditions, and τ_f is the characteristic mixing time for the particular fire scenario. For nacelle model #2, the minimum amount of agent is obtained by a numerical iterative procedure (Gann, 1995).

The model calculations show that the agent mass needed for extinguishment is not a function of the nacelle volume in the plug flow model if the cross section of the nacelle is held constant. That is to be expected since the nacelle volume does not play a role in free stream concentration or duration for the plug flow configuration. The perfectly stirred nacelle results do show variation with air flow and nacelle volume. In addition, it appears that air flow and total volume are essentially independent parameters for the ranges of air flow, free volume, and injection times examined. It follows therefore that a "design equation" of the form:

$$W = a\,V + b\,\dot{W}_{air} \tag{5}$$

could fit the model results for fixed characteristic mixing times. Here, W is the agent mass (kg), V is the nacelle free volume (m^3), and $\dot{W}_{air}$ is the mass flow of air (kg/s). This equation is of the same form as the design equations in the current Military Specification. Table 2 gives the coefficients for each agent and fire scenario. The (a) coefficient is not simply the critical concentration divided by the agent density. These results approach those limiting values at very low air flows only, much lower than the flows considered here. Again, no allowances for un-modeled phenomena are included in the above design equations, and appropriate safety factors must be applied. It should be noted that Equation (5) was developed for ambient conditions and the coefficients (a) and (b) are functions of temperature. It is

Table 2. The coefficients in Equation (5) for each agent and fire scenario

Agent	(a) spray fire (kg/m^3)	(b) spray fire ($kg/kg_{air}/s$)	(a) pool fire (kg/m^3)	(b) pool fire ($kg/kg_{air}/s$)
halon 1301	0.17	0.165	0.52	0.542
HFC-125	0.37	0.397	0.84	0.974
HFC-227	0.37	0.397	1.1	1.26
CF_3I	0.21	0.225	0.77	0.819

anticipated that the pressure dependence is small. The temperature dependence can be obtained from calculations using the model and based on the results discussed in Gann (1995).

In real nacelles, the flow will be characterized by imperfect mixing. Because of the mixing problem, it is recommended that temporal concentration measurements be conducted at many possible fire locations in full scale nacelles to ensure suppression system effectiveness.

5. Summary of the Mixing Model

There is no simple generic solution to the nacelle fire protection problem. The model developed here illustrates the importance of injection duration, air flow, nacelle free volume, fluid mixing, and fire scenario on the minimum agent suppression requirements. A comparison of the results of the model for halon 1301 suppression requirements with the current Military Specifications showed that the trends with air flow and nacelle volume were well predicted, and that the Specification requires larger agent mass. Comparison of the alternative agent requirements to those predicted for halon 1301 showed that a constant multiplier between them exists for each fire scenario. Preliminary guidelines in the form of simple algebraic equations were proposed for the minimum agent delivery rates. A step-by-step procedure was proposed as a guideline for system design and certification (Gann, 1995). Before application, it is strongly advised that the model be adequately validated using full scale testing.

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