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**AN ANALYSIS OF THE WRIGHT PATTERSON  
FULL-SCALE ENGINE NACELLE FIRE  
SUPPRESSION EXPERIMENTS**

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Anthony Hamins, Thomas Cleary, and John Yang

November 1997  
Building and Fire Research Laboratory  
National Institute of Standards and Technology  
Gaithersburg, MD 20899



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## **SUMMARY**

An analysis is presented on the full-scale suppression experiments conducted during 1996 and 1997 in the F-22 engine nacelle fire simulator at Wright Patterson Air Force Base. Experiments investigated the relative effectiveness of halogenated agents and solid propellant gas generators (SPGG) in suppressing a series of spray fires with and without a fuel re-ignition source. Several agents were tested including halon 1301, HFC-125, and two basic types of SPGG which included those that produced inert gases in conjunction with a fine solid particulate (some which contained  $K_2CO_3$ ), and those that produced inert gases only. The SPGG devices were more or less effective depending on the agent composition and the agent delivery rate. The SPGG effluent which contained a significant percentage of  $K_2CO_3$  particulate was particularly effective for re-ignition protection, a scenario which dominates agent mass requirements for the compressed halogenated liquids.

A number of measurements were made during the suppression tests. Measurements included gas temperatures, the re-ignition source temperature, the cold-flow agent concentrations (no fuel spray or fire present), and velocity measurements. This information was utilized to gain insight into the mechanisms of fire suppression with the different suppressant types.

A simple model for SPGG delivery was developed. Assuming plug type flow, the transient average agent concentrations were calculated in the nacelle and compared to measurements. The results give reasonable agreement.

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## 1. INTRODUCTION

Halon 1301, or trifluorobromomethane ( $\text{CF}_3\text{Br}$ ), has been used as a fire extinguishing agent in many applications because of its myriad positive attributes. Due to its high ozone depletion potential, however, its production has been terminated. In the search for a suitable replacement, a large number of halogenated agents have been tested in both laboratory-scale and full-scale screening devices. In addition, novel types of extinguishing agents and delivery mechanisms are under testing and development. One class of such devices is the solid propellant gas generator (SPGG), a device where rapid combustion forms an exhaust which has been successfully used in fire suppression [Yang and Grosshandler, 1995]. In order to investigate the suppression effectiveness of SPGG, a series of full-scale fire tests was undertaken utilizing a simulated F-22 engine nacelle in the Wright Patterson Aircraft Engine Nacelle Test Facility.\* This report is an analysis of a portion of the data acquired during that test program.

The full-scale experiments investigated the relative effectiveness of halogenated agents and solid propellant gas generators (SPGG) in suppressing a series of spray fires with and without a fuel re-ignition source. Many details describing the experimental program including, experimental methods, location of instrumentation, data uncertainty, and results can be found in the report by Reuther [1997]. Further information can be found in the Appendix of this report which contains an overview of the F-22 test program [Gillespie, 1997]. The testing was broken into three phases. The Phase I experiments involved characterizing fuel ignition of the JP8 fuel spray. There was no agent addition in these experiments. The Phase II experiments tested the suppression effectiveness of HFC-125 and halon 1301 for several combustion configurations (two fuel spray locations, one hot surface) and many nacelle conditions. The Phase III experiments tested the suppression effectiveness of SPGG for three of the most hazardous conditions determined from the Phase II testing.

Five different SPGG formulations provided by two different vendors were tested. Primex provided four propellants. The vendor described two of these as fast burning (FS01-40 and PAC-3302) and two as slow burning (FS-20 and PAC-3303). The vendor also described the FS01-40 and FS-20 as "inert", and the PAC-3302 and PAC-3303 as "chemically active". The inert formulations were

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\* Certain commercial materials and equipment are identified in this report in order to specify adequately the procedure. In no case does such identification imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the material or equipment is necessarily the best for the purpose.

designed to produce inert gases in conjunction with a fine solid particulate that was filtered such that the effluent was composed almost entirely of inert gases. The other SPGG supplier, Walter Kidde/Atlantic Research Corporation, provided a single propellant, described as "chemically active" (FS-59). This formulation produced a solid particulate, which was not filtered.

Gas generators consist of an igniter, propellant grains, hardware components, and possibly a particle filter. Grain size and composition among other parameters will determine the propellant burning rate. The chemical formulations of the propellants used in SPGG are based on a solid phase oxidizer (e.g., potassium nitrate or ammonium nitrate), a carbon source, a binder, a stabilizer, and a burning rate catalyst. The hot exhaust products are principally gaseous  $N_2$ ,  $CO_2$ , and  $H_2O$  vapor as well as particulate, which may be filtered from the effluent. Small concentrations of CO and  $O_2$  may also be included in the exhaust. A number of enhanced SPGG devices are under development [Yang and Grosshandler, 1995].

The key parameters that affect flame stability and thereby control flame extinction and the prevention of re-ignition are agent effectiveness and flow field dynamics. Flow field dynamics govern the rate of agent entrainment, the local fluid mechanical strain, and the concentration of agent in a fire zone. Pitts et al. [1990] outlined current understanding of fire suppression, incorporating a comprehensive review of the relevant literature, in addition to a discussion of agent effectiveness, test methods, and the role of different suppression mechanisms. Whereas there is general understanding of fire suppression by gaseous agents, there has been little published in the scientific literature on the fire suppression mechanisms using SPGG devices. Nor has there even been laboratory-scale tests of the relative effectiveness of SPGG as compared to other agents such as  $CF_3Br$ . Because there are myriad types of SPGG, each with its own composition, packaging geometry, and ignition sequencing, variation in gas species and particulate yields would be expected in addition to particulate size distributions, exhaust temperatures and transient rate and duration of effluent generation. Each of these parameters may impact the effectiveness of the SPGG effluent in suppressing a fire and preventing ignition.

Recent experiments at NIST [Hamins et al, 1995] investigating the suppression of baffle stabilized flames showed that agent suppression requirements were related to two parameters: the agent concentration at extinction and a characteristic agent entrainment time. The combustion configuration was found to be critical with agent suppression requirements of baffle stabilized pool fires and spray flames corresponding to peak flammability limits and non-premixed flame situations respectively [Hamins et al., 1995]. In general, baffle stabilized pool fires were more difficult to extinguish than the baffle stabilized spray fires.

Higher agent concentrations and longer characteristic agent mixing times were required to achieve suppression in the pool fires [Hamins et al., 1995]. This information was used to develop a simple model for determining agent requirements in nacelle applications. The model emphasized the importance of injection duration, air flow, nacelle free volume, fluid mixing, and fire scenario on the minimum agent suppression requirements. Two mixing processes were considered: agent mixing with the airflow and the agent/air entrainment into combustion/recirculation zones. Example calculations using this model are employed in Section 3 of this report to gain insight into the full-scale F-22 results.

Before a decision is made regarding the utilization of SPGG on aircraft, it would be beneficial to understand its mechanism of operation. There are many operating conditions for which suppressants are needed. Beyond the F-22 program, understanding the mechanism of SPGG fire suppression may also assist in decisions on future applications. Because testing cannot be performed for all possible conditions, knowledge is needed which will provide guidance in the extension of the full-scale data to untested conditions. Without a full appreciation of SPGG operation, there are risks that a system may fail. For example, "worst case" test conditions developed in this program were selected from tests using compressed halogenated liquids. These do not necessarily represent worst case fire conditions for SPGG utilization. In addition, if SPGG is to be eventually used in generic aircraft, then a detailed understanding of flame suppression requirements must be well-understood to develop certification guidelines (analogous to the procedure currently used for compressed halogenated liquids).

This report endeavors to address key issues of SPGG operation. Approximately one gigabyte of information was acquired during the full-scale fire suppression test program at Wright Patterson Air Force Base. The data acquired included agent mass requirements to achieve suppression, thermocouple temperature measurements, pressure transducer measurements, pitot-tube velocity measurements, and gas concentrations from Statham, CO<sub>2</sub>, and O<sub>2</sub> gas analyzer measurements in conjunction with gas sampling. Experimental details describing those measurements, including calibration, positioning of probes, data processing, and uncertainty analysis are not described here, but can be found in the complementary report by Reuther, 1997. This report does not attempt to analyze all of the experimental data from the full-scale test program, but instead focusses on key experiments to gain insight into the physics of fire suppression and more specifically, the differences in fire suppression mechanisms associated with the assorted suppressant types. This report investigates the HFC-125 and halon 1301 results in addition to the SPGG results, because analysis of those data complements our understanding of the physics of fire suppression. If

uncertainties exist regarding the use of simple halogenated compounds, then understanding suppression mechanisms of a mixture of agents with uncertain composition will only be more speculative.

In Section 1 of this report, the effect of temperature on the effectiveness of agent suppression of non-premixed and premixed flames is discussed. Suppression of re-ignition is also discussed. In Section 2, the full-scale test conditions are described and the results are analyzed. In Section 3, a simple model for the time varying spatially-averaged agent concentrations, velocities and temperatures within the nacelle is presented. Comparison of the results to experimental measurements indicates the importance of agent dispersion and mixing. In Section 4, our conclusions are summarized and recommendations are made for future work.

### 1.1 Fire Suppression

In general, there are two categories of fire safety problems associated with engine nacelles, namely, fire suppression and prevention of re-ignition. Each of these can be thought of as independent from each other. The occurrence of re-ignition and flame extinction are controlled by the Damköhler number criterion, which represents a critical value of the ratio of a characteristic flow time to a characteristic chemical reaction time. In realistic applications such as the engine nacelle problem, the Damköhler number criterion is based on local phenomena, although it may be related to global parameters. As such, the characteristic flow time is related to the local strain rate which is associated with the nacelle air ventilation rate. The characteristic chemical reaction time is related to the flame temperature which is a function of the ambient conditions in the nacelle, the fuel type, the agent type, the temperature of the nacelle, and the combustion configuration (i.e., is the fire premixed or non-premixed). Re-ignition, on the other hand, is kinetically and phenomenologically distinct from flame extinction. The temperature regimes are different, indicating possible differences in the controlling kinetic processes. Re-ignition can only occur if the local fuel/air ratio is within flammability limits. If an agent is present, or the temperature or pressure are changed, then those limits are shifted. From a fire safety perspective, the re-ignition problem can be considered independently from the flame suppression problem, perhaps requiring a separate solution or strategy.

In terms of flame suppression there are two classes of fire configurations, namely, premixed and non-premixed flames. Either of these combustion types may occur in an engine nacelle and each is characterized by different agent suppression requirements. Also affecting agent suppression requirements are conditions



within an engine nacelle. These include the initial air and agent temperature, the nacelle pressure, fuel type, and so on. Consideration of the two classes of flames allows quantification of the impact of nacelle conditions on agent requirements.

In order to compare the fire suppression effectiveness of SPGG and the halogenated agents HFC-125 and halon 1301, it is important to understand agent concentrations required to suppress possible combustion situations. Unfortunately, peak flammability limits and cup burner agent requirements are not available for SPGG. It is possible, however, to estimate these factors. Peak flammability limits are available for  $C_2HF_5$ ,  $CF_3Br$  and some of the constituent species in the SPGG effluent including  $N_2$  and  $CO_2$  for propane/air mixtures. A methodology for estimating SPGG effluent is discussed below. Such calculations may also lend insight into the amount of improved SPGG effectiveness possible through optimization of the effluent composition and temperature.

### 1.1.1 Suppression of Non-Premixed Flames

A standard burner used by industry for comparing the fire suppression efficiency of gaseous agents has been the cup burner, which is an enclosed over-ventilated co-flowing diffusion flame. Agent is quasi-statically added to the oxidizer stream until the flame "blows-off" and is extinguished. Agent concentration requirements in the cup burner have been shown to correspond to the extinction of large fires under total flooding conditions [Sheinson, 1989]. There is no analogous bench-scale screening test for laminar non-premixed flames where an agent is delivered in a transient manner, although there are at least two laboratory-scale suppression screen devices that exist where agent is injected in a transient fashion (the turbulent jet spray flame and the pool fire/wind tunnel [Dyer et al., 1977a; 1977b; Hamins et al., 1994; 1995]). Unfortunately, there are no results in the open literature regarding the suppression effectiveness of SPGG. Nor is there information regarding the suppression effectiveness of  $K_2CO_3(s)$  particulate, a key component of the SPGG effluent, in a standard laminar diffusion flame.

Fortunately, it is possible to estimate agent suppression requirements if the agent composition is known. Table 1 shows the species composition of the effluent from the FS-59 ARC/Walter Kidde [Cauffman, 1997] and the FS01-40 Primex SPGG [Gillespie, 1997] formulations, two of the key formulations used during the suppression testing. For interest, a hypothetical mixture associated with unfiltered effluent from the FS01-40 Primex SPGG is also listed. For this analysis, the solid particulate in the unfiltered effluent is assumed to be  $K_2CO_3(s)$ . The composition of the PAC formulations are apparently very similar to the FS-20 and FS01-40 formulations [Gillespie, 1997]. The "chemically active" constituents of the PAC-3302 and PAC-3303 propellants are

Table 1 SPGG mole based fractional effluent composition			
Species	filtered Primex FS01-40	unfiltered Primex FS01-40	ARC/Kidde FS-59
CO <sub>2</sub>	0.313	0.264	0.0917
H <sub>2</sub> O	0.219	0.183	0.559
N <sub>2</sub>	0.468	0.395	0.325
CO	-	-	0
O <sub>2</sub>	-	-	0.0083
K <sub>2</sub> CO <sub>3</sub> (s)	≈0	0.158*	0.0236
- unknown			
* particulate assumed to be K <sub>2</sub> CO <sub>3</sub> (s)			

proprietary. For the analysis presented here, the composition of the effluent from all of the Primex formulations are assumed to be identical to the effluent from the FS01-40 propellant. Table 1 shows that there is approximately one-third as much CO<sub>2</sub>, more than twice as much H<sub>2</sub>O, and almost two-thirds as much N<sub>2</sub> produced in the ARC/Kidde effluent than in the filtered Primex effluent. The ARC/Kidde effluent is assumed to be unfiltered, so that it contains K<sub>2</sub>CO<sub>3</sub>, whereas the filtered Primex effluent is assumed to contain no particulate. K<sub>2</sub>CO<sub>3</sub> is a solid for temperatures below 700°C [Gordon and McBride, 1976] and is expected to be in this form when the SPGG exhaust is delivered to the engine nacelle.

Agent concentration requirements for flame suppression were determined using the NASA CEC computer code and data base [Gordon and McBride, 1976] using a critical temperature criterion for flame extinction [Sheinson, 1989]. The critical temperature (1587°C) was determined from N<sub>2</sub> concentration requirements for suppression of heptane cup burner flames [Hamins et al., 1995]. Heptane was selected because it is a pure fuel that is characterized by agent suppression concentrations very similar to JP8, the fuel of interest [Hamins et al., 1994]. Cup burner studies have shown that flames burning JP8 require 4 mole percent more agent to extinguish than flames burning heptane. Many small scale tests have been performed using heptane and the use of other fuels yield similar results [Hamins et al., 1994]. An estimate of the required concentration for H<sub>2</sub>O was determined using the critical temperature criteria assuming that this agent acted thermally. It is possible that H<sub>2</sub>O(g) has some chemical effectiveness, but those effects are likely small. The results

for the other gaseous components of the filtered Primex SPGG effluent, namely  $\text{CO}_2$  and  $\text{N}_2$ , have been measured [Hamins et al., 1995]. The concentration requirements for  $\text{K}_2\text{CO}_3(\text{s})$ , which has unknown suppression effectiveness, was estimated using experimental results on enclosed moderate diameter heptane pool fires reported by Ewing et al. [1992].

In the experiments by Ewing et al. [1992], 15 cm diameter heptane pool fires were extinguished using powder agents. For particles below a limiting size ( $\approx 14 \mu\text{m}$  and  $16 \mu\text{m}$ ), 31 mg/L and 46 mg/L of  $\text{K}_2\text{CO}_3$  and  $\text{NaHCO}_3$  respectively were required, corresponding to mass fractions of 0.024 and 0.036. Ewing's results for  $\text{NaHCO}_3$  are pertinent because cup burner results are available for this species. The critical mass fraction for  $\text{NaHCO}_3$  determined from cup burner suppression experiments is approximately 0.06 [Hamins et al., 1994], a factor of two larger than Ewing's results. A possible explanation is that Ewing's flames were weakened by aerodynamic effects associated with the agent delivery. Interestingly, the cup burner result is consistent with CEC flame temperature calculations if 50% of the  $\text{NaHCO}_3$  effectiveness is attributed to chemical, rather than physical effects. A critical agent mass fraction for suppression using  $\text{NaHCO}_3$  is calculated to be 0.064. Because no cup burner results have been reported for  $\text{K}_2\text{CO}_3$ , its effectiveness was estimated using the ratio of the Ewing results in conjunction with the cup burner results for  $\text{NaHCO}_3$ . This calculation yields a mass fraction of 0.042, denoted in Table 2 as " $\text{K}_2\text{CO}_3(\text{s})$ active".

To determine an upper bound for the required agent concentration,  $\text{K}_2\text{CO}_3(\text{s})$  was also treated as an inert, resulting in an oxidizer mass fraction of 13%, more than a factor of three larger than  $\text{K}_2\text{CO}_3(\text{s})$ active. This "effectiveness factor" was used to estimate the required concentration of SPGG effluent for particulate containing mixtures where the  $\text{K}_2\text{CO}_3(\text{s})$  was considered chemically active, (i.e., unfiltered Primex FS01-40 ["active"] and the ARC/Kidde FS-59 ["active"]) by modifying the  $\text{K}_2\text{CO}_3(\text{s})$  effectiveness. Assuming that  $\text{K}_2\text{CO}_3(\text{s})$  was chemically active as suggested by Ewing's experiments and that the reported  $\text{NaHCO}_3$  cup burner results are correct, the suppression effectiveness of  $\text{K}_2\text{CO}_3$  is approximately 80% chemical and 20% physical, which is similar to results for  $\text{CF}_3\text{Br}$  [Sheinson, 1989]. This analysis provides a preliminary estimate of agent effectiveness. Bench-scale suppression testing of  $\text{K}_2\text{CO}_3(\text{s})$  and the SPGG effluent needs to be conducted to verify the estimates presented here.

Table 2 shows literature values and estimates of agent suppression concentrations for heptane cup burner flames for the species  $\text{N}_2$ ,  $\text{H}_2\text{O}(\text{g})$ ,  $\text{CO}_2$ ,  $\text{C}_2\text{HF}_5$ ,  $\text{CF}_3\text{Br}$ ,  $\text{K}_2\text{CO}_3(\text{s})$ , and for the SPGG mixtures given in Table 1 which include the filtered Primex SPGG effluent with  $\text{K}_2\text{CO}_3$  particulate removed (gas species only), the unfiltered effluent from the ARC/Kidde SPGG (consisting of gas species and  $\text{K}_2\text{CO}_3$  particulates), and the hypothetical unfiltered Primex SPGG effluent (composed of gas species and  $\text{K}_2\text{CO}_3$

Table 2 Agent concentration requirements for suppression of heptane cup burner flames.				
Agent	M g/mole	X <sub>i</sub> Mole %	Y <sub>i</sub> Mass %	Reference
N <sub>2</sub>	28	32	31	[1]
H <sub>2</sub> O(g)	18	27	19	estimate <sup>1</sup>
CO <sub>2</sub>	44	23	32	[1]
C <sub>2</sub> HF <sub>5</sub>	120	8.7	28	[1]
CF <sub>3</sub> Br	149	3.1	14	[1]
NaHCO <sub>3</sub>	84	2.3	6.4	[1]
K <sub>2</sub> CO <sub>3</sub> (s)	138	3.1	13	estimate <sup>1</sup>
K <sub>2</sub> CO <sub>3</sub> (s) ("active")	138	0.91	4.2	estimate <sup>2</sup>
filtered Primex FS01-40	30.8	28	29	estimate <sup>1</sup>
unfiltered Primex FS01-40	47.8	12	19	estimate <sup>1</sup>
unfiltered Primex FS01-40 ("active") <sup>+</sup>	47.8	5.0	8.0	estimate <sup>3</sup>
ARC/Kidde FS-59	26.5	23	22	estimate <sup>1</sup>
ARC/Kidde FS-59 ("active")	26.5	17	15	estimate <sup>3</sup>
<p>+ assuming that the particulate is K<sub>2</sub>CO<sub>3</sub>(s) "active".</p> <p>1. estimate based on CEC calculation, treating agent as inert.</p> <p>2. estimate based on the results of Ewing et al., 1992.</p> <p>3. estimate based on CEC calculation, using an "effectiveness factor" to treat a chemically acting agent.</p>				

particulate). Agent concentrations in Table 2 are presented in terms of both mole and mass percent of agent in the oxidizer.

Estimates of the suppression effectiveness of the filtered Primex SPGG effluent were also determined using Saito's method [Saito et al., 1996] which required the effectiveness of each mixture component as input. The mole based suppression effectiveness of a mixture of gases ( $X_{mix}$ ) is related to the effectiveness of the components weighted by the agent concentration in the mixture ( $C_i$ ):

$$(X_{mix})^{-1} = \sum C_i/X_i \quad (1)$$

For the SPGG, the  $C_i$  are listed in Table 1 and the  $X_i$  are listed

in Table 2. The sum of constituents in the mixture must equal one: ( $\sum C_i = 1$ ). The critical concentration of  $H_2O(g)$  was determined using the CEC code (see Table 2). Saito's method yielded a critical volume fraction of 0.28 for the filtered Primex SPGG effluent, in agreement with the calculations shown in Table 2 using the CEC code. Saito's method allows calculation of the fractional contribution (FC) of a constituent species to the suppression effectiveness of a mixture ( $X_{mix}$ ):

$$FC = (C_i/X_i) / \sum C_i/X_i \quad (2)$$

The largest contributor to FC for the Primex SPGG was  $N_2$  (FC=0.40) followed by  $CO_2$  (FC=0.38), whereas the largest contributor for the WKA SPGG was the  $K_2CO_3$  particulate (FC=0.43), followed by  $H_2O$  (FC=0.34).

Table 2 shows that the concentration requirement for the Primex SPGG filtered effluent is not unlike that of its inert constituents (see Table 1).  $K_2CO_3(s)$  and the "active"  $K_2CO_3(s)$  containing SPGG effluent, on the other hand, are predicted to be more effective suppressants than the inert agents. Chemically active  $K_2CO_3(s)$  is predicted to be very effective, a factor of three times more effective on a mass basis than even  $CF_3Br$ . It is not surprising, therefore, that the filtered Primex effluent with particulate removed is calculated to be less effective than the unfiltered Kidde SPGG with 2% (by moles)  $K_2CO_3$ . The effectiveness of potassium containing agents has been investigated in methane/air diffusion flames [Milne et al., 1970]. Their results show that Purple K (primarily  $K_2CO_3$ , a compound similar to  $K_2CO_3$ ) is an order of magnitude more effective than  $CF_3Br$ . Maximizing the  $K_2CO_3$  concentration in the SPGG effluent should increase its effectiveness. Table 2 shows that the ARC/Kidde FS-59 ("active") propellant is predicted to be a factor of two less effective (on a mass basis) than the (hypothetical) unfiltered Primex effluent with its (assumed) factor of three higher  $K_2CO_3(s)$  concentration.

#### 1.1.1.1 Suppression Effectiveness per Kilogram of Agent

Table 2 also lists the average molecular weight ( $M_i$ ) of the agents including the SPGG effluent mixtures. The number of moles of agent per kilogram of agent or propellant deployed ( $n_i$ ) is defined as:

$$n_i = 1 \text{ kg}/M_i \quad (3)$$

Table 3 lists  $n_i$ . The available moles of the Primex FS SPGG were reduced when the particulate, assumed to be  $K_2CO_3$ , was filtered from the effluent, leaving 84% or 17.6 moles, approximately half that provided by the ARC/Kidde propellant. The largest  $n_i$  was from the effluent of the WKA SPGG which was almost a factor of 6 larger than  $n_i$  from 1 kg of halon 1301, and a factor of 2 larger

than the  $n_i$  from 1 kg of the Primex (PRM) SPGG.

Factoring in the mole based suppression effectiveness of an agent ( $X_i$ ) listed in Table 2, the number of moles of air protected ( $n_a$ ) by the deployment of 1 kg of agent or propellant is defined as:

$$n_a = (n_i / (0.01 \cdot X_i)) - n_i \quad (4)$$

The value of  $n_a$  is listed in Table 3 for each of the agents. The constant 0.01 in Eq. 4 converts  $X_i$  from mole percent to mole fraction. The uncertainty in  $X_i$  is taken as 10% for all agents and  $K_2CO_3$  is assumed to be chemically active. The predicted agent effectiveness per kilogram of agent normalized to halon 1301 ( $E_p$ ), is:

$$E_p = n_a / n_a(\text{halon}) \quad (5)$$

The values of  $E_p$  in Table 3 suggest that the unfiltered (hypothetical) Primex (PRM) SPGG would have been the most effective agent on a per kilogram basis, followed by halon 1301, the WKA SPGG, HFC-125, and the filtered PRM SPGG. For 1.0 kg of agent, the unfiltered PRM SPGG was more effective than halon 1301 because of its large  $n_i$ , as noted in Table 3. It is assumed that the combustion efficiency of the SPGG propellants is 100%. In fact, the efficiency is probably closer to 90% (on a mass basis) [Cauffman, 1997] and may be a function of propellant temperature. Unfortunately, data is not available to quantify this effect.

$E_p$  is a prediction of the relative suppression effectiveness of an agent as compared to halon 1301 due to its composition in a low strain rate non-premixed flame. From estimates of  $E_p$  it is

Table 3 Predicted mass based agent effectiveness per kilogram of agent deployed ( $E_p$ ).			
Agent	$n_i$ (moles)	$n_a$ (moles)	$E_p$
halon 1301	6.7	210±21	1.00±0.10
HFC-125	8.3	87±9	0.42±0.04
WKA*	37.7	184±18	0.88±0.09
PRM (FS**)	17.6	45±5	0.22±0.02
PRM* (FS**) unfiltered	20.9	397±40	1.89±0.19
* $K_2CO_3$ assumed to be chemically active (see Table 2). ** these tests involved a combination of FS01-40 and FS-20.			

possible to optimize SPGG agent formulations. Propellant manufacturers realize this and have been engaged in proprietary studies of bench-scale suppression testing for some time.

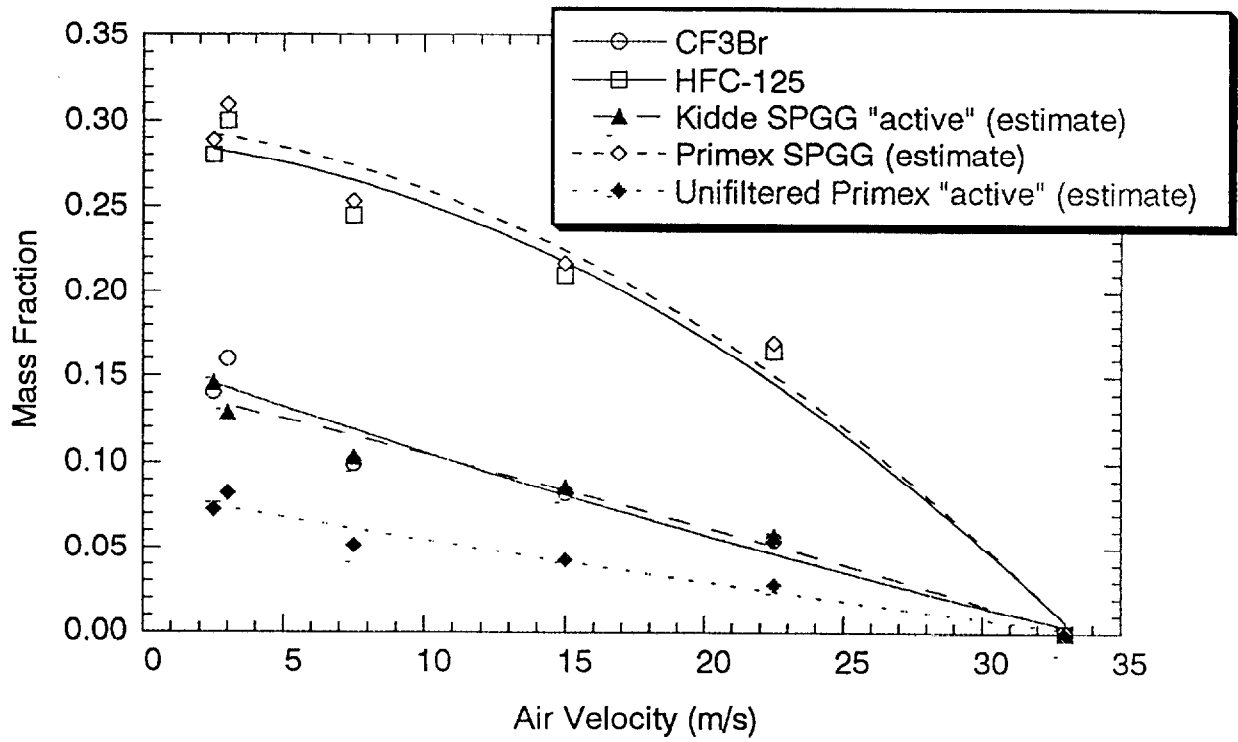
Although  $E_p$  includes both chemical and physical suppression behavior, it does not include flow field effects, agent temperature effects, the rate of agent deployment, agent mixing and dispersion, rates of phase changes and so on. These "other" effects may be very important in the suppression capability of an agent. In Section 2.2, the predictions in Table 3 will be compared to the experimental results.

#### 1.1.1.2 Velocity Effects

Fluid mechanical straining of a flame is due to the local flow field. The rate of agent deployment and the number of agent moles deployed ( $n_i$  in Table 3), may be as important as the agent effectiveness ( $x_i$ ) in the ability of an agent to suppress a fire in a nacelle. In this sense, the SPGG may have an edge over the halogenated agents with its very large  $n_i$  values. Unfortunately, such effects cannot be predicted in a complex geometry without resorting to comprehensive computational fluid dynamic models. Such models are not currently available.

In engine nacelles, the ventilation rate has been observed to have an effect on agent requirements [Hughes, 1953]. This is due to local straining of the fires. In bench scale suppression testing on spray flames, this effect has been documented, as the upstream air velocity effects the stability of the flames [2]. Figure 1 shows experimental results for mass fraction (in the oxidizer) requirements for  $CF_3Br$  and  $C_2HF_5$  as a function of air velocity in the NIST JP8 spray burner. Also shown are predicted mass requirements for Primex SPGG, and chemically active Kidde and unfiltered Primex SPGG in the NIST spray burner. The predictions are scaled, based on the results in Table 1, with the scaling accounting for the air velocity and differences due to fuel type which are small [Hamins et al., 1995]. The spray flames become easier to extinguish as the air velocity increases, until the flames blow-off with no agent required for air velocities of 33 m/s. The trends in the NIST suppression experiments should be comparable to the full-scale results. The data in Figure 1 is replotted in Figure 2 in terms of mole (rather than mass) fraction in the oxidizer as a function of air velocity normalized by the air blow-off velocity, 33 m/s in this case. Although the value of the blow-off velocity for the full-scale fires is not known, the trends in the suppression requirements should be similar to Figure 2.

Previous suppression experiments using halogenated agents in the spray flames in the Wright Patterson nacelle corresponded to the NIST results [Bennett, 1995]. This was not surprising because of



**Figure 1.** The critical mass fraction (in the oxidizer) of various agents as a function of air velocity for suppression of JP8 spray flames in the NIST burner.



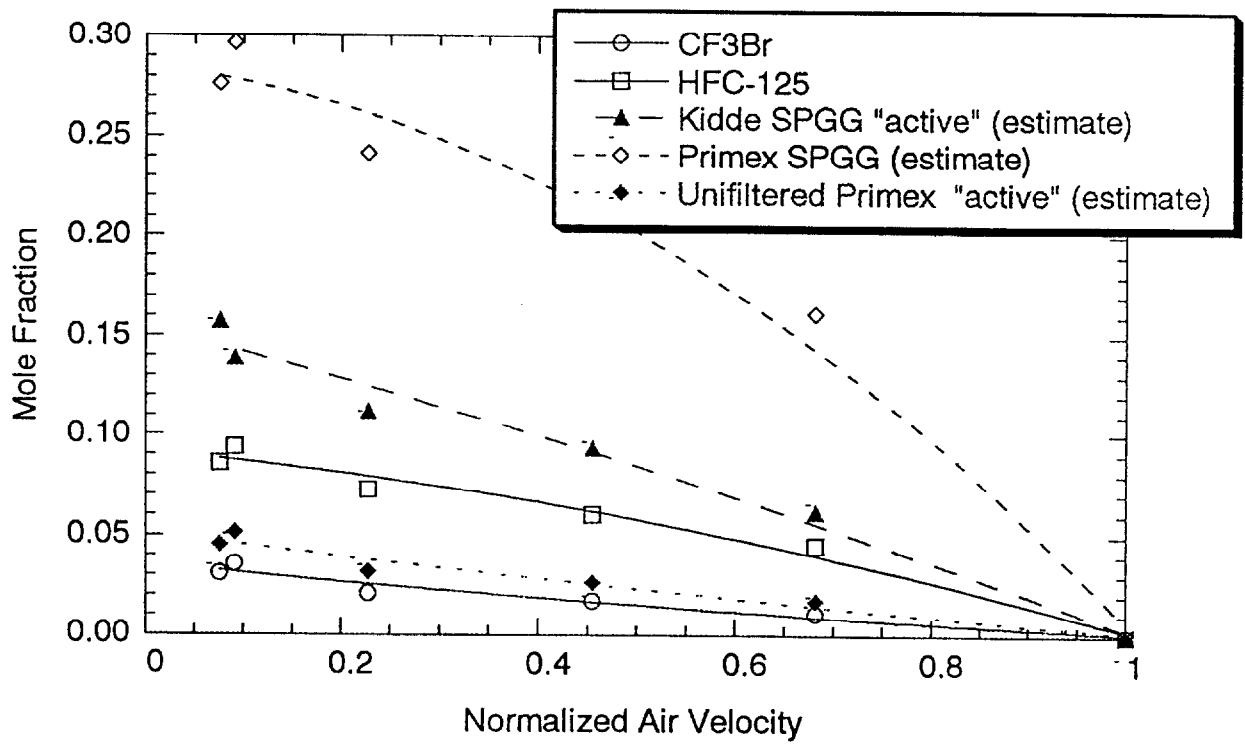
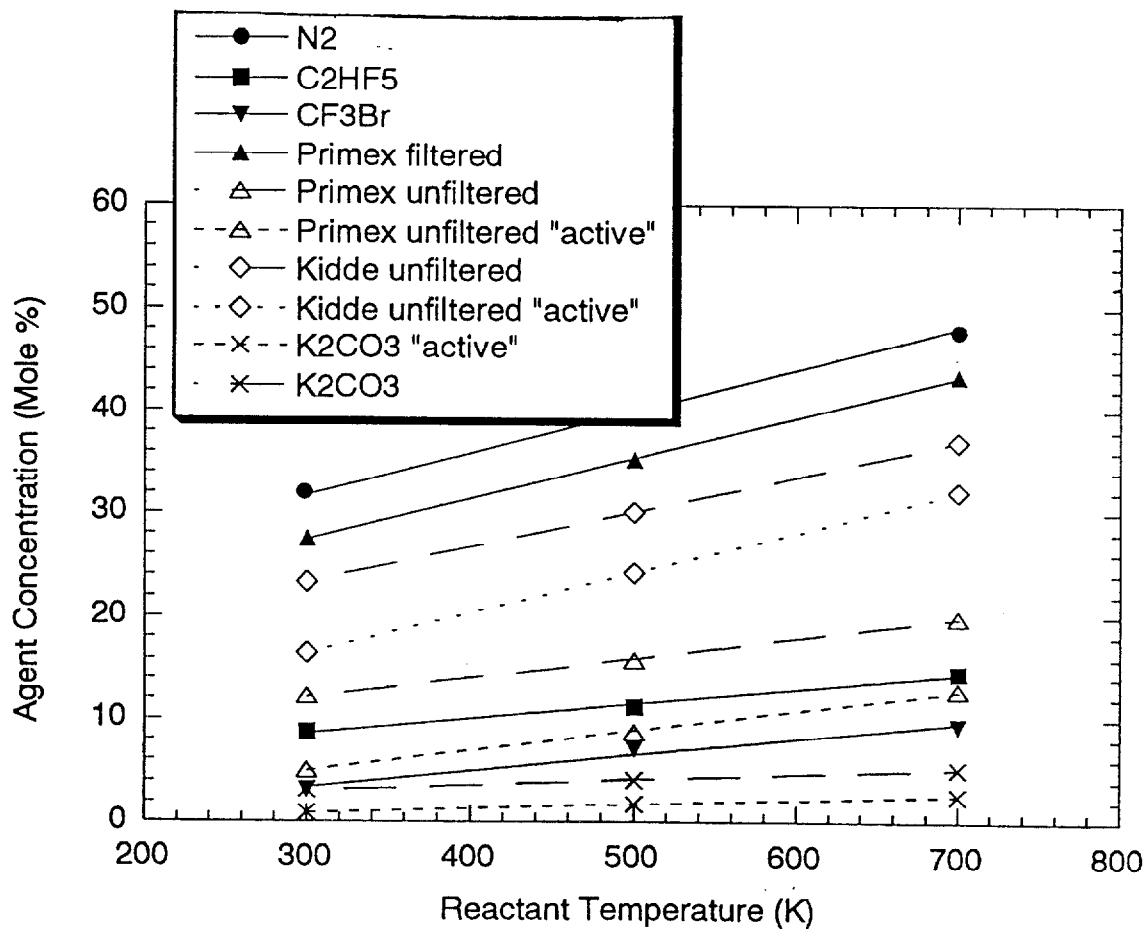


Figure 2. The critical mole fraction (in the oxidizer) of various agents as a function of the normalized air velocity for suppression of JP8 spray flames in the NIST burner.

the many similarities between the two experiments. Both the NIST and the full-scale results used spray flames burning JP8. The nozzles in both cases had a  $\approx 4$  cm washer attached just upstream of the nozzle tip, creating recirculation zones which anchored the flames to the tip of the spray nozzle. The fuel flow, however, significantly differed in the two experiments. Over a small range of fuel flow this has been shown not to impact agent suppression requirements [2], yet the full-scale fuel flow was  $\approx 600$  ml/min and the NIST flow was 20 ml/min. Also, the nozzle type differed, so that the distributions of fuel momentum and droplet size were different. With all of these differences, the absolute agent concentrations cannot be expected to correlate in the two experiments, but general trends can be expected to be similar. In terms of agent concentration, the most dangerous conditions correspond to low air velocities where agent concentrations in the spray burner are not unlike cup burner flames whereas higher air flows are easier to extinguish.

### 1.1.1.3 Temperature Effects

Changes in reactant temperature impact agent mass requirements in a flame. Increasing the initial temperature of the fuel, air or agent adds enthalpy to a reactive system and increases the maximum flame temperature ( $T_f$ ). For increasing reactant temperatures, it is possible to calculate the quantity of agent required to reduce  $T_f$  to a critical temperature corresponding to flame suppression. Agent concentrations required to obtain flame suppression at ambient temperature are available to calculate the reference or critical temperature. Results of such a calculation are shown in Figure 3 for pure gaseous agents ( $N_2$ ,  $CF_3Br$ ,  $C_2HF_5$ ) and SPGG where the agent concentration (in the oxidizer) required to achieve critical flame temperatures is calculated as a function of the initial reactant temperature for stoichiometric heptane/air flames. The range of temperatures considered corresponds to possible air/SPGG effluent mixtures upstream of the fire zone in the nacelle. Figure 3 includes the ambient temperature results listed in Table 2. The SPGG mixture compositions are listed in Table 1. The results in Figure 3 show that as the reactants are preheated, more agent is required to extinguish the flame. The increases in concentration are approximately linear over a broad range of temperatures. This is consistent with experimental results for methanol/air non-premixed flames extinguished by  $N_2$  [Hamins, 1985]. The slopes in Figure 3 vary for the different agents which can be attributed to differences in gas phase heat capacity. For temperature increases of 100 K, Figure 3 indicates that suppression requires a factor of 12%, 14% and 60% larger agent concentrations for  $N_2$ ,  $C_2HF_5$ , and  $CF_3Br$ , respectively. The calculation assumes that the effectiveness of chemically acting agents do not "saturate" as additional agent is added to a flame. This assumption is consistent with suppression experiments in JP8 spray flames with



**Figure 3.** The critical mole percentage of agent in the oxidizer required to suppress non-premixed heptane cup burner flames as a function of the initial oxidizer temperature.

the air temperature varying from 20°C to 350°C [2]. Figure 3 can be used to compare the suppression requirements for different agents if the oxidizer temperature of the agent/air mixture is known or can be estimated. Extrapolation of the results shown in Figure 3 suggest that under cold-flow (no fuel spray or fire present) conditions, lower agent concentrations are required for suppression. Of course, other factors come into play such as the rate of agent fluid flashing and agent dispersion.

#### **1.1.1.4 Pressure Effects**

Changes in pressure should have negligible effect on the critical agent concentration at extinction over the small range of pressure changes in a nacelle. A series of suppression experiments in JP8 spray flames with the pressure varying from 0 to 5 kPa showed that agent suppression concentrations do not change with pressure [Hamins et al., 1995].

The cup burner or other simple test of diffusion flame extinction (such as the opposed flow burner [Hamins et al., 1994]), however, is not the most conservative approach to suppression system design. A more conservative approach would involve consideration of flammability limits, which defines agent requirements to inert or suppress any fuel/air mixture. Such requirements are discussed below.

#### **1.1.2 Suppression of Premixed Flames**

Premixed flames are relevant to a discussion of suppression of engine nacelle fires. For example, a mechanism for the prevention of re-ignition of a fuel near a hot surface is by agent inerting. Discussion of this necessitates consideration of premixed flames and agent induced flammability limits. In addition, although many fire scenarios involve non-premixed reactants initially, it is possible that premixed flame regions may occur, for example, in the combustion/recirculation zone downstream of an obstructed pool fire. Such a situation may exist in ventilated engine nacelles if a fuel puddle is located downstream of a structural rib or baffle.

Suppression of premixed flames requires higher agent concentrations than non-premixed flames. Agent concentrations which suppress the most flammable premixed flames insure that all reactant mixtures are inert or inflammable. When the fuel concentration is plotted as a function of the critical agent inerting concentration, typical flammability limit curves are "D" shaped, with conditions outside of the "D" representing non-combustible mixtures. The fat part of the "D" represents the most hazardous condition, requiring the highest agent concentration to inert the mixture. This condition is known as the peak

flammability limit. Interpretation of experiments in the combustng recirculation zone of a baffle stabilized pool fire have shown that agent suppression requirements are consistent with peak flammability limit concentrations [Hamins et al., 1995]. The peak flammability limits also represent a reasonable target for agent concentrations near a hot surface when ignition may be possible.

Inerting concentrations or flammability limits have been measured in a variety of ways. A standard test apparatus is a vessel filled with gaseous reactants equipped with an ignition device as described in ASTM-E 681-94 [1994]. Although the device is cumbersome and somewhat subjective, the device has been extensively employed to determine the flammability limits of agent/hydrocarbon/air mixtures.

Flammability limits have been measured for many gaseous species including halogen containing molecules. Data for alkanes larger than methane result in similar peak limits [Zabetakis, 1965]. Fuel type and initial temperature have been shown to impact the halocarbon concentration required to inert the reactant mixture (Malcolm, 1950; Landesman and Basinski, 1964). Thus, care must be taken in interpreting flammability limit data as the peak flammability limits varies with initial temperature, pressure, and reactant type. These considerations may be important for engine nacelle applications.

For ambient conditions, agent inerting concentrations in the literature are 42%, 13%, 6% for N<sub>2</sub>, HFC-125, and halon 1301, respectively [Zabetakis, 1965; Hamins et al., 1995]. Testing shows that the peak inerting concentration of N<sub>2</sub> is approximately the same for a variety of fuel types including many alkanes (larger than methane), benzene (an aromatic), methanol (an alcohol) and acetone (a ketone).

The peak flammability limits of a fuel/air/agent mixture can be related to the limiting laminar flame speed ( $S_L$ ). A reasonable value for the limiting speed is approximately 3.5 cm/s [Noto et al., 1998]. At this speed, heat generation cannot keep up with heat losses and flame chemical reactions cannot be sustained. Flame speed calculations using detailed kinetics were conducted to determine the flame speeds of propane/air flames containing H<sub>2</sub>O and CO<sub>2</sub>, which along with N<sub>2</sub> make up primary components of the SPGG. Propane was selected rather than methane, because detailed kinetics are available for this fuel and its combustion has many of the complexities associated with larger hydrocarbons including carbon-carbon bond destruction. The calculated flame speed ( $S_u$ ), normalized by the flame speed without agent addition ( $S_o$ ), was related to the concentration of agent  $C_{in}$  for a particular fuel/air equivalence ratio [Noto et al., 1998]:

$$S_u/S_o = \exp(-b \cdot C_{in}) \quad (6)$$

A mixing rule for the flame speed of mixtures with known  $b$  is given as [Noto et al., 1997]:

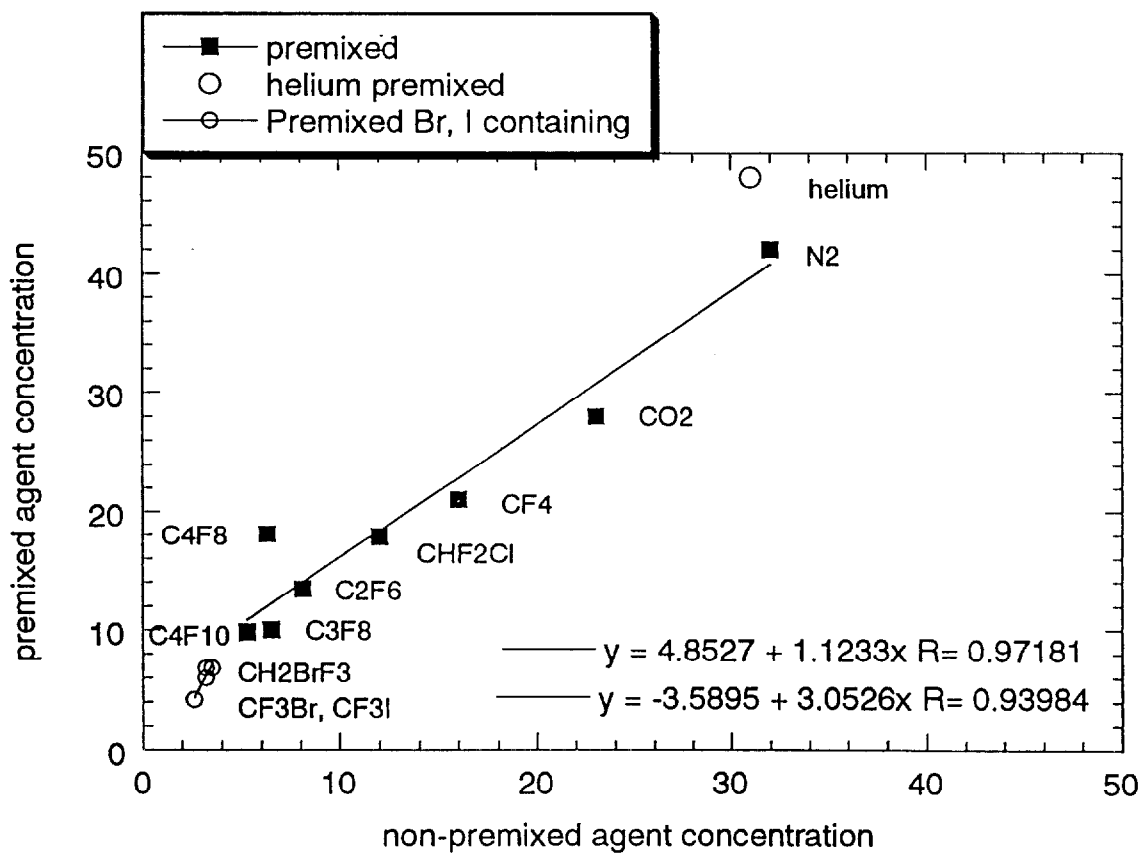
$$b = \sum b_i \cdot C_{in} \quad (7)$$

The coefficients  $b$  were calculated using the PREMIX flame code [Kee et al., 1985] with detailed kinetics for propane [Peters, 1993]. Calculations used an equivalence ratio of 1.4 which was close to the peak in flammability.  $S_o$  was calculated to be equal to 26.3 cm/s. Calculated flame speeds with  $H_2O$ ,  $N_2$ , and  $CO_2$  additions led to best fit values for the coefficient  $b$  in Eq. 7 equal to 5.47, 4.89 and 7.13, respectively. At extinction ( $S_u = 3.5$  cm/s), the mole based concentrations for  $H_2O$ ,  $N_2$ , and  $CO_2$  were 37%, 42%, and 28%, respectively. These extinction results for  $N_2$  and  $CO_2$  are consistent with previously measured flammability limits [Zabetakis, 1965]. Using Eq. 7, the effective mixture coefficient for the Primex SPGG (see Table 1) was 5.72, yielding an extinction concentration of 35% by moles. The inerting concentration for the WKA SPGG was not calculated because a quantitative kinetic mechanism which would allow calculation of  $b_i$  for  $K_2CO_3$  is not available.

An alternative approach to determining inerting concentrations is shown in Figure 4, which presents an empirical relationship between the critical agent mole percent in the oxidizer of non-premixed heptane cup burner flames and the peak flammability limits for an agent or inerting concentration in mole percent of reactants for propane/air/agent premixed flames [Malcolm, 1950; Zabetakis, 1965; Hamins et al., 1995;]. Figure 4 shows that flame extinction in these two combustion systems scale with each other. Results for helium do not correlate with the other agents probably because of large preferential diffusion effects which assist its effectiveness in the suppression of non-premixed flames. Curiously, the chloro-fluorinated compounds yield a different slope than the bromine containing compounds. If information is known about one system, then Figure 4 can be used to estimate the agent concentration required for extinction in the other system.  $H_2O$  and the filtered Primex SPGG which require 27% and 28% (by moles), respectively (see Table 2) to extinguish heptane cup burner flames, can be expected to require 35% and 36% (by moles) to inert premixed flames. These results are in agreement with the results determined above using the PREMIX flame code. Using this approach, the inerting concentration for the WKA SPGG was estimated as 24% (by moles) from the results presented in Figure 4 and Table 2.

#### 1.1.2.1 Temperature Effects

Changes in air temperature may affect agent requirements in a number of ways including changes in the peak flammability limits with increasing reactant temperature. A literature search



**Figure 4.** Empirical data showing the relationship between the critical agent mole percentage in premixed propane/air flames as a function of the critical agent mole percentage (in the oxidizer) in heptane non-premixed cup burner flames.

revealed scant data on such effects. The little data that is available showed that there is a broadening of flammability limits and an increase in peak agent inerting requirements with increasing temperature.

The temperature dependence in the flame speed ( $S_u$ ) is dominated by an exponential term [Glassman, 1987]. Since the heat release is dominated by the highest flame temperature ( $T_m$ ), it is possible to assume that:

$$S_u \approx \{\exp(-E/RT_m)\}^{1/2} \quad (8)$$

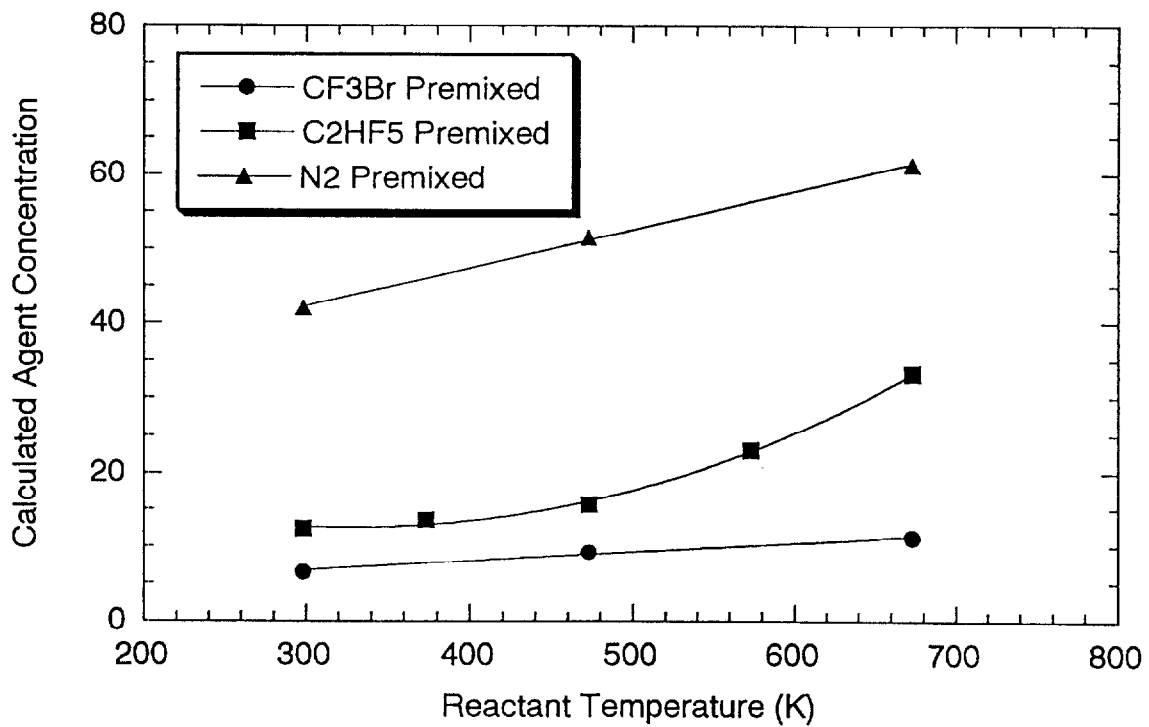
Varying the initial temperature of the reactants alters the maximum flame temperature ( $T_m$ ). For increasing reactant temperatures, it is possible to calculate the amount of agent required to reduce  $T_m$  to a particular value. The reference flame temperature,  $T_m$  in Eq. 8, is calculated using the CEC code [Gordon and McBride, 1976] for the limiting mixture concentrations (see above:  $H_2O$ ,  $N_2$ , and  $CO_2$  equal to 37%, 42%, and 28%, respectively) with the reactants initially at ambient temperature. Subsequent calculations used the CEC code to determine the  $N_2$  concentration required to inert the propane/air mixture (with an equivalence ratio of 1.35) as a function of the initial reactant temperature. Similar calculations were completed for HFC-125 and halon 1301. The results are shown in Figure 5. The range of temperatures considered corresponds to mixtures of air and SPGG effluent just upstream of the fire zone in the nacelle. Propane was used in these calculations because many hydrocarbons yield approximately the same agent inerting requirements [Zabetakis, 1965] and no information is available for JP8.

The results in Figures 3 and 5 show that as reactants are preheated, more agent is required to inert a mixture under both premixed and nonpremixed conditions. The increases in concentration are nearly linear over a range of temperatures for both combustion configurations and for a variety of gas species. These calculations are consistent with experimental results for methanol/air non-premixed flames extinguished by  $N_2$  [Hamins, 1985] and for JP8 spray flames suppressed by halogenated compounds [Hamins et al., 1994]. For an increased initial temperature of 100°C, Figure 5 indicates that agent requirements increase by approximately 12%. Similar results were found for other inert agents. The calculation assumed that the equivalence ratio at the peak flammability limit does not shift with increasing mixture temperature for premixed flames. This should be experimentally verified.

#### 1.1.2.2 Pressure Effects

Pressure variations can occur in a nacelle. Pressure has an





**Figure 5.** The calculated  $N_2$ , HFC-125 and  $CF_3Br$  concentration required to inert a propane/air mixture with an equivalence ratio of 1.35, as a function of the initial reactant temperature.

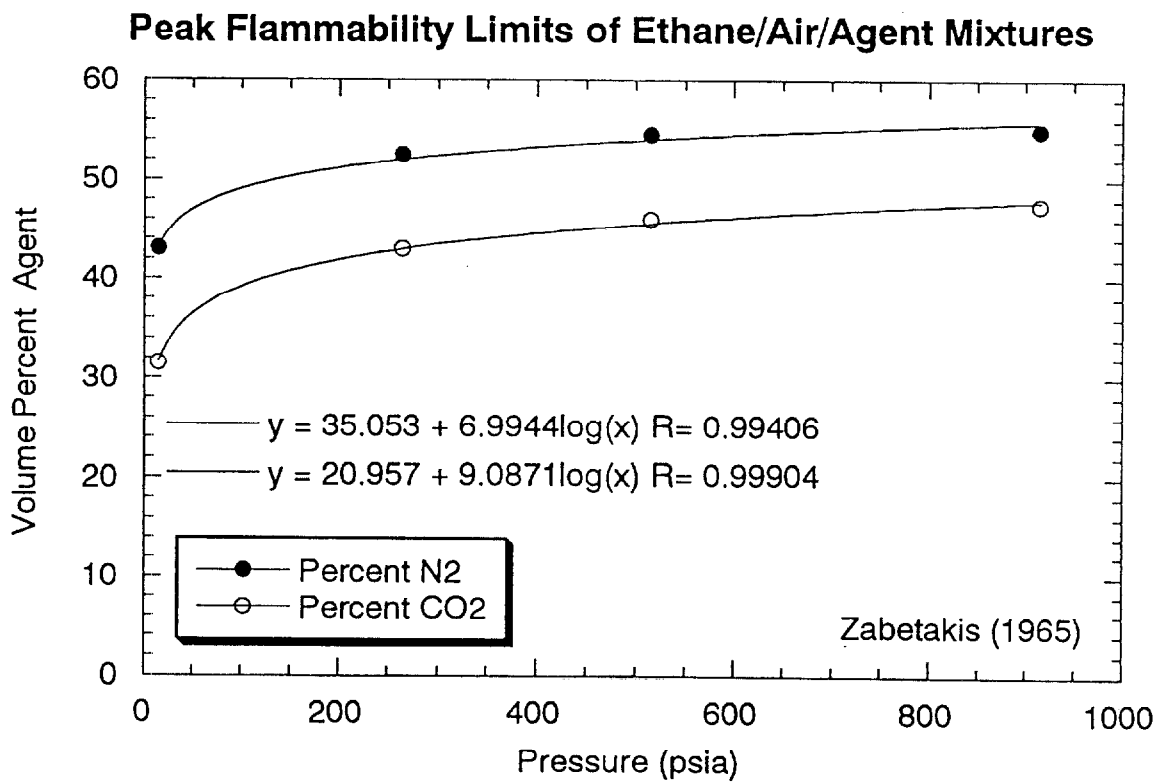
effect on peak agent concentrations at the flammability limits, but probably has a negligible impact for the range of pressure encountered in nacelles where pressures are near atmospheric. Figure 6 shows data taken from Zabetakis [1965] for the peak agent flammability limits in ethane/air/agent mixtures for  $\text{CO}_2$  and  $\text{N}_2$  as a function of pressure. Elevated pressures require increased agent concentrations. If flight conditions result in a pressure of 1.1 atm, then interpolating from Figure 6 suggests that agent inerting requirements would increase approximately 0.7% for  $\text{N}_2$  and 1.2% for  $\text{CO}_2$ , as compared to atmospheric pressure inerting concentrations. Scant information is available on pressure effects on the flammability limits of mixtures of fuel, air, and halogenated agents such as  $\text{CF}_3\text{Br}$ .

## 1.2 Re-ignition Prevention

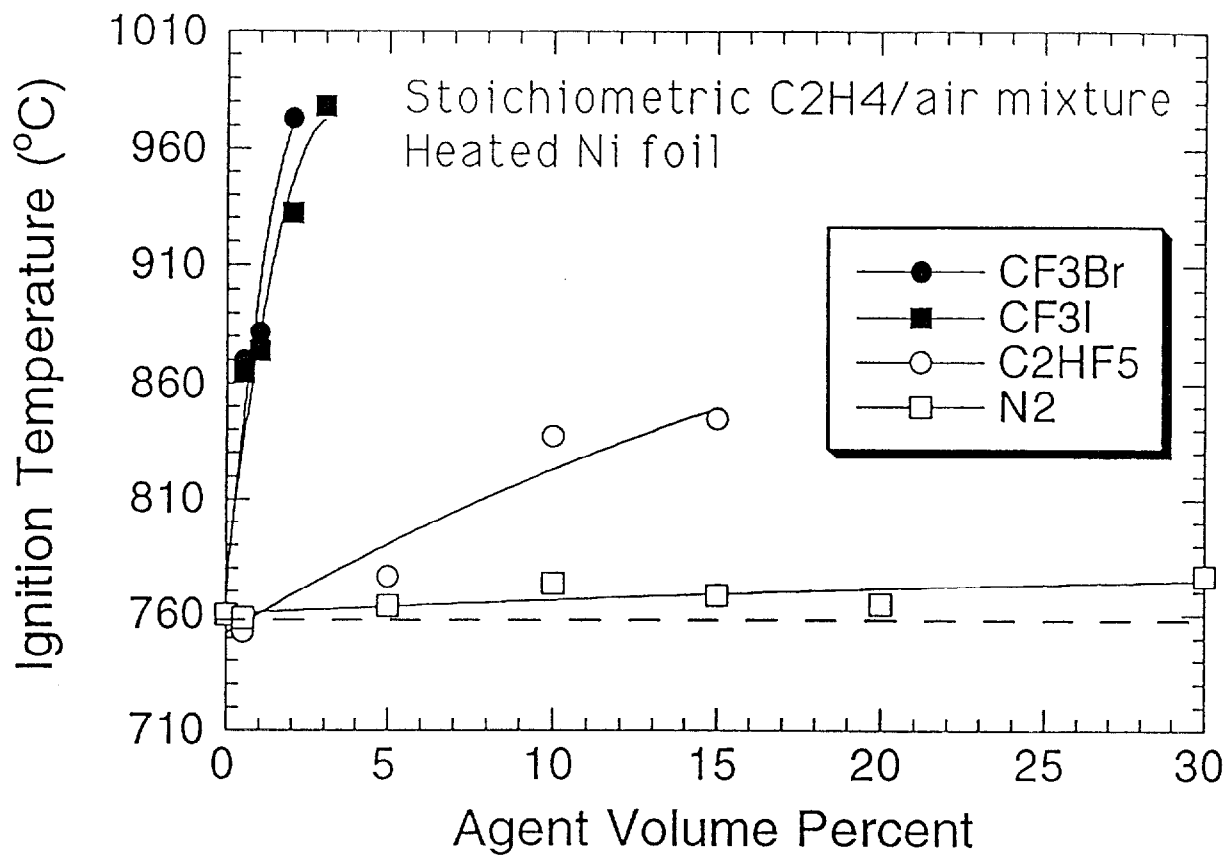
Conditions which lead to re-ignition are controlled by the time/temperature history of the reactive mixture and to a lesser extent by the type of metal surface and chemical composition of the fuel. Under certain conditions, when a hydrocarbon fuel spray is near a hot surface, fire suppression and prevention of re-ignition is much more difficult and agent requirements can increase by a factor of two or more as compared to conditions when the hot surface is not present. Through observation, this was attributed to re-ignition [Reuther, 1997]. Re-ignition was prevented only after very large amounts of halogenated agent were applied, presumably due to high agent concentration near the hot surface for a sufficient duration. In the experiments described here, that interval was defined as a period of 8 s when the fuel spray operated after flame extinction. Agent cooling of the hot metal surface ( $610^\circ\text{C}$ ) in Run 3 likely was not a significant mechanism in preventing the re-ignition because the difference in heat transfer between the heated agent ( $77^\circ\text{C}$ ) and the hot air flow itself ( $135^\circ\text{C}$ ) was small.

The surface temperature required to cause ignition of reactant mixture is highly influenced by the type and the concentration of the fire suppression agents considered here. Inert agents such as  $\text{H}_2\text{O}$ ,  $\text{CO}_2$  and  $\text{N}_2$  which are major constituents of SPGG have a negligible effect on the ignition temperature of a hot metal surface, until the agent concentration is beyond the flammability limits. Figure 7 shows results for the ignition temperature of a heated Nickel foil with a stoichiometric  $\text{C}_2\text{H}_4$ /air mixture and various agents flowing over its surface. The dotted line represents the ignition temperature with no agent added. The ignition temperature was nearly constant as  $\text{N}_2$  was added to the mixture. Ignition was prevented only when high concentrations of agent, beyond the flammability limits, were present.

Other strategies may exist to prevent re-ignition by a hot surface. Local application of a small amount of a possibly



**Figure 6.** The peak agent flammability limits in ethane/air/agent mixtures are shown for CO<sub>2</sub> and N<sub>2</sub> as a function of ambient pressure. The data is taken from Zabetakis (1965).



**Figure 7.** The ignition temperature of a heated Nickel foil with a stoichiometric mixture of C<sub>2</sub>H<sub>4</sub>/air and various agents flowing over its surface.

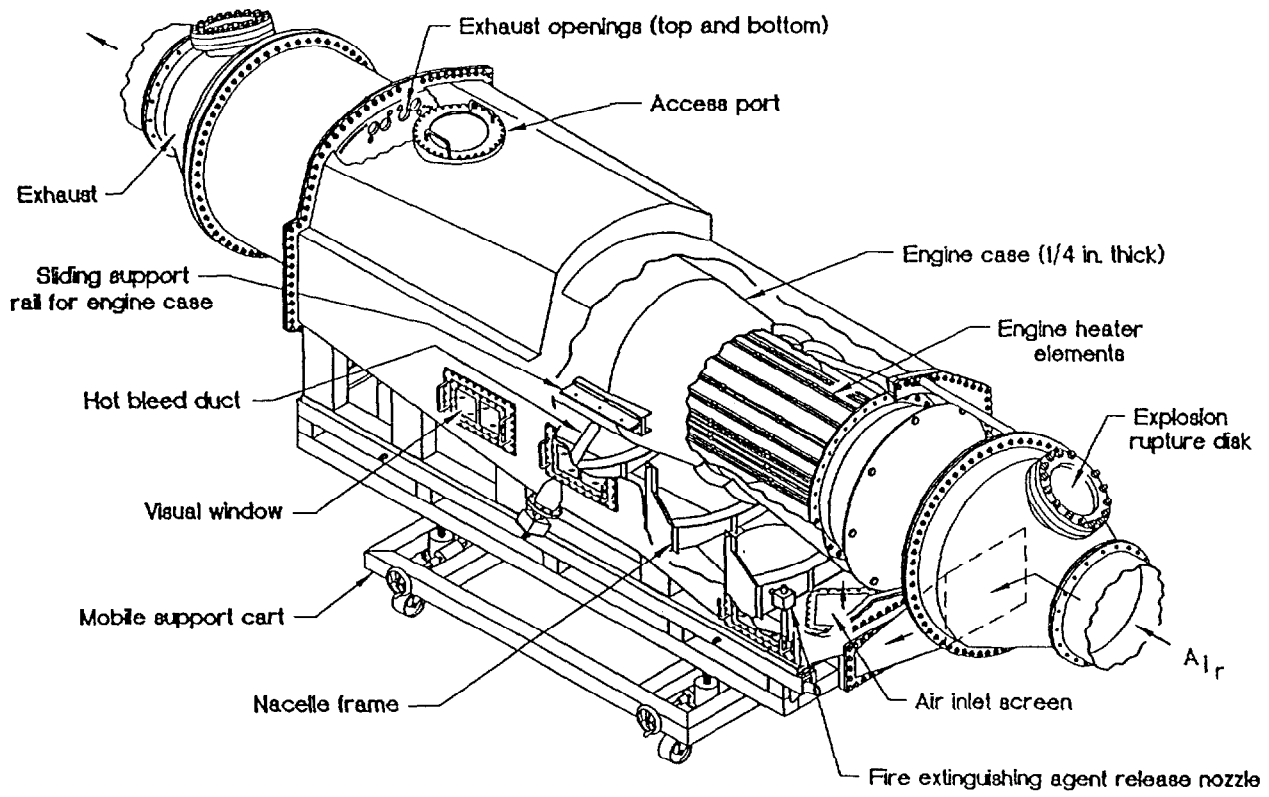
different type of agent (liquid, foam, or powder) directly on the hot surface is a possibility. This phenomena was observed to occur in the case of the SPGG experiments, where  $K_2CO_3(s)$  sticking to the surface of the hot bleed air duct operated like an insulating barrier and also may have diminished surface catalytic effects, preventing re-ignition of the fuel spray.

## 2. FULL-SCALE TEST CONDITIONS AND RESULTS

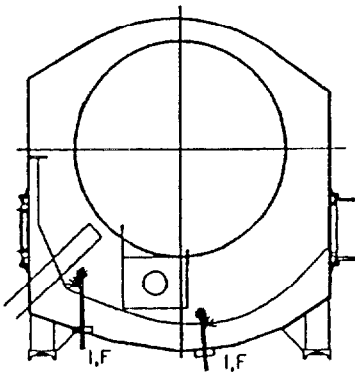
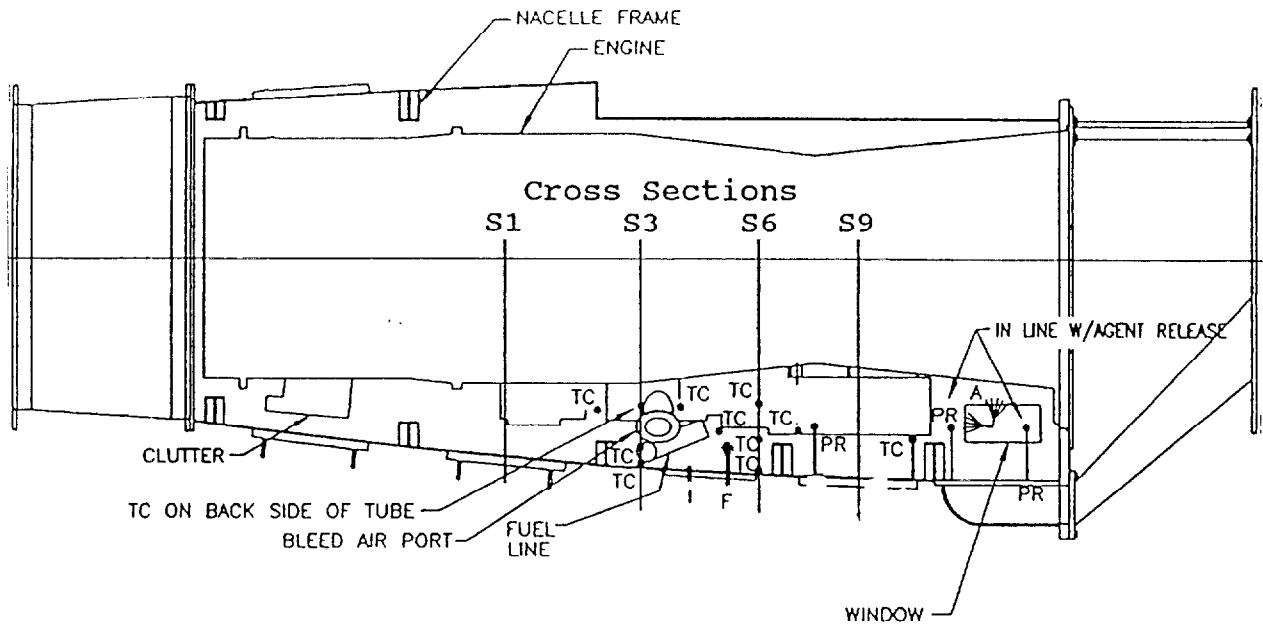
Table 4 outlines the key experimental conditions used during the full-scale F-22 tests. The conditions in each of the runs was different in terms of the fire zone location, the air temperature, the agent storage temperature, the hot bleed air duct temperature, the inner-wall surface temperature of the nacelle, and the air flow. Figure 8 is a perspective drawing of the exterior of the full-scale engine nacelle. Figures 9 is a schematic of the interior of the nacelle. The fuel nozzles were located near Section S5 in the nacelle. The downstream side of the hot bleed air duct was 30 cm downstream from the fuel nozzles in Section S3 of the nacelle. Figure 10 is a photograph of the hot bleed air duct (diameter  $\approx 15$  cm). Ventilation air moved from right to left in Figures 8-10.

The hot bleed duct surface appears very dark due to a build-up of soot and possibly corrosion. Cleaning of the duct before measurements became standard practice during SPGG testing. A thermocouple was held under a ring clamp on the downstream side of the hot bleed air duct to monitor the surface temperature. Figure 10 is illustrative of the large amount of clutter inside the nacelle which included fuel lines, electrical lines and components, hydraulic lines, structural ribs, and so on. A portion of the fuel spray cloud emitted from the nozzle in Fire Zone 1 flowed towards the hot bleed air duct where re-ignition of the JP8 fuel spray occurred under certain conditions. The spray flame heated the bleed air duct and the duct acted as an ignition source for the fuel spray. The hot bleed air duct was isolated from Fire Zone 2, nor were there other components that might act as re-ignition sources for the fuel spray in Zone 2.

Figure 11 is a schematic drawing of the two agent delivery nozzle configurations which were tested which included the alternative configuration (labeled "incorrect") and the "correct" configuration matching the actual F-22 plumbing. The delivery system was composed of a tube which split into two branches, oriented at right angles to each other. One branch was directed downstream, nominally towards the hot bleed air duct, whereas the other branch was oriented directly up. The placement and orientation of the delivery system in the two configurations did not differ, but the orientation of the inlet line into the nozzles differed. The alternative configuration had the inlet nozzle oriented parallel to the vertical outlet branch, whereas



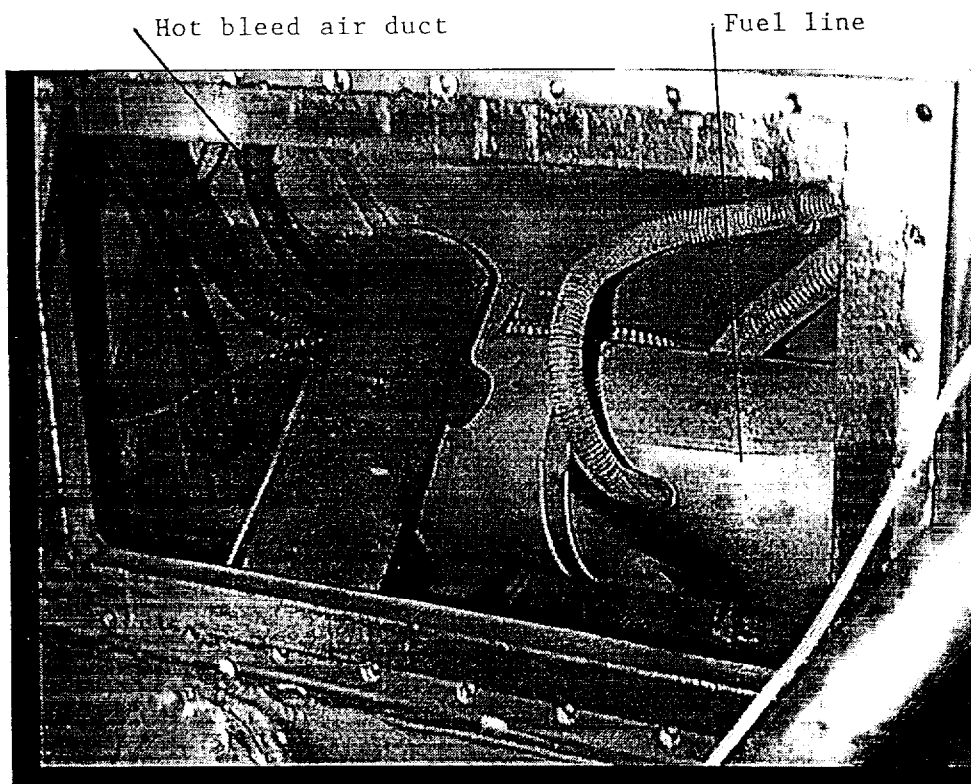
**Figure 8.** A perspective illustration of the external portion of the full-scale engine nacelle.



SECTION AT INJECTORS

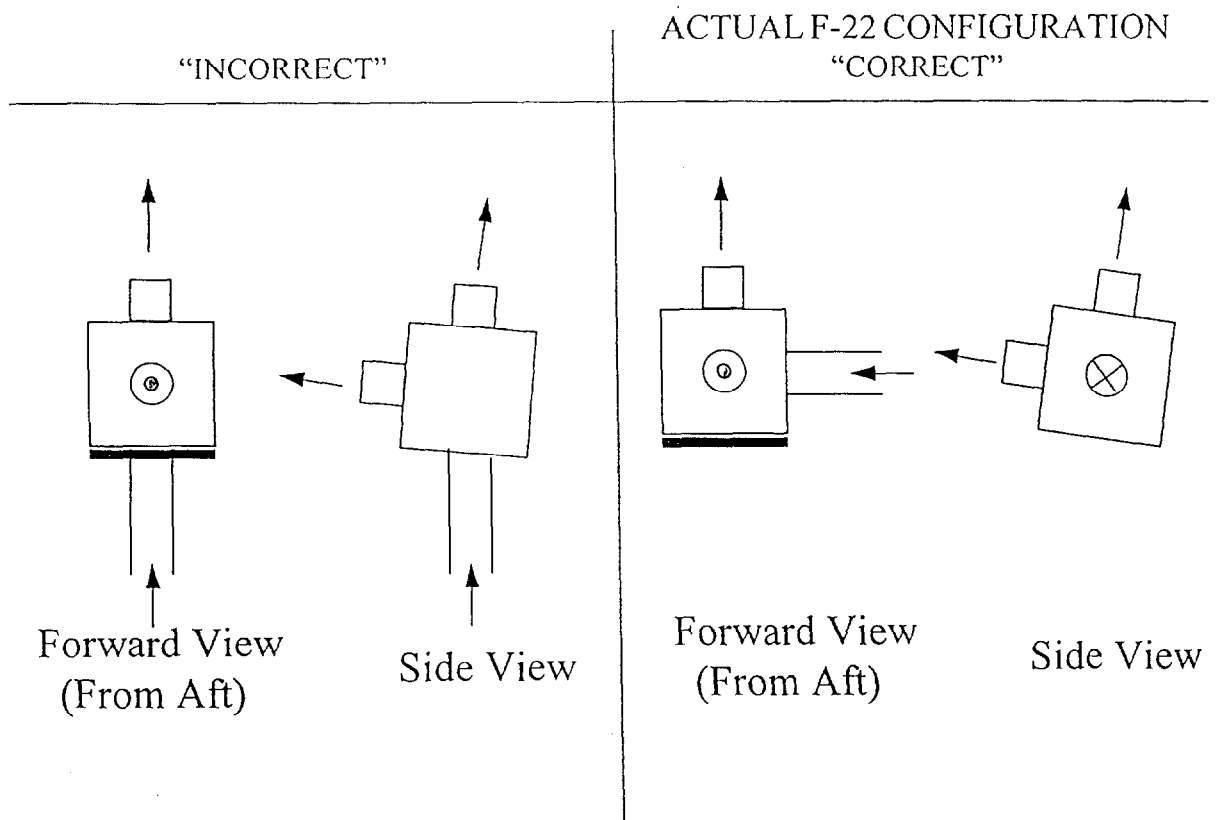
- I IGNITOR
- F FUEL INJECTION
- A AGENT RELEASE POINT
- PR PRESSURE TRANSDUCER
- TC THERMOCOUPLE
- PT PITOT TUBE
- ↑ FIXED DEPTH

Figure 9. A schematic drawing of the interior of the engine nacelle.



**Figure 10.** A photograph of the hot bleed air duct and fuel line.





**Figure 11.** A schematic drawing of the two agent delivery nozzle configurations which were tested.

Test Run	Fire Zone	T <sub>air</sub> (°C)	T <sub>agent</sub> (°C)	T <sub>duct</sub> (°C)	T <sub>surf</sub> (°C)	Airflow (kg/s)
conf	1	52	21	371	149	0.45
1	1	135	77	610	316	1.1
2	1	135	77	610	316	0.68
3	1	135	77	610	316	0.36
4	1	56	21	454	177	1.1
5	1	-37	-40	610	177	0.36
6	1	56	21	454	316	0.36
7	1	-37	-40	232	27	1.1
8	1	-37	-40	232	27	0.68
9	1	-37	-40	232	27	0.36
10	2	135	77	610	316	1.1
11	2	135	77	610	316	0.68
12	2	135	77	610	316	0.36
13	2	56	21	454	177	1.1
14	2	-37	-40	610	316	0.36
15	2	-37	21	454	177	0.36
16	2	-37	-40	232	27	1.1
17	2	135	-40	232	27	0.68
18	2	135	-40	232	27	0.36

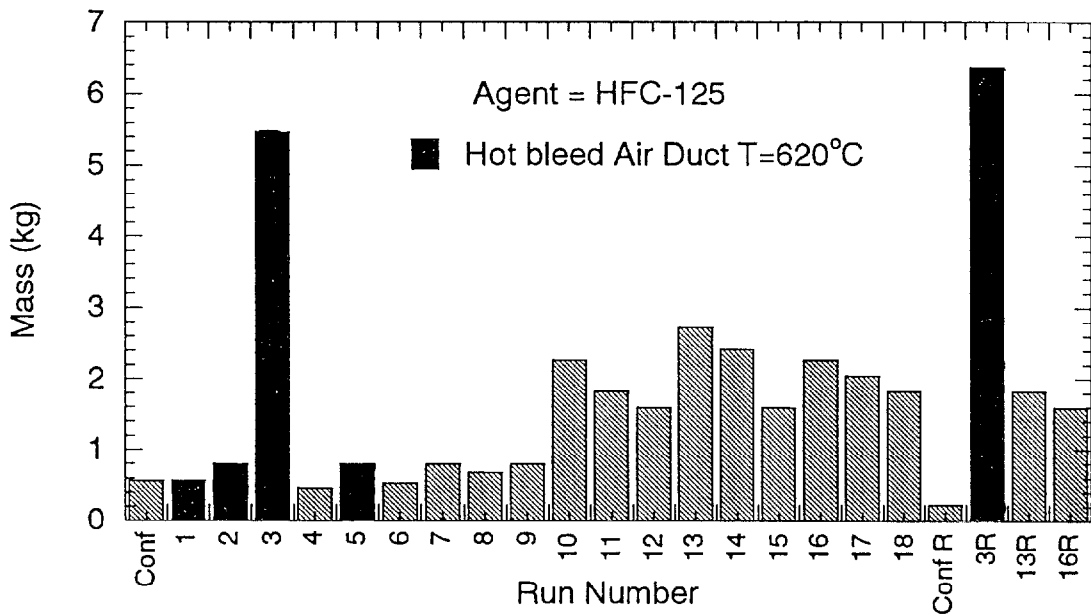
the actual F-22 system had the inlet branch at right angles to both the outlet branches. This likely resulted in a larger percentage of agent exiting from the vertical branch in the alternative configuration, whereas an even split of agent mass would be expected for the actual F-22 system. Tests using the actual F-22 plumbing system are referred to with the suffix "R" after the run number.

Data taken during agent testing showed that the temperature on the surface of the hot bleed air duct increased when the fuel spray ignited and decreased when the flame was extinguished. The initial temperature varied by as much as 80°C from run to run. This variability probably had an impact on the probability of re-

ignition.

The mass requirements corresponding to the conditions in Table 4 for suppression tests using HFC-125 are shown in Figure 12. Agent requirements for the Runs denoted as Conf were determined during Phase I testing using a procedure different from the other experiments and the experimental uncertainty associated with those experiments is smaller. Runs 3 and 3R, with fires in Zone 1 and with the bleed air duct initially at 620°C required the largest agent mass to extinguish and prevent re-ignition. Other runs with the hot bleed air duct at 620°C (and the fire in Zone 1), such as Runs 1, 2, and 4, did not require large agent mass. The reasons for this can be rationalized in terms of the Phase I fuel spray re-ignition experiments which were conducted without agent addition and with the hot bleed air duct temperature initially at 621°C [Gillespie, 1997]. The surface and air temperatures in the Phase I testing were also the same as in Runs 1 and 2. The Phase I experiments showed that lower airflow or longer preburn durations increased the probability of ignition. For the airflows used in Runs 1 and 2, a 20 s preburn duration yielded re-ignitions only 20% and 80% out of the 5 tests, respectively. To achieve 100% ignition for airflows of 1.5 lb/s and 2.4 lb/s, longer preburn times were required (25 s and 35 s respectively). For low airflows (similar to that used in Run 3), re-ignition repeatedly occurred for the 20 s preburn duration. Agent addition in Runs 1 and 2 diminished the probability of re-ignition probably due to increased convective cooling of the bleed air duct. It is also possible that the shape of the spray flame changed as agent was delivered, directing the flame away from the hot bleed air duct. Run 4 also had a hot bleed air duct and an air flow similar to Run 3. In Run 4, however, the air temperature was much lower (-37°C) than in the Phase I experiments (135°C) which would lower the flame temperature and would lead to faster cooling after flame suppression. In fact, re-ignition was not observed during the Phase II tests for Run 4. Complementary HFC-125 concentration measurements for conditions in Run 4 showed that only small agent concentrations were present in Fire Zone 1, 8 s after the initiation of agent delivery. This suggests that inerting of the region near the hot bleed air duct was not the mechanism by which re-ignition was prevented.

Figure 12 shows that the mass requirements for suppression of fires in Zone 1 (Runs 1-8, Conf, and ConfR) were generally smaller than the mass requirements for fires in Zone 2 (Runs 9-18, 13R and 16R). The exception to this was Runs 3 and 3R, the two Zone 1 fire tests when re-ignition played a controlling role. The reasons for the mass requirements should be related to factors which impact flame stability such as agent mixing or fluid mechanical strain.



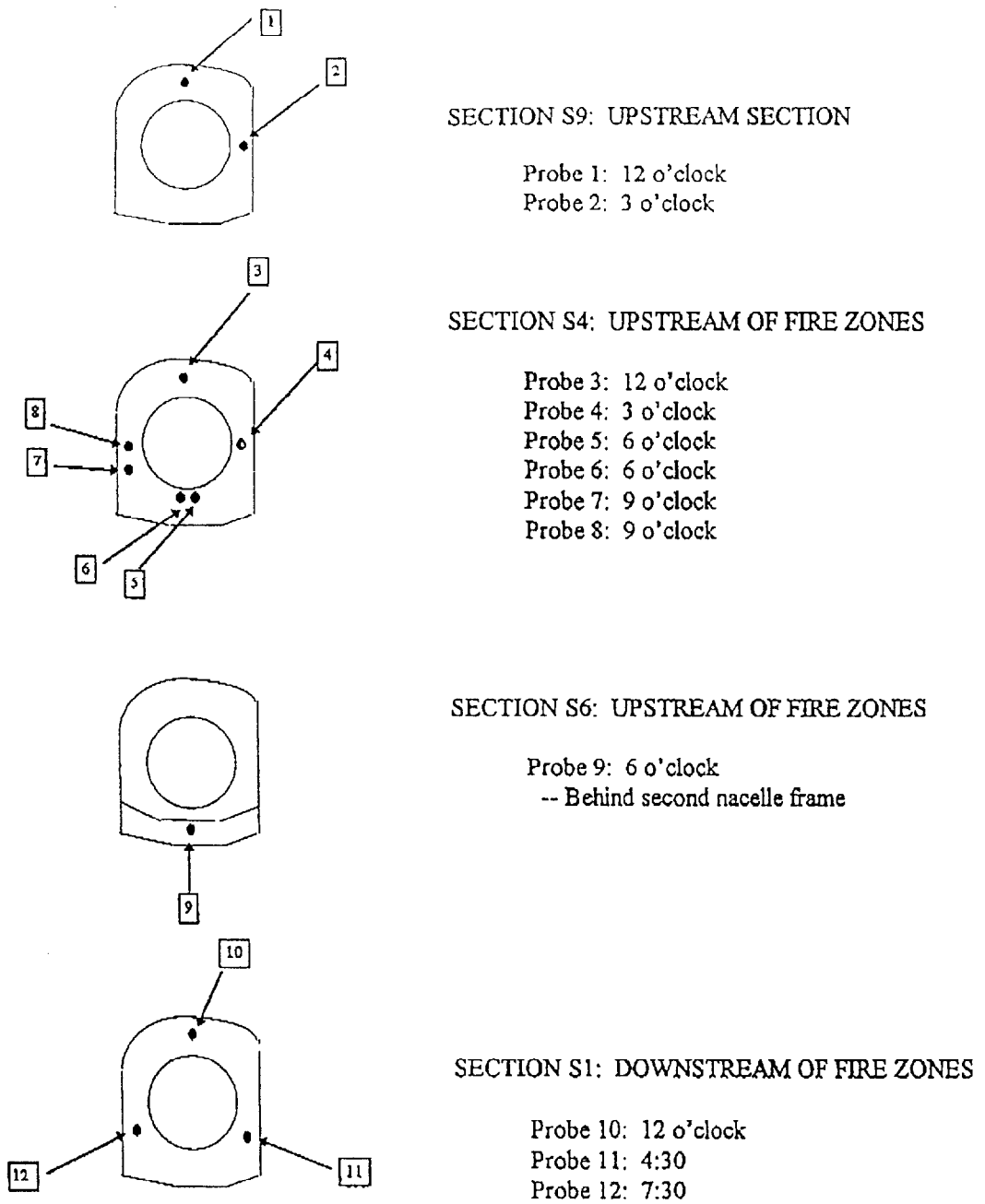
**Figure 12.** The HFC-125 mass requirements corresponding to the conditions in Table 4 for the suppression experiments Runs 1 to 18, 3R, 13R, and 16R, Conf, and ConfR.

## 2.1 Agent Distribution

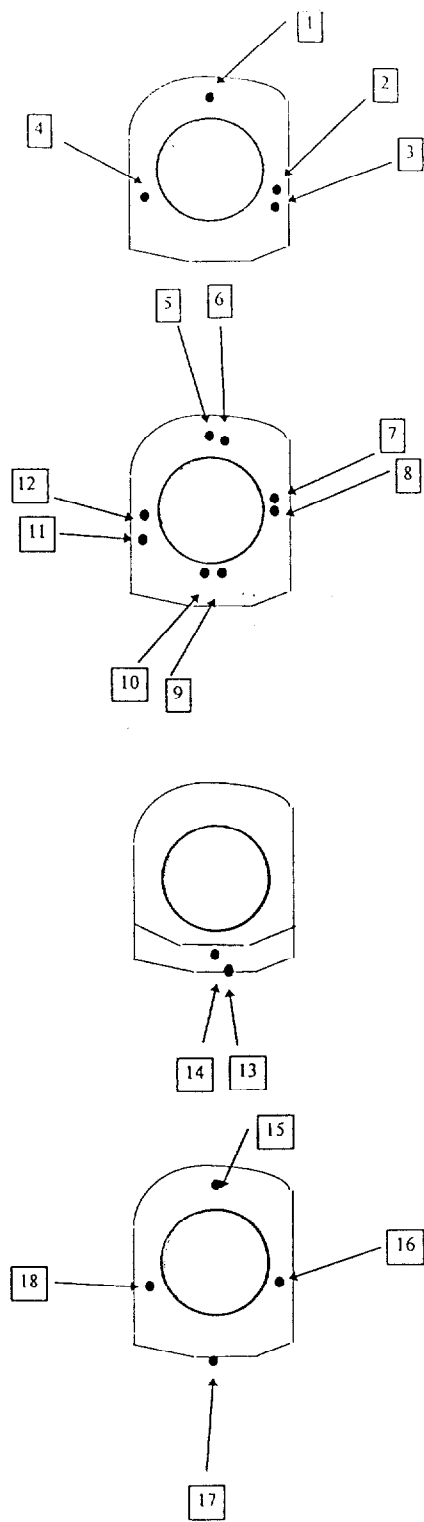
A series of cold-flow measurements (no fuel spray or fire present) were conducted to determine the agent concentration distribution for tests with HFC-125,  $\text{CF}_3\text{Br}$ , and SPGG effluent, emphasizing locations near the fire zone. The rationale for measuring agent concentrations in cold flow assumes that the upstream agent mixing behavior and dispersion which controls suppression was unaffected by the gas expansion and buoyancy associated with the fire or the momentum associated with the fuel spray. The methodology for the cold-flow (no fuel spray or fire present) concentration measurements are analogous to the measurements conducted during nacelle certification with halon 1301. The concentration profiles for  $\text{CF}_3\text{Br}$  and HFC-125 were conducted using a Statham analyzer which measures the differential pressure across a critical flow orifice. The time response is on the order of 100 ms. The  $\text{CO}_2$  and  $\text{O}_2$  concentration measurements were conducted using Primex gas analyzers. The  $\text{CO}_2$  measurement is based on IR transmission at  $4.3 \mu\text{m}$ . The  $\text{O}_2$  sensor is electrochemical in nature. The manufacturer claims that the time response for the gas analyzers is on the order of 100 ms. Figures 13 and 14 show the location of the sampling probes which were used in conjunction with the analyzers. Probe numbers were designated by the section number and clock position as viewed from the upstream portion of the nacelle. Figure 9 indicates the relative location of the different sections. In Figure 14, corresponding channel numbers are indicated next to the probe numbers. The key probe locations were those which represented agent concentrations in Fire Zones (1) and (2). These were Statham probe numbers (5 & 6) and (7 & 8), and Primex gas analyzer probe numbers (9 & 10) and (11 & 12), respectively. The Primex gas analyzer probe numbers 9 and 11 were also referred to as  $\text{CO}_2$  channel numbers 6 and 7, while the Primex gas analyzer probe numbers 10 and 12 were also referred to as  $\text{O}_2$  channel numbers 4 and 5.

### 2.1.1 Halogenated Agents

Measured peak agent concentrations for different probes locations are indicative of agent distributions. Figure 15 shows the calibration factors which were applied to the relative agent concentrations measured by the Statham analyzer to determine absolute concentrations. Figure 16 is an example of the transient agent concentration sampled by Probes 5, 6, 7, and 8 for cold-flow conditions (no fuel spray or fire present) defined by Run 3R (Test 26C) with 6.4 kg of HFC-125 delivered to the nacelle. As seen in Figure 13, Probes 5 and 6 were located approximately 10 cm downstream from the fuel injector in Fire Zone 2 and within 15 cm of each other. Probes 7 and 8 were located approximately 10 cm downstream of the fuel injector in Fire Zone 1, midway between the engine casing and the outer



**Figure 13.** The location of the sampling probes which were used in conjunction with the Statham analyzer for determination of the concentrations of  $CF_3Br$  and HFC-125 under cold-flow conditions.



SECTION S9: UPSTREAM SECTION

Probe 1 - CO <sub>2</sub> :	12:00	CO <sub>2</sub> -1
Probe 2 - CO <sub>2</sub> :	4:30	CO <sub>2</sub> -2
Probe 3 - O <sub>2</sub> :	4:30	O <sub>2</sub> -1
Probe 4 - CO <sub>2</sub> :	7:30	CO <sub>2</sub> -3

SECTION S4: UPSTREAM OF FIRE ZONES

Probe 5 - CO <sub>2</sub> :	12:00	CO <sub>2</sub> -4
Probe 6 - O <sub>2</sub> :	12:00	O <sub>2</sub> -2
Probe 7 - CO <sub>2</sub> :	3:00	CO <sub>2</sub> -5
Probe 8 - O <sub>2</sub> :	3:00	O <sub>2</sub> -3
Probe 9 - CO <sub>2</sub> :	6:00	CO <sub>2</sub> -6
Probe 10 - O <sub>2</sub> :	6:00	O <sub>2</sub> -4
Probe 11 - CO <sub>2</sub> :	9:00	CO <sub>2</sub> -7
Probe 12 - O <sub>2</sub> :	9:00	O <sub>2</sub> -5

SECTION S6: UPSTREAM OF FIRE ZONES

Probe 13 - CO <sub>2</sub> :	9:00	CO <sub>2</sub> -8
Probe 14 - O <sub>2</sub> :	9:00	O <sub>2</sub> -6
-- Behind second nacelle frame		

SECTION S1: DOWNSTREAM OF FIRE ZONES

Probe 15 - CO <sub>2</sub> :	12:00	CO <sub>2</sub> -9
Probe 16 - CO <sub>2</sub> :	3:00	CO <sub>2</sub> -10
Probe 17 - CO <sub>2</sub> :	6:00	CO <sub>2</sub> -11
Probe 18 - CO <sub>2</sub> :	9:00	CO <sub>2</sub> -12

Figure 14. The location of the sampling probes which were used in conjunction with the Primex gas analyzers for determination of the concentrations of CO<sub>2</sub> and O<sub>2</sub> under cold-flow conditions.

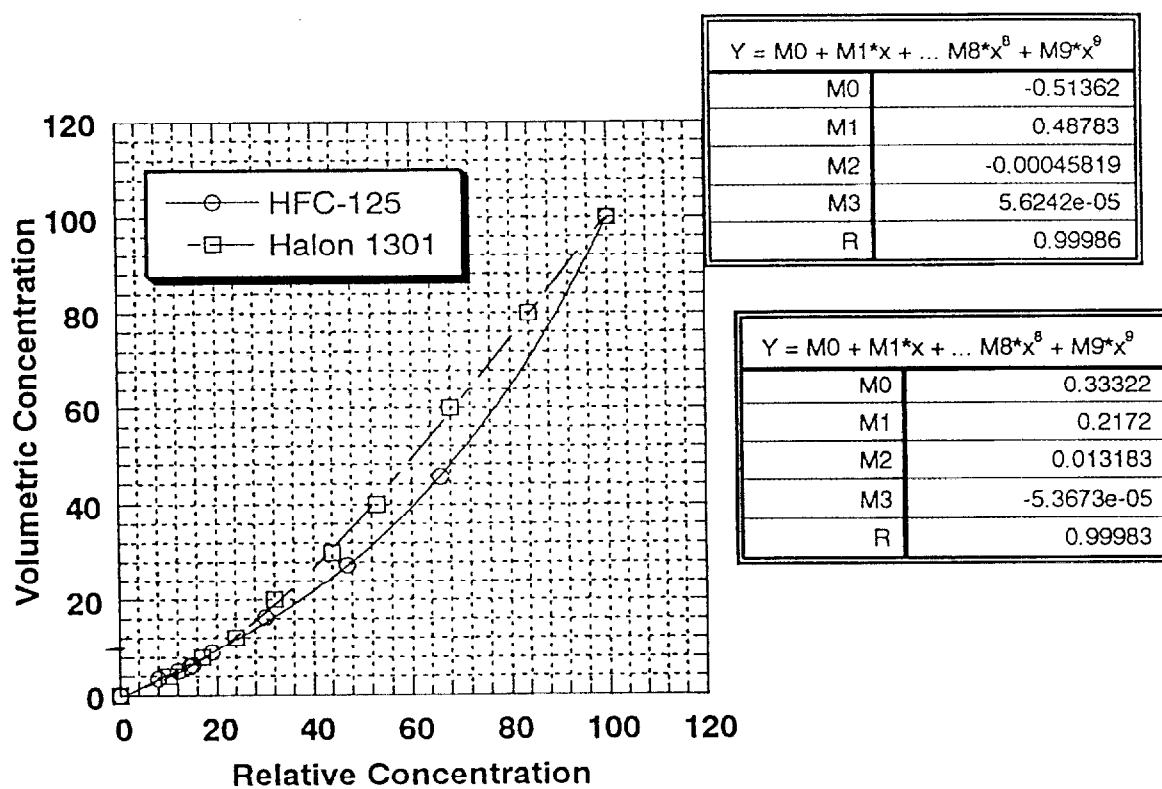
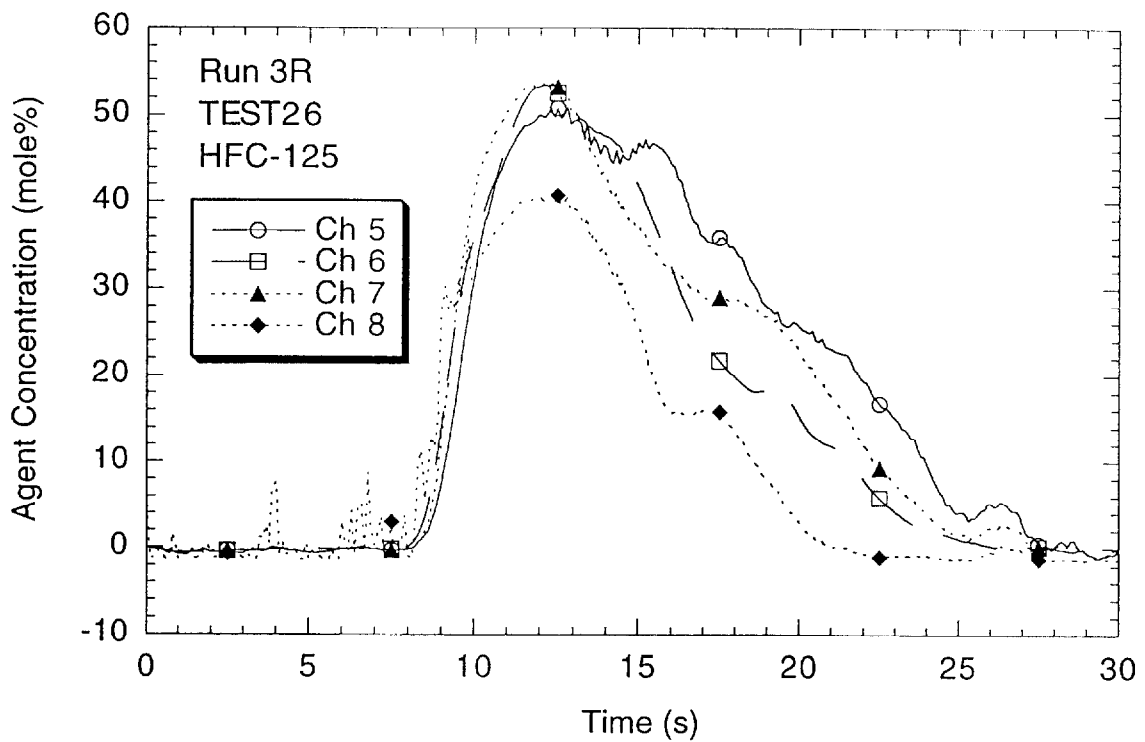


Figure 15. The calibration factors which were applied to the relative agent concentrations measured by the Statham analyzer to determine absolute concentrations.





**Figure 16.** The transient HFC-125 concentration sampled by Probes 5, 6, 7, and 8 for cold-flow conditions defined by Run 3R (Test 26C); 6.4 kg of HFC-125.

nacelle wall, just upstream of the hot bleed air duct, and within approximately 15 cm of each other [Gillespie, 1997]. In Figure 16, the duration of the agent peaks was of interest. The concentration peaks for Probes 7 and 8 in Figure 16 differ significantly, suggesting the existence of large concentration gradients for the agent in Zone 1. Large concentration gradients were not observed for Probes 5 and 6. The agent concentration remained above the peak flammability limits ( $\approx 15\%$  by volume) for approximately 7 and 13 s, respectively, for Probes 7 and 8.

Measured peak agent concentrations for the probes in the appropriate fire zones should be indicative of agent mass requirements for flame extinction as exemplified by the results shown in Table 2 and Figure 2. Figure 17 shows the measured peak HFC-125 concentrations as a function of the mass required to suppress the spray flames for the conditions described in Table 4. Peak agent concentrations are shown for Probes 5 and 6 for fires in Fire Zone 2, and Probes 7 and 8 for fires in Fire Zone 1. Data for both the alternate and the actual nozzle configurations are shown. For tests when the bleed air duct was  $620^{\circ}\text{C}$ , concentration results are labeled with a "+". The results cluster into three distinct groups. The lowest mass requirements were for the fires in Zone 1 (represented by concentration data from Channels 7 and 8) as seen in Figure 12. The associated agent concentrations for fires in Zone 1 were generally lower than the agent concentrations for fires in Zone 2. The highest mass requirements were for the two tests (Runs 3 and 3R) where the mass requirements were driven by re-ignition. Other tests (Runs 1, 2, and 5) with the hot bleed air duct surface at  $620^{\circ}\text{C}$  did not cause re-ignition and did not require large agent masses.

Figure 2 shows that the maximum HFC-125 concentration required to suppress the NIST spray flames was  $\approx 10\%$  (by moles) for reactants initially at room temperature. Figure 17, however, shows that much larger agent concentrations were required. More than half of the concentration results for Fire Zone 2 (Runs 14-16 and 18), were characterized by peak agent concentrations larger than 10%. In general, the average HFC-125 concentration associated with the critical agent mass required for suppression was significantly higher in Zone 2 than in Zone 1 for nearly all of the Runs (except Run 9). The ratio of the peak HFC-125 concentration in Zone 2 to the peak HFC-125 concentration in Zone 1 was a value of approximately  $2.5(\pm 1.2)$ . Thus, it is not surprising that less agent was needed to extinguish fires in Zone 1 which required an average of  $0.7 \text{ kg} \pm 0.1 \text{ kg}$  (excluding Run 3 which was dominated by re-ignition rather than suppression), as compared to Zone 2 which required an average of  $2.1 \text{ kg} \pm 0.4 \text{ kg}$ ; a factor of 3.0 difference.

It is not obvious, however, why the agent concentrations measured for delivery of critical agent mass for the fires in Zone 2 were higher than for the fires located in Zone 1. Bench-scale



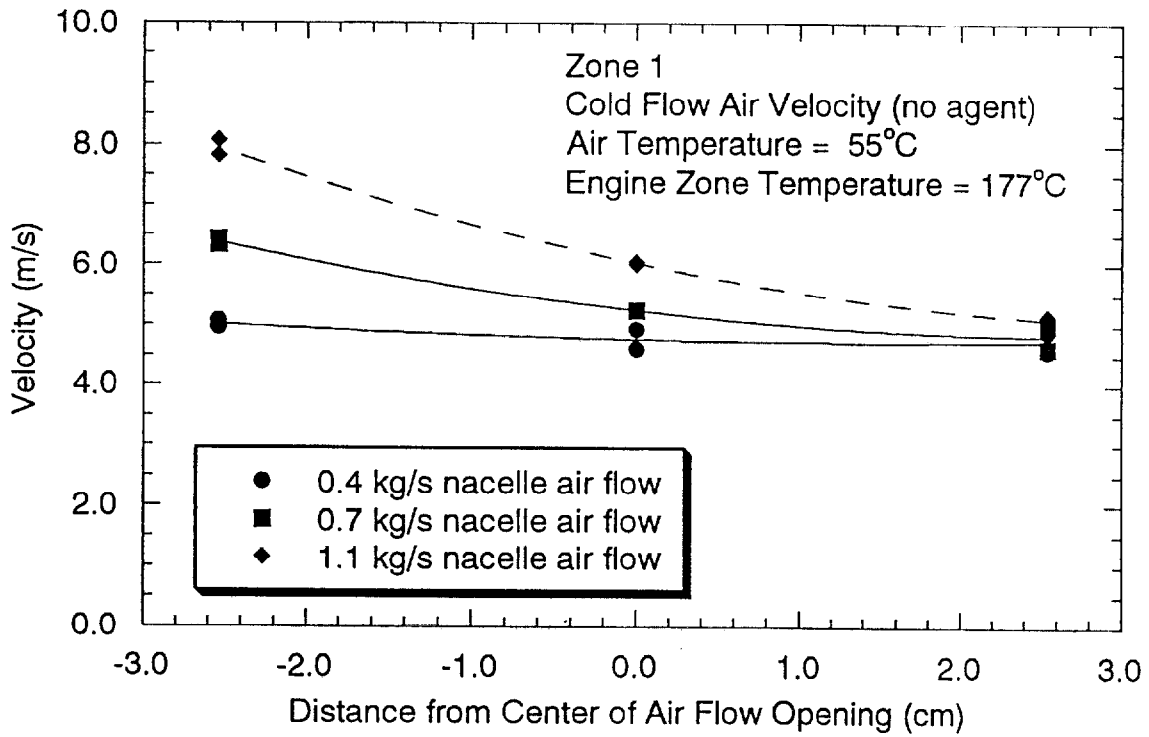
experiments show that flame suppression is governed by the critical agent concentration, with air temperatures, oxidizer velocity, and geometric blockage playing a limited role (see Figures 2 and 3) [Hamins et al., 19995]. Each of these effects is discussed below where we speculate on the discrepancy posed by the results in Figure 17.

#### 2.1.1.1 Flame Stability and Fluid Flow

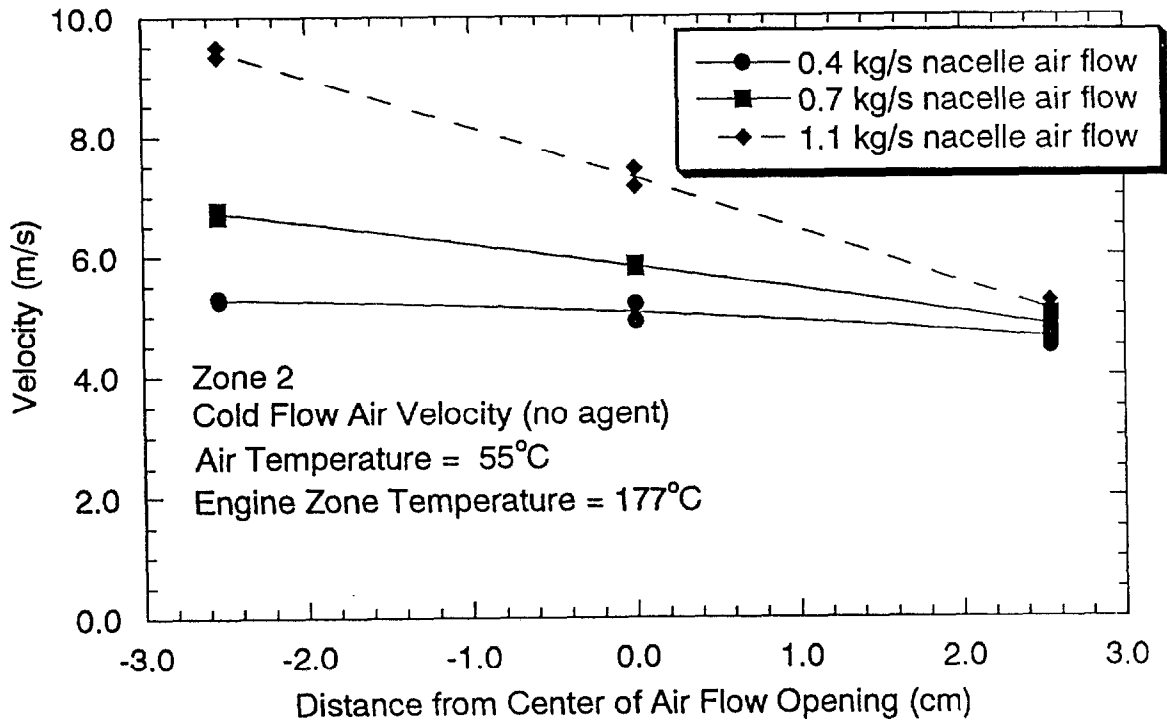
Flame stability and agent mass requirements are affected by the fluid mechanical strain in the flame anchoring region which is related to the free stream velocity just upstream of the flame holder. In addition, there is no transient velocity information available for experiments when HFC-125 was injected. Qualitatively, we speculate that the higher agent concentrations measured in Zone 1 (as discussed above) were likely accompanied by larger increases in local velocity than in Zone 2. This would destabilize the spray flame and allow suppression with lower agent concentrations. This may be the explanation for some of the small HFC-125 concentrations (less than 10% by mole) associated with suppression of Zone 1 spray flames (see Figure 17).

Figures 18 and 19 show the average velocity 15 cm upstream of the two fire zones as a function of distance from the midpoint between the inner and outer nacelle walls for several air flows under conditions cold-flow conditions (no fuel spray or fire present) and no agent addition. Without agent addition, the velocity was quite similar in the two zones. There are some questions regarding the integrity of these measurements, however. An estimate of the average nacelle velocity for the conditions shown in Figures 18 and 19 yields a result a factor of 5 less than that indicated in the Figures. This suggests either that the velocity measurements were flawed, the experimental conditions were incorrectly recorded, or that the amount of geometric blockage about the nacelle at the station where the pitot tubes were located leads to an effective cross-sectional area of  $\approx 0.1 \text{ m}^2$ , one-fifth of the free stream cross-sectional area of  $0.5 \text{ m}^2$ .

Observation of the flames suggests that reverse flow in the nacelle did not occur. Velocity measured in the nacelle during SPGG testing yielded similarly strange results. In those experiments, the differential pressure measured by the pitot tube decreased upon agent injection, indicating a decrease in local velocity in the axial downstream direction. Intuitively, it is difficult to accept the possibility of backflow in such a simple two dimensional system with an inlet at one end and an exhaust at the other. The flow results need to be rechecked and the flow field needs to be better characterized in order to have confidence in the experimental results.



**Figure 18.** The average velocity measured 15 cm upstream of Fire Zone 1 as a function of distance from the midpoint between the inner and outer nacelle walls for several steady air flows.



**Figure 19.** The average velocity measured 15 cm upstream of Fire Zone 2 as a function of distance from the midpoint between the inner and outer nacelle walls for several steady air flows.

#### **2.1.1.2 Flame Stability and Geometrical Blockage**

Another key parameter impacting flame stability and agent mass requirements is the geometrical blockage associated with nacelle components in the vicinity of the flame anchoring location. Flame anchoring was observed to occur at the fuel nozzle tip [Gillespie, 1997]. The geometrical blockage factor (B) can be quantified as the ratio of the total free stream cross-sectional area just upstream of the fuel nozzle to the cross-sectional area at the fuel anchoring location. Lower values of B tend to stabilize a flame. The value of the cross-sectional area at the stations where flame anchoring occurred were identical for Fire Zones 1 and 2 as the nozzles were located at the same downstream location. That cross-sectional area was 0.53 m<sup>2</sup> [Gillespie, 1997]. Thus, differences in flame stability due to geometrical blockage between fires in Zones 1 and 2 would be small. The effect of blockage by the nozzle itself was inconsequential with the blockage factor B taking on very small values (<0.01).

#### **2.1.1.3 Flame Stability and Temperature**

Another parameter impacting flame stability and agent mass requirements is the gas temperature just upstream of the flame anchoring location as discussed in Sections 1.1.1.3 and 1.1.2.1 above. It was possible that Fire Zones 1 and 2 were characterized by different temperature conditions due to local heating. Thermocouples were placed 10 cm upstream of the fuel nozzles in Fire Zones 1 and 2 during the SPGG testing. Data from those tests, involving Runs 3, 13, and 16, showed that the temperatures in Zones 1 and 2 were within 20°C in all three Runs. Figure 2 suggests that this would have negligible effect on agent concentration requirements. For a number of Runs (see Table 4) the air temperature was as high as 135°C. Even under those conditions, the maximum HFC-125 concentration would be expected to be approximately 12% by moles (see Figure 3), lower than the required concentration for fires in Zone 2.

It is possible that the heated inner nacelle wall preferentially heated regions near the spray fire in Zone 2, enhancing the stability of the fire in this region, although there is no thermocouple data to support this.

#### **2.1.1.4 Rationalizing Figure 17**

Bench-scale testing and reasoning exemplified by Figures 1 to 3 shows that flame extinction should have occurred for peak agent concentrations equal to ≈15 mole percent for HFC-125 (under moderate temperature conditions as shown in Figure 5), significantly smaller than many of the peak agent concentrations shown in Figure 17.

A possible explanation may be associated with the large agent concentration gradients measured. On average, the difference between the peak concentrations measured by Probes 7 and 8 in Zone 1 was a factor of  $1.5(\pm 0.5)$ , whereas the average ratio between Probes 5 and 6 in Zone 2 was  $1.4(\pm 0.3)$ . And flame extinction occurs only through simultaneous inerting of the entire flame anchoring region. Finally, the spatial extent of this region was never characterized. It was assumed that one or two concentration measurements 15 cm upstream of the spray nozzle was representative of the agent concentration throughout the anchoring region. This may not have been the case, particularly when it is recognized that the data in Figure 17 represents two independent sets of experiments, linked through the critical agent mass. The cold-flow (no fuel spray or fire present) agent concentration measurements were conducted with the fuel spray off. Certainly agent dispersion and air/agent mixing were different in the presence of a combustive/entraining fuel spray. If concentration measurements were made upstream of the combustive spray flame, then some of these questions may have been answered.

It should be noted that the instrument response time for the Statham and other gas analyzers was approximately 100 ms. Gas dispersion within the sampling lines was also probably significant [Pitts et al., 1995], leading to a system response much broader than the instrument response alone. If the gas concentration measuring system had a response time of 250 ms or more, then sharp temporal changes in agent concentration would have been smoothed. This could have led to erroneous conclusions regarding the duration agent concentrations were greater than critical values.

The issues raised in trying to rationalize the results presented in Figure 17 underscores the complexities associated with agent mixing which complicates interpretation of full-scale results. Even more difficulties are anticipated for the analysis of the SPGG results, where agents of unknown suppression effectiveness and uncertain composition were tested. On the other hand, our experience with halogenated agents suggests that the effectiveness of SPGG agents and their mechanisms of flame extinction can be understood through well-controlled bench-scale experimentation.

### **2.1.2 SPGG Concentration Measurements**

Measurements were made of the  $\text{CO}_2$  and  $\text{O}_2$  concentrations during the SPGG suppression experiments in an attempt to characterize agent dispersion. The concentration of these species is related to the total SPGG mixture concentration assuming that species transport is dominated by convection rather than preferential diffusion. For flow past obstacles even at moderate speeds



(greater than 1 m/s) this is a good approximation for gas phase species [Hamins et al., 1997] or solid particles with small diameters (<10  $\mu\text{m}$ ) as is the case with SPGG generated particulates [Cauffman, 1997]. With the mole based fraction of each component given by:

$$\text{Effluent} = c \cdot [\text{CO}_2] + h \cdot [\text{H}_2\text{O}] + n \cdot [\text{N}_2] + o \cdot [\text{O}_2] + co \cdot [\text{CO}] + k \cdot [\text{K}_2\text{CO}_3] \quad (9)$$

The mole based concentration of SPGG effluent in the sample extracted from the nacelle was related to the measured carbon dioxide  $[\text{CO}_2]_m$  and oxygen  $[\text{O}_2]_m$  concentrations as:

$$[\text{SPGG mixture}] = [\text{CO}_2]_m \cdot (c+h+n+o+co)/c \quad (10)$$

$$[\text{SPGG mixture}] = ([\text{O}_2]_a - [\text{O}_2]_m)/[\text{O}_2]_a \quad (11)$$

where  $[\text{O}_2]_a$  is the ambient oxygen concentration. Equation (11) shows that as agent is added to the flow, the measured oxygen concentration decreases by a factor related to the normalized difference in the oxygen concentration. In the limit when  $[\text{O}_2]_m$  is equal to 0 or  $[\text{O}_2]_a$ , the  $[\text{SPGG mixture}]$  is equal to 1 or 0, respectively. The sampled components are presumed to be air flowing in the nacelle and the SPGG effluent, whereas the small amount of  $\text{O}_2$  associated with the SPGG effluent is assumed to be negligible:

$$[\text{SPGG mixture}] + [\text{air}] = 1 \quad (12)$$

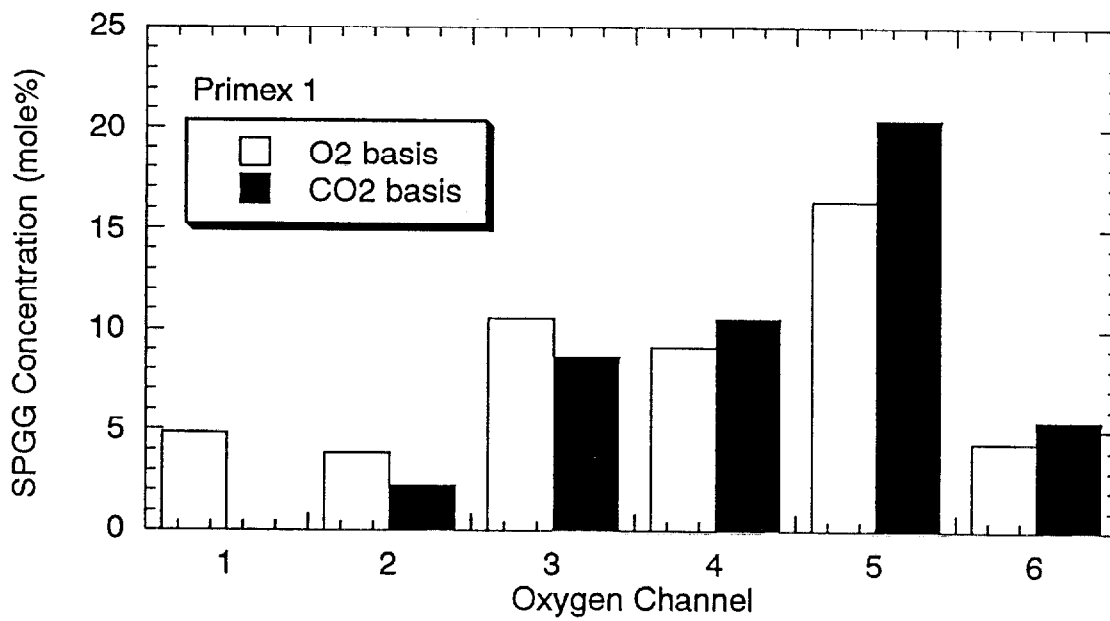
From Eq. 10, mole fraction concentration of  $\text{CO}_2$  in the SPGG effluent is:

$$[\text{SPGG mixture}] = 3.19 \cdot [\text{CO}_2]_m \text{ for the Primex FS01-40 SPGG} \quad (13)$$

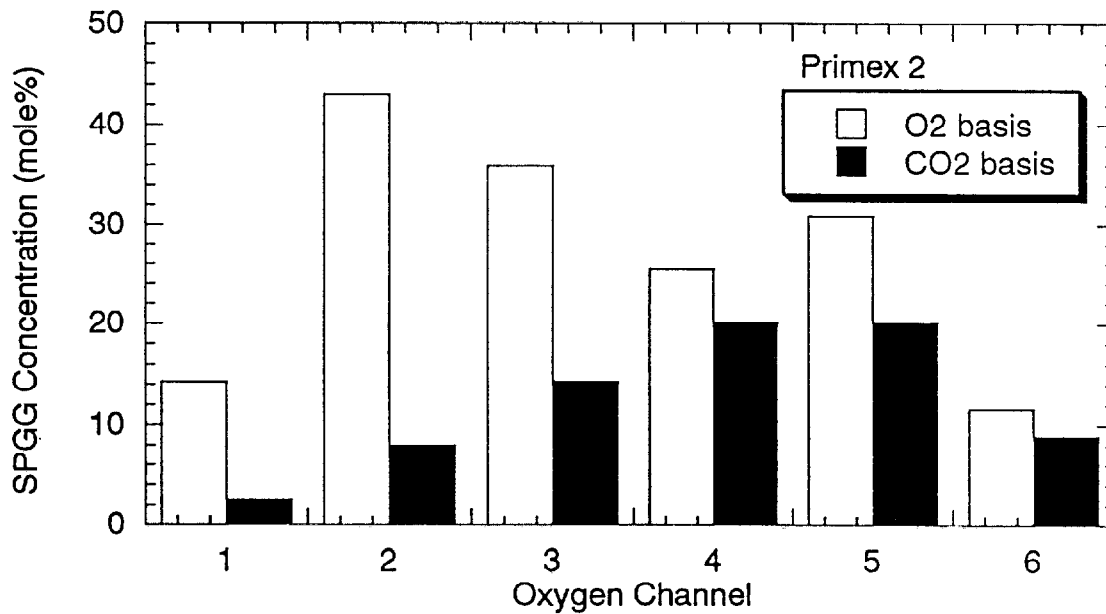
$$[\text{SPGG mixture}] = 10.73 \cdot [\text{CO}_2]_m \text{ for the ARC/Kidde SF-59 SPGG} \quad (14)$$

#### 2.1.2.1 $\text{O}_2$ and $\text{CO}_2$ Measurements During SPGG Testing

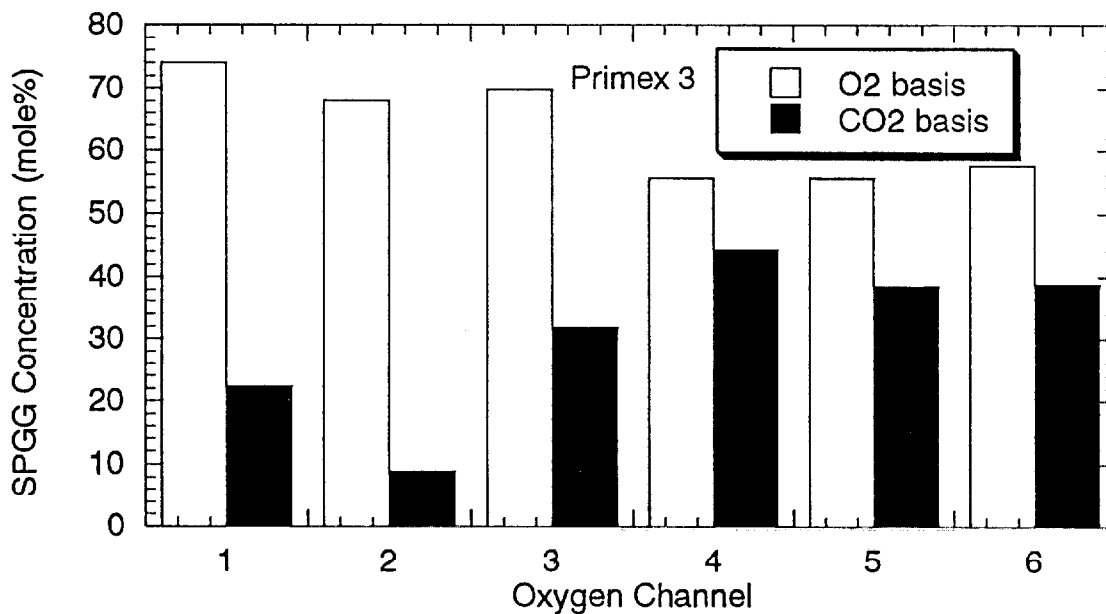
A comparison of the peak SPGG concentrations (using Eqs. 10 and 11) based on the measurements of the peak  $\text{CO}_2$  and the minimum  $\text{O}_2$  concentrations at the various locations in the nacelle are shown in Figures 20-22 for the Primex SPGG Concentration Tests 1c, 2c and 3c corresponding to the deployment of 0.2 kg, 1.1 kg, and 1.8 kg of SPGG, respectively, for cold-flow (no fuel spray or fire present) conditions in Run 3. A comparison of the mixture concentrations inferred from the  $\text{O}_2$  and  $\text{CO}_2$  measurements (using Eqs. 10 and 11) shows very poor agreement. This was also true for the other SPGG tests, indicating that at least one of the sampling/measurement techniques was flawed. There were few repeat tests, but test 2c was replicated one day later in Test 8c. The  $\text{CO}_2$  concentration results differed by a factor of two for all of the channels. There were many possible interferences



**Figure 20.** A comparison of the peak SPGG concentrations based on the measurements of the peak CO<sub>2</sub> and the minimum O<sub>2</sub> concentrations at various locations for Primex Concentration Test 1c (0.2 kg of FS01-40 for Run 3).



**Figure 21.** A comparison of the peak SPGG concentrations based on the peak CO<sub>2</sub> and the minimum O<sub>2</sub> concentrations at various locations for Primex Test 2c (0.2 kg of FS-20 and 0.9 kg of FS01-40 for Run 3).



**Figure 22.** A comparison of the peak SPGG concentrations based on the measurements of the peak CO<sub>2</sub> and the minimum O<sub>2</sub> concentrations at various locations during the Primex Concentration Test 3c (1.8 kg of FS-20 for Run 3).

associated with the gas sampling analysis including possible instrument contamination by particulates (possibly soot laden), water vapor, condensed water vapor, or hydrocarbon vapor. It is likely that careful instrument calibration using a representative SPGG effluent could elucidate the source of the measurement errors. Unfortunately, no such calibration information was available at the time of this report. Model calculations presented in Section 3 indicate that the CO<sub>2</sub> measurements were not unreasonable.

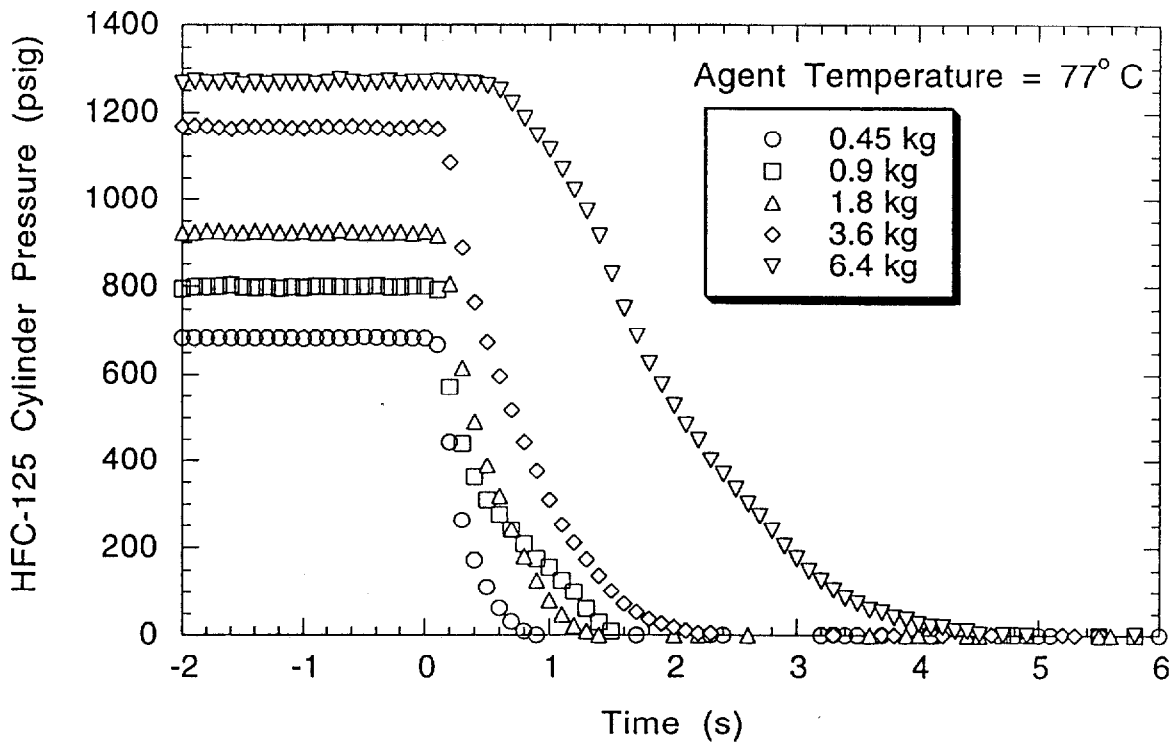
### 2.1.3 Agent discharge and mixing

There are a number of ways to characterize the average agent mixing in the nacelle. Agent mixing can be idealized as a plug flow, a well stirred reactor or as a series of reactors. These simple models cannot, however, predict radial agent distribution in the nacelle. Computational fluid dynamic models need to be developed for such predictions. To gain understanding of agent dispersion, the duration of measured agent concentration profiles are compared to the agent pressure traces which represent agent delivery duration.

Figure 23 shows the transient pressure in the agent cylinder (temperature at 77°C) for a series of HFC-125 deliveries. Larger agent masses required longer periods to dispense the agent. Data such as that shown in Figure 23 was used to construct Figure 24 which shows the measured agent delivery time as a function of agent mass for halon 1301 and HFC-125 for two agent bottle temperatures. For the same mass, the delivery rate of HFC-125 was faster than halon 1301. Temperature had little impact on agent delivery times.

Pressure traces from the SPGG manifold are shown in Figure 25. The character of the pressure trace depended on the type and mass of propellant and the number of canisters used. The ARC/Kidde SPGG and the Primex FS01-40 were fast and triangular in shape, whereas the other shots were more complicated. Figure 24 also shows some of the triangular shaped SPGG deliveries which are very fast compared to the halogenated agents. In bench-scale suppression tests, fast agent delivery rates have been found to be advantageous in terms of total agent mass requirements [Hamins et al., 1995].

Figures 26 and 27 show the concentration profiles of CO<sub>2</sub> during the release of 0.9 kg (twice the mass required for suppression) of the ARC/Kidde SPGG effluent and of 1.8 kg (the critical mass required for suppression) of HFC-125 during Run 13R. Figure 26 shows that the duration of HFC-125 near Fire Zone 2 (Channels 5 and 6) was approximately 6 s, whereas emptying of the agent cylinder took  $\approx$ 3 s, indicating that the agent did not mix into the ventilation air as a simple plug flow. This was a general



**Figure 23.** The transient pressure in the agent bottle for a series of tests using different amounts of HFC-125.

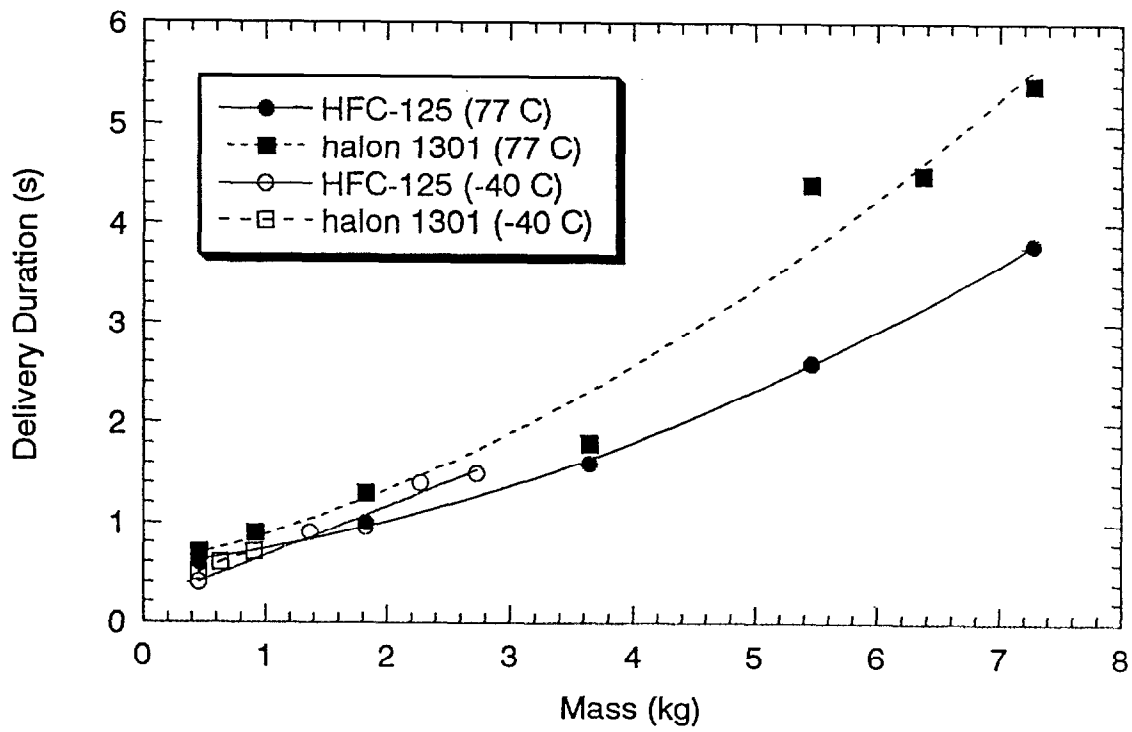
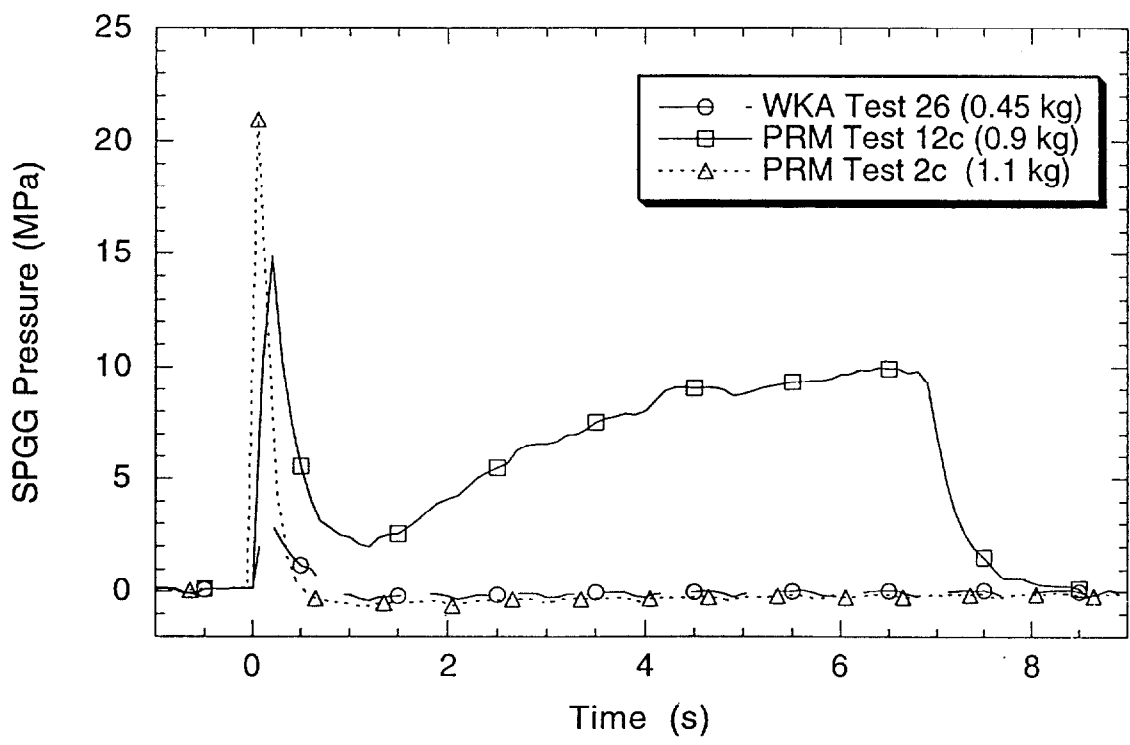
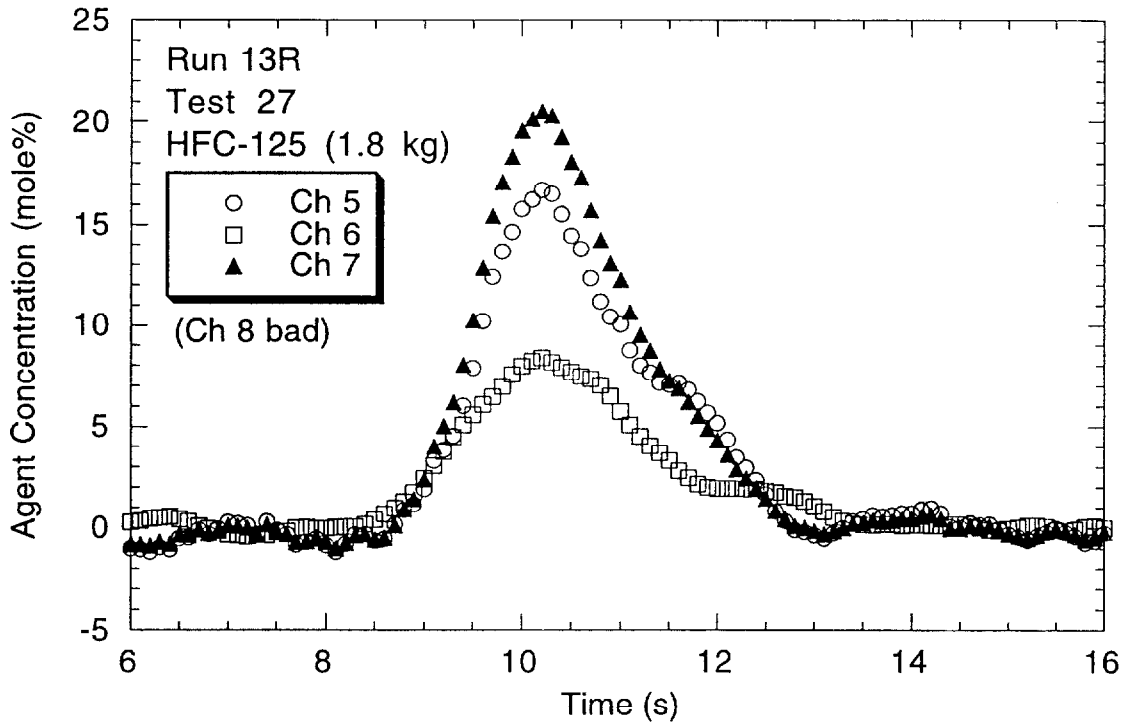


Figure 24. The measured agent delivery time as a function of agent mass for halon 1301 and HFC-125 for two agent bottle temperatures.



**Figure 25.** The pressure in the agent manifold as a function of time for SPGG.





**Figure 26.** HFC-125 concentration profiles as a function of time for Run 13R (test 27); 1.8 kg of HFC-125.

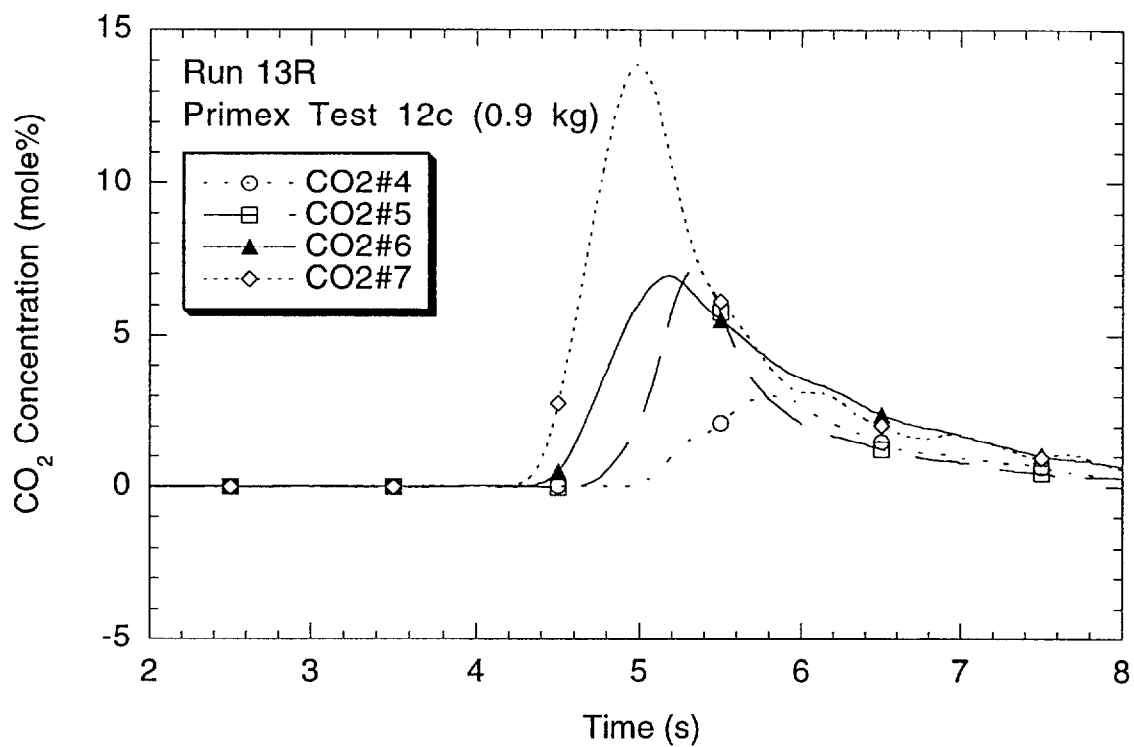


Figure 27. CO<sub>2</sub> concentration profiles as a function of time for Run 13R (Primex Test 12c); 0.9 kg of SPGG.

trend observed for the other runs using the halogenated agents. A well-stirred reactor model would be more appropriate than a plug flow model for this type of flow [Hamins et al., 1995]. Figure 27 shows that the duration of SPGG effluent near Fire Zone 2 (Probe 6) was approximately 2 s, whereas emptying of the agent cylinder took  $\approx 1.5$  s, indicating that a simple plug flow model may be appropriate for the SPGG. This was a general trend observed for the other runs using the SPGG for both the fast and the slow burning propellants.

## 2.2 Comparison of Agent Effectiveness

Suppression experiments using HFC-125, halon 1301 and SPGG were conducted for the alternative nozzle configuration for Runs 3R, 13R and 16R. The results of the suppression tests with the actual nozzle configuration are denoted with the suffix "R". The experimental protocol stipulated that successful suppression must be achieved at least five times without a failure for a mass to be deemed the minimum required value. If the number of successful tests was less than five which was true for some of the SPGG testing, then those numbers are also listed in Table 5.

Estimated uncertainties for the suppression mass requirements are also listed in Table 5. The upper bound is taken as the repeatability in agent mass. For the compressed halogenated gases, this is estimated as 5% based on the average of pressure measurements in the storage vessel. This is always smaller than the lower bound of the uncertainty which is due to both the uncertainty in agent mass and the difference between the critical mass and the largest mass which yielded unsuccessful suppression. The uncertainty in agent mass for SPGG is assumed to be 2%, associated with proper weighing of the propellant. The uncertainty may actually be lower. The values listed in Table 5 are initial propellant masses and do not include associated hardware which may be higher than that required for halogenated compounds. Nor is the efficiency of propellant combustion considered. Four types of SPGG were tested by Primex. These were the FS01-40 and FS-20 propellants (here denoted FS) and the PAC-3302 and PAC-3303 propellants (here denoted PAC). The PAC propellants were termed "chemically active" by the manufacturer.

The most difficult fire to control (requiring the largest halogenated agent mass) was Run 3, attributed to re-ignition of the fuel spray by the hot bleed air duct. In that experiment, the critical mass requirements for HFC-125 and halon 1301 were identical and greater than a factor of 5 and 28 over the Primex and ARC/WKA SPGG mass requirements. Post-experiment examination of the hot bleed air duct showed that the duct was coated by particles, which may have prevented re-ignition of the JP8 fuel spray [Gillespie, 1997]. The particulate coating may have acted like an insulator, diminishing heat transfer and the temperature

of gases near the bleed duct. In addition, the particulate may have impacted heterogeneous reactions on the metal duct surface. This situation necessitated cleaning of the metal surface between tests to insure repeatability of the HFC-125 experimental results [Gillespie, 1997].

Agent requirements in the other two experiments (Runs 13 and 16) were not driven by re-ignition. In those two experiments, the fuel spray was located in zone 2 and not directed towards the hot bleed air duct. The air flow was 1.1 kg/s. The conditions in Run 16 included cold air and agent at  $\approx -40^{\circ}\text{C}$ .

The results from Table 5 also suggest that:

(1) Halon 1301 was not more effective than HFC-125 in Run 3 which involved suppression of re-ignition.

(2) the SPGG devices were more effective than the halogenated compounds except for Run 16, the cold flow condition where halon 1301 was as effective as SPGG within experimental uncertainty.

(3) the WKA SPGG was more effective than the Primex SPGG for Run 3 due to particulate in the effluent of the WKA SPGG.

(4) the most difficult scenario for the WKA SPGG was for fires in Fire Zone 2 (Runs 13 and 16), rather than the hot surface re-ignition scenario (Run 3). This was not true for the Primex SPGG.

(5) experimental uncertainty precludes differentiating the performance of the SPGG systems in Runs 13 and 16. Further suppression testing could discriminate between SPGG effectiveness.

Run	HFC-125 (kg)	halon 1301 (kg)	PRM (FS <sup>+</sup> ) (kg)	PRM (PAC) (kg)	WKA (kg)
3R	$6.4 \pm_{1.0}^{0.3}$	$6.4 \pm_{1.0}^{0.3}$	$1.1 \pm_{0.20}^{0.02}$	* $1.4 \pm_{0.45}^{0.02}$ 3 of 3 tests	$0.23 \pm_{0.23}^{0.01}$
13R	$1.8 \pm_{0.2}^{0.1}$	$1.1 \pm_{0.2}^{0.1}$	$0.91 \pm_{0.45}^{0.04}$	** $0.45 \pm_{0.15}^{0.01}$ 2 of 2 tests	$0.45 \pm_{0.23}^{0.01}$
16R	$1.6 \pm_{0.2}^{0.1}$	$0.68 \pm_{0.10}^{0.08}$	$0.91 \pm_{0.45}^{0.04}$ 3 of 3 tests	-	$0.68 \pm_{0.23}^{0.01}$

\* PAC-3303  
 \*\* PAC-3302  
 + a combination of FS01-40 and FS-20 propellants were used.  
 - experiment not conducted

### 2.2.1 Agent Suppression Effectiveness per Kilogram of Agent

Table 6 lists the predicted (from Table 3) and measured agent suppression effectiveness per kilogram of agent deployed normalized to halon 1301,  $E_p$ , for Runs 13R and 16R, the only tests where agent mass requirements were measured for all agents in a fire suppression scenario. The measured mass based agent effectiveness normalized to halon 1301 ( $E_m$ ) was defined as:

$$E_m = (\text{Mass}_{\text{halon}} / \text{Mass}_i) \quad (15)$$

where  $\text{Mass}_i$  was the measured mass requirement for the  $i^{\text{th}}$  agent from Table 5. Results for Run 3R were not considered, because the predicted  $E_p$  pertains to flame suppression, but not re-ignition prevention. Although the predicted  $E_p$  values (from Table 3) are for an oxidizer at ambient temperature, the difference in  $X_i$  (see Figure 3) and  $E_m$  due to differences associated with the average temperatures ( $\approx 80^\circ\text{C}$  and  $10^\circ\text{C}$ , respectively) measured upstream of Fire Zone 2 for Runs 13R and 16R was less than 10%.

The experimental uncertainty for the measured agent effectiveness per kilogram of agent ( $E_m$ ) is large, due to the uncertainty associated with the mass requirements in Table 5. Table 6 shows that the  $E_p$  is similar to  $E_m$  for HFC-125 in Run 16R, but just beyond experimental uncertainty for Run 13R.

$E_p$  was significantly smaller than  $E_m$  for the SPGG in Runs 13R and 16R. Physics beyond agent composition was probably responsible for the enhanced performance of the PRM and WKA SPGG. This enhanced performance was probably associated with flame straining due to fast agent deployment. Agent mixing, dispersion, or thermodynamics could also have played a role.

Two parameters are defined to quantitatively compare the measured and predicted normalized agent effectiveness on a kilogram basis. They are  $F_o$ , the fractional agent effectiveness due to straining

Table 6 Predicted and measured mass based agent effectiveness ( $E_p$ and $E_m$ ) for Runs 13R and 16R.				
	HFC-125	halon 1301	PRM (FS*)	WKA
$E_m$ Run 13R	$0.61 \pm_{0.13}^{0.15}$	$1.0 \pm 0.3$	$1.2 \pm_{0.3}^{1.0}$	$2.4 \pm_{0.5}^{1.5}$
$E_m$ Run 16R	$0.43 \pm 0.10$	$1.0 \pm 0.3$	$0.75 \pm_{0.14}^{0.47}$	$1.0 \pm_{0.17}^{0.46}$
$E_p$ Predicted <sup>+</sup>	$0.42 \pm 0.04$	$1.0 \pm 0.1$	$0.22 \pm 0.02$	$0.88 \pm 0.09$
+ from Table 3.				
* a combination of FS01-40 and FS-20 propellants were used.				

(and other effects) and  $F_c$ , the expected fractional agent effectiveness:

$$F_o = E_p \cdot (1/E_p - 1/E_m) = (1 - E_p/E_m) \quad (16)$$

$$F_c = 1 - F_o = E_p/E_m \quad (17)$$

Values of  $F_o$  close to 0 indicates that the agent performed similarly to that expected from the cup burner tests, whereas a value of  $F_o$  close to 1 implies that the full-scale performance was superior to that expected from the cup burner. Table 7 shows that a large fraction of the PRM SPGG performance was related to flame strain and other physical effects. The HFC-125 result for Run 16R was highly similar to the halon results, but Run 13R had some small differences. The physics responsible for this are not clear from these global measurements. The halon 1301 results are shown in Table 7 to indicate the uncertainty associated with this species.

For Run 13R, the moles of agent ( $Mass_i \cdot n_i$ ) were nearly equal for the two SPGG agents and the measured SPGG canister pressure traces showed that both agents were rapidly released in  $\approx 0.5$  s, implying that the fluid strain effects were similar. If the local velocity measurements had been reliable, they would have yielded valuable information regarding flow field effects. Unfortunately, those measurements were not reliable (see Section 3).

Run	HFC-125	halon 1301	PRM (FS*)	WKA
13R	$0.31 \pm_{0.24}^{0.21}$	$0.00 \pm 0.37$	$0.84 \pm_{0.15}^{0.06}$	$0.64 \pm_{0.25}^{0.11}$
16R	$0.02 \pm 0.42$	$0.00 \pm 0.37$	$0.73 \pm_{0.19}^{0.08}$	$0.12 \pm_{0.49}^{0.24}$

\* a combination of FS01-40 and FS-20 propellants were used.

### 2.2.2 Local Agent Concentration Data

Table 8 lists the measured peak agent mole percentages for Runs 3R, 13R and 16R based on the  $CO_2$  measurements (in the appropriate fire zone) for agent delivery corresponding to the masses listed in Table 5. The peak agent concentrations for Run 3R were very high for the halogenated agents due to the large agent masses deployed. For SPGG, the peak concentrations were smaller. Interestingly, the ARC/Kidde peak agent concentration for Run 3R was lower than for the Primex SPGG experiments, because prevention of re-ignition was due to particulates coating the hot

Table 8 Peak agent mole percentages corresponding to the agent masses listed in Table 5.					
Run	HFC-125	halon 1301	PRM (FS)	PRM (PAC*)	WKA
3R <sup>++</sup>	54	56	24, 12 <sup>**</sup>	17	38
13R <sup>+</sup>	17	-	22	-	40
16R <sup>+</sup>	8	23	-	-	-

\* PAC-3303 assuming validity of Eq. 13.  
 \*\* data points from Tests 2c and 8c.  
 - experiment not conducted.  
 ++ Zone 1  
 + Zone 2

bleed air duct, whereas the Primex approach was to inert the system for the duration of the experiment. Unfortunately only a scant amount of concentration data was available for Runs 13R and 16R. For Run 16, a very high peak halon 1301 concentration was measured in Fire Zone 2, which was consistent with the results shown in Figure 17.

Table 5 shows that the HFC-125 and halon 1301 mass requirements were identical for Run 3. The mechanism for re-ignition prevention is of interest. Figure 5 shows that over the range of temperatures considered, the inerting concentration of halon 1301 was approximately a factor of two smaller than that of HFC-125. At ambient temperature, the inerting concentrations are 6% and 12% (by mole) for halon 1301 and HFC-125, respectively. Table 9 shows that 8 s after agent delivery, the agent concentrations in Fire Zone 1 for halon 1301 and for HFC-125 were well above the required inerting concentrations shown in Figure 5 when temperatures just upstream of the spray fire in Zone 1 were initially  $\approx 200^\circ\text{C}$ . The agent concentration at 8 s is of interest because the test protocol defined suppression successful if the fire did not re-light for 8 s after suppression.

The results for SPGG were very different. In Run 3R, the concentrations 8 s after agent delivery of the WKA and the Primex SPGG were significantly below the inerting concentration which was  $\approx 35\%$  at 300 K as described in Section 1.1.2.

For the WKA/ARC SPGG, the concentration was nearly zero after 8 s due to the rapid deployment and small agent mass utilized. For the PRM SPGG, the concentration was approximately 8% by moles after 8 s. There is no explanation for the effectiveness of the "filtered" Primex SPGG, except if some amount of particulate escaped filtering and like the ARC/Kidde SPGG effluent, acted on

the surface of the hot bleed air duct. This needs to be experimentally verified. Other explanations for the effectiveness of the Primex SPGG in Run 3R are not apparent.

Although agent cooling of the surface of the hot bleed air duct may have contributed to the prevention of ignition, this effect was probably small. The bleed air duct heater was on during agent release and the difference in heat transfer due to the agent/air mixture as compared to the agent alone was small. Similar to SPGG (see below), the agent/mixture temperature was likely to rapidly equilibrate with the temperature of the ventilation air. Fast thermocouple measurements in the fire zone would be useful in answering this question.

Table 9 Agent mole percentages in Fire Zone 1, 8 s after initiation of the critical agent mass for Runs 3 and 3R.					
Run	HFC-125	halon 1301	PRM (FS)	PRM(PAC*)	WKA
Run 3	22, 12 <sup>+</sup>	-	-	-	-
Run 3R	16, 32 <sup>+</sup>	29, 22 <sup>+</sup>	19, 8 <sup>**</sup>	6	≈1
* PAC-3303 assuming validity of Eq. 13. ** two data points from Tests 2c and 8c. + data from two probes (ch. 7 and 8) upstream of Fire Zone 1 - experiment not conducted.					

### 2.3 Comparison of Nozzle Effectiveness

As seen previously, peak agent concentrations are useful benchmarks of potential agent suppression effectiveness. Figure 17 indicates some differences in the effectiveness of the two nozzle configurations. Less agent mass was required for the alternate configuration in Runs 13, 16, and Conf, whereas more agent mass was required in Run 3. Because the actual F-22 nozzle configuration likely delivered a higher proportion of agent mass through the branch directed towards Fire Zone 1 and the hot bleed air duct, it was somewhat surprising that more agent mass was required for Run 3R as compared to Run 3 (see Figure 12). This explanation, however, is inconsistent with the results for the test condition labeled Conf, where the fire was also located in Zone 1. In that case, more agent mass was required to suppress the fire in Run Conf as compared to Run ConfR. These inconsistencies are likely associated with the rather large experimental uncertainties (see Table 5 for Run 3R). Further study on the effects of various agent nozzle configurations



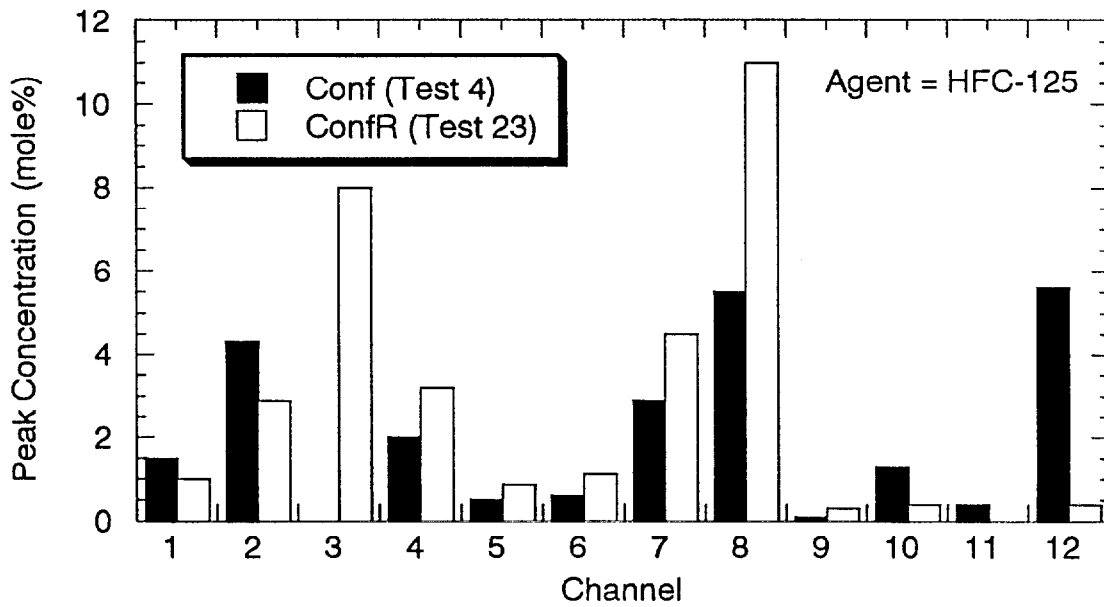
would be useful for optimization of agent mass requirements.

Figure 28 shows the peak HFC-125 concentration for each channel in Runs Conf and ConfR (Tests 4 and 23, respectively). This is the only direct comparison of agent distribution for the two nozzle orientations available, where agent mass (0.2 kg) and all nacelle conditions were identical. Figure 28 shows that the peak agent concentration in the alternate nozzle orientation (Conf) were lower than the actual nozzle configuration (ConfR) in both Fire Zones 1 and 2. The duration of the agent peaks in these Zones were also longer for the actual nozzle configuration. A comparison of the peak HFC-125 concentrations in Zone 1 from probes 7 and 8 which were separated by 15 cm and which occurred simultaneously, indicate that large agent concentration gradients existed in Zone 1. The gradients appear smaller in Zone 2, but occurred for both nozzle orientations. The large concentration gradients suggest that regions with a large variation in agent concentration may occur for locations that are in close proximity.

#### 2.4 Temperature Effects of SPGG

Measurements showed that the increased temperature associated with SPGG was measured to be very small near the fire zones (less than  $\approx 30^\circ\text{C}$ ) during the Primex Concentration Tests 2c, 8c, and 9c. Figure 3 shows that this has a very small effect on agent concentration requirements. In nacelle regions close to the agent nozzle exit, the temperature of the SPGG effluent/air mixture could stabilize a fire, leading to small increases in agent concentration requirements depending on the effluent temperature at the nozzle exit and nacelle conditions. Local heat transfer could also play a role.

Unfortunately, the time response of the thermocouple near the nozzle exit during SPGG testing was so slow (18 s), that those measurements were ineffectual. In Section 3, we discuss a method to estimate the temperature of the SPGG effluent at the nozzle exit. The calculation results show that SPGG temperatures were approximately  $400^\circ\text{C}$  near the nozzle exit, due to rapid agent expansion. Further cooling would be expected as air was entrained into the SPGG effluent. For regions very close to the nozzle exit, agent concentrations will be beyond the flammability limits for even rather high temperatures (see Figure 3). But for regions with moderate agent concentration (less than  $X_i$  in Figure 3), flame stability would be enhanced due to the super ambient temperatures associated with mixtures of air and SPGG effluent.



**Figure 28.** The peak HFC-125 concentration for each channel in Runs Conf and ConfR (Tests 4 and 23).

### 3. MODEL OF ENGINE NACELLE FIRE SUPPRESSION

The NIST engine nacelle fire suppression model predicts agent mass requirements for spray and pool fires in engine nacelles [Hamins et al., 1995]. The model provides a framework for making preliminary engineering design of a nacelle fire protection system. Unlike the statistical model developed in the halon replacement program [Bennett, 1995], the NIST model is based on physical phenomena, albeit idealized descriptions of many complex phenomena. This leads to model output which facilitates an understanding of the experimental results. Application of the model to other agents, such as SPGG, is easily accomplished.

A detailed description of the nacelle mixing model is found in Hamins et al. [1995]. Agent mixing in the nacelle was considered to behave either as a perfectly stirred volume, or a completely segregated volume (plug flow). The perfectly stirred volume instantly and always maintains a constant concentration spatially as a consequence of efficient mixing. A plug flow of agent in the nacelle mixes only with the ventilation air and the resulting mixture is carried downstream. Real mixing in a nacelle is complicated and can be thought of as a series of separate volumes either perfectly stirred or segregated. For any unknown system, these two extremes bound the idealized behavior as a consequence of a particular discharge.

#### 3.1 SPGG Model Description

The NIST engine nacelle model [Hamins et al., 1995] was extended to handle SPGG discharge. Unlike the compressed liquid agents, where physical property data is available, the SPGG's were proprietary, engineered systems. Thus, to predict the rate of discharge, test data was used to initialize the simulation. Ideally, the burning rate, effluent composition and burning temperature would be supplied by the manufacturer. The model solves the simple mass and energy balance equations for a given SPGG formulation (effluent) and nacelle conditions and calculates the transient spatially averaged agent concentration. Details relating to the SPGG model are outlined below.

The transient pressure in the SPGG combustion chamber (canister) was required input to the model. The total moles of gaseous effluent was calculated from the composition and the product of the mass of the propellant and the mass fraction of the gas-phase portion of the effluent. The burning efficiency was assumed to equal 100 percent. Solid particulate was assumed not to affect the discharge flow. A critical flow isentropic gas discharge calculation was performed. An effective discharge nozzle area was guessed, and for discrete pressure values, the mass flow of agent was calculated. The mass flow was integrated to give the total mass and the effective nozzle area was corrected until the

calculated total mass equaled the experimental mass discharged. The equation for mass flow (M) is:

$$M = c \cdot \beta (\rho \cdot \Delta P)^{0.5} \quad (18)$$

where  $c$  is an orifice coefficient (=0.61) and  $\Delta P$  is the pressure difference between the SPGG chamber and the outlet.  $\beta$  is a function of the ratio of the specific heats of the gases,  $\gamma$ , given by:

$$\beta = \gamma(2/[\gamma+1])^{(\gamma+1)/(\gamma-1)} \quad (19)$$

$\rho$  is obtained by solving for the roots of the Redlich-Kwong equation of state for the gas phase mixture at a given pressure and temperature.  $\gamma$  is taken as 1.3 for the inert gases considered here. The temperature was taken as a constant value equal to 2000 K, representative of the adiabatic flame temperature of the propellant. Although the adiabatic flame temperature is a function of pressure, it is a weak function. Thus, the mass flow was assumed not to be a function of the assumed adiabatic temperature. The assumed adiabatic temperature serves to yield a plausible agent temperature as it discharged into the nacelle.

The experimental pressure was taken as the highest recorded pressure, which in some cases may have been an intermediate pressure such as inside the manifold. It was not clear whether or not the pressure in the SPGG combustion chamber was recorded for each test. The error using an intermediate pressure for the mass flow calculation is minimal, though it has some impact on the adiabatic isentropic expansion calculation leading to possibly increased effluent exit temperatures. Given the fact that the process was idealized, and the adiabatic flame temperature was an estimate, the effluent exit temperature was considered an upper limit.

The SPGG effluent mixes with the nacelle ventilation air and travels downstream. The model yields transient average agent concentrations for this plug flow. In real nacelles, deviations from the average are expected depending on agent mixing. This may depend on the nozzle orientation, the nacelle geometry, the air flow and so on. Predictions of the spatial distribution of agent would require detailed computational fluid dynamic modeling, beyond the scope of this study.

### 3.2 Comparison of Model to Experiments for the Halogenated Agents

The measured critical mass requirements for HFC-125 and halon 1301 were compared to the model results for the two extreme mixing conditions, the plug flow and the perfectly stirred region (PSR) models. Although, the model can account for temperature

effects and discharge dynamics, simplifications were made since uncertainties associated with flame stability and imperfect mixing discourages such detailed calculations at this time. The simplifications applied to the F-22 tests included assuming that the agent was discharged in 1.0 s at a constant rate, that the agent was in the gas phase and mixed isothermally at 20°C. These simplifications allow use of the previously published figures presented by Hamins et al. [1995]. For the PSR model, an effective nacelle volume of 2 m<sup>3</sup> was assumed.

Figure 29 shows the measured critical mass requirements for HFC-125 as a function of air flow for Runs 4, 6, 7, 9, 10, 12-16, and 18. These tests included the low and high air flow runs with fires in both Zones 1 and 2, using both the alternative and the correct nozzle configurations. Also shown are the model predictions for suppression of spray fires assuming that agent mixing is like a plug flow or a PSR [Hamins et al., 1995]. For the model predictions shown in Figure 29, plug flow is the lower bound and PSR is the upper bound. Plug flow always requires significantly less agent than PSR mixing.

For low air flows, four out of six of the experimental points fall outside of the plug flow/PSR range indicated. For high air flows, five out of seven experimental points fall outside the range. Interestingly, all of the results falling within the calculated range were for fires located in Zone 1, whereas all of the results falling outside the calculated range were for fires located in Zone 2. This suggests that either the flame in Zone 2 was more stable than expected, and/or that the agent was not efficiently transported to Zone 2. This conclusion is consistent with our conclusions regarding Figure 17 discussed in Section 2.1.1. The cold flow concentration data supports the notion that poor mixing was the primary cause of the elevated agent requirements. Fire Zone 1 (near the hot bleed air duct) almost always recorded higher agent concentration in the cold flow tests than Fire Zone 2. And Figure 17 shows that flame stability may also have been a factor.

The opposite was observed when the measured critical mass required for suppression during the Halon Replacement Program [Bennett, 1995] was compared to the model calculations for CF<sub>3</sub>I, CF<sub>3</sub>Br, HFC-125, and HFC-227 [Hamins et al., 1995]. In those experiments, the critical mass was frequently below the plug flow mass requirement for suppression, suggesting that the agent discharge was directed preferentially toward the fire zone.

Analogous results for halon 1301 are shown in Figure 30. Only two experimental points were measured (both at high air flows). The model predictions are also shown. The measured critical mass requirements were higher than the calculated range. Both fires were located in Fire Zone 2 for these experiments. And the results are consistent with those in Figure 29 for HFC-125.

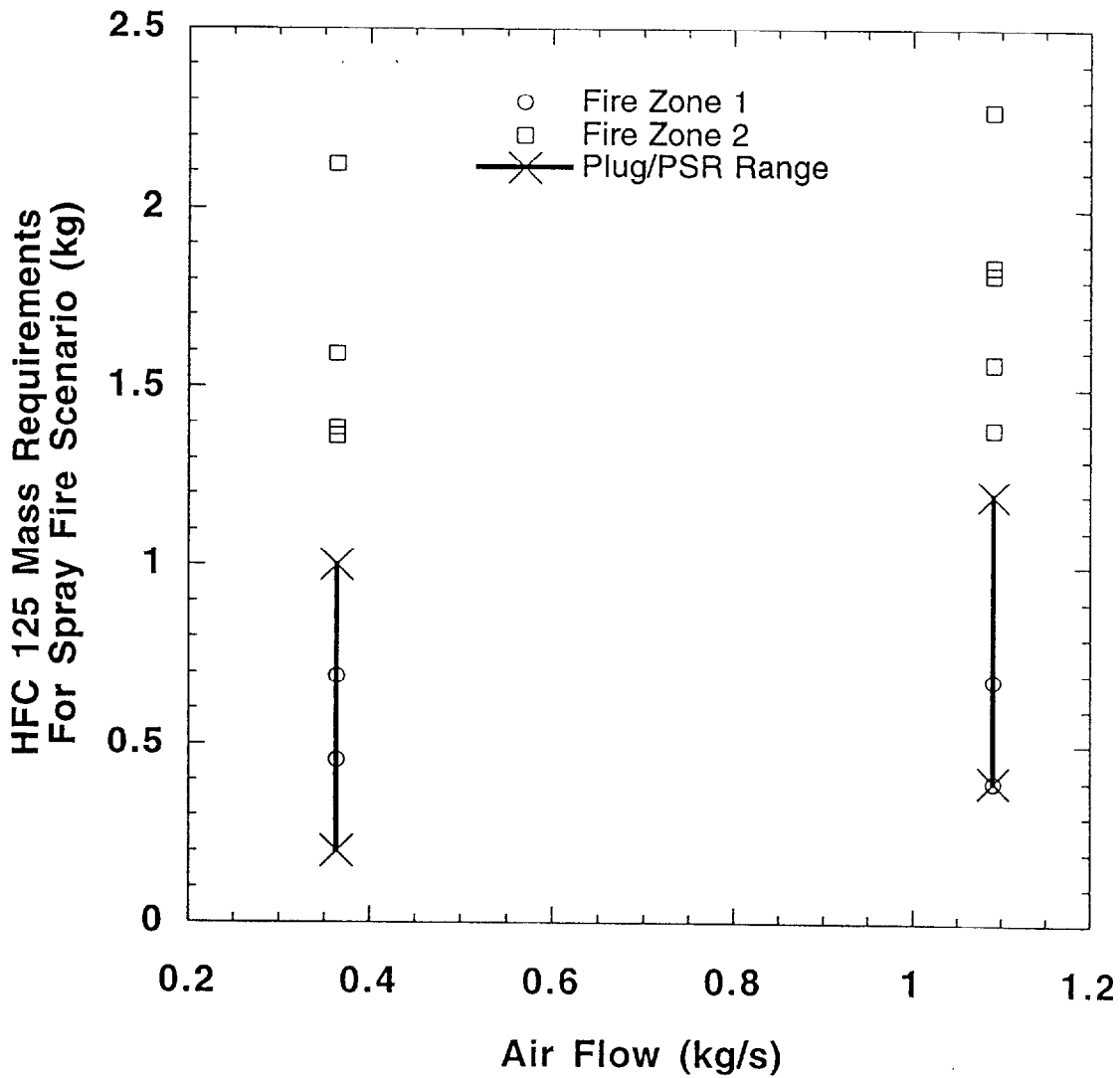


Figure 29. The measured HFC-125 mass requirements as a function of air flow for conditions in Table 4 corresponding to Runs 1 to 18, 3R, 163, and 16R.

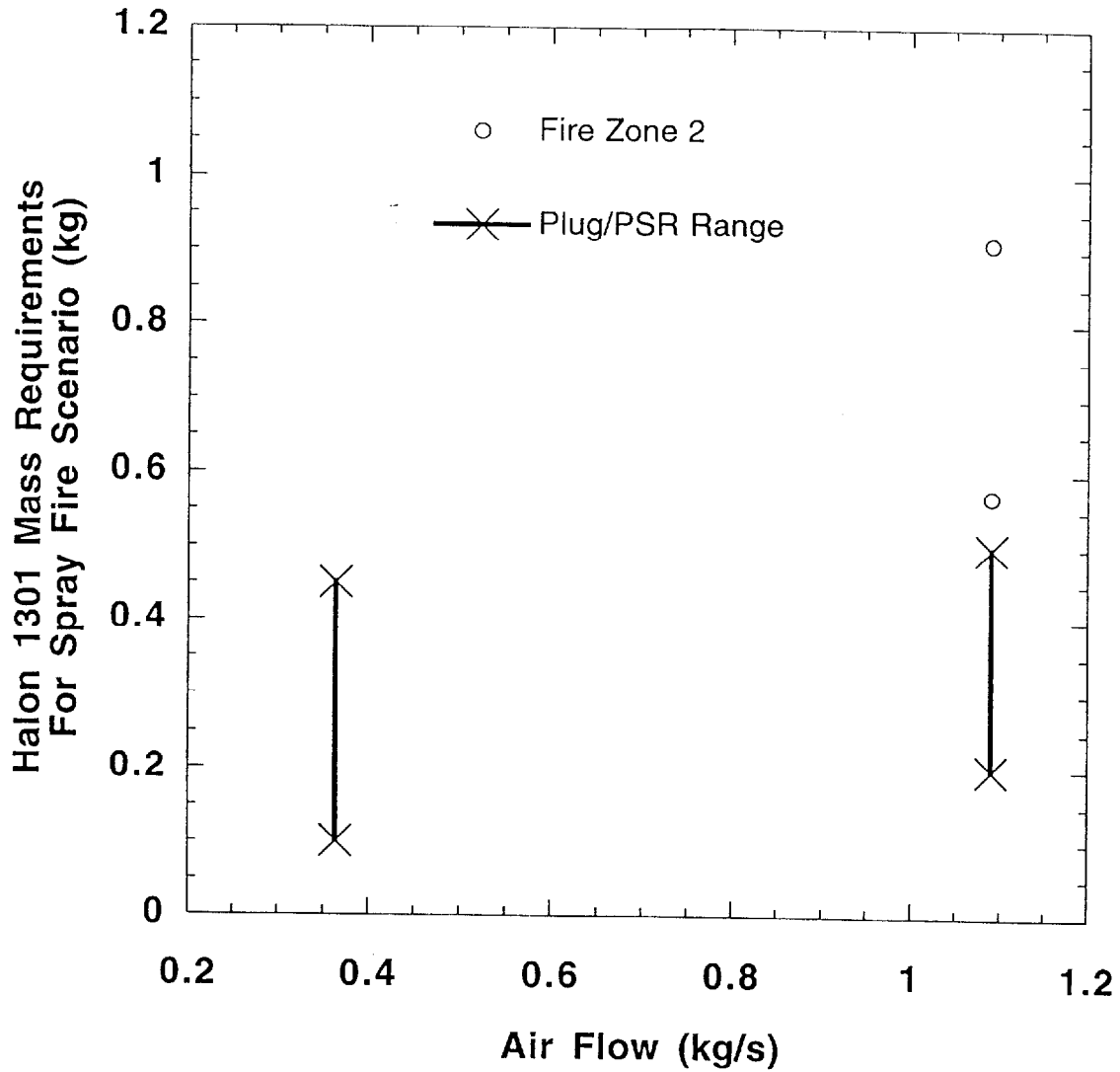


Figure 30. The measured halon 1301 mass requirements as a function of air flow for conditions in Table 4 corresponding to Runs 13R and 16R.

One pool fire scenario was tested at high air flows. It was a combined spray/pool fire in Zone 2. For the model calculation, the suppression requirements were assumed to be dominated by the pool fire. Figure 31 shows the measured critical mass requirements for HFC-125 as compared to the model predictions. The experimental mass requirement fell outside the calculated range. This result further suggests that poor radial mixing increases the mass requirements for Fire Zone 2 under very different conditions.

### 3.2.1 Minimum Agent Mass Requirements

It is possible to estimate minimum agent mass requirements for fire suppression from consideration of agent concentration requirements. Agent mass would be minimized if agent was uniformly distributed throughout the nacelle, mixing with ventilation air in a plug-like flow. A reasonable criteria requires that the agent concentration is above the peak flammability limit (see Figure 5) throughout the entire nacelle for an appropriate duration. For this series of experiments, the fuel spray remains on for 8 seconds. Based on this period, the mass requirement for HFC-125 is 1.6 kg injected uniformly over 8 s. A safety factor should be added to this value.

The measurements for Run 3R in fact required 6.4 kg of HFC-125 to suppress the flame and prevent re-ignition (Table 5). To achieve a value closer to the minimum mass presumes that (1) the agent distribution in the nacelle is optimized (with a different nozzle arrangement) to achieve uniform mixing and (2) that the agent discharge is controlled such that a plug like flow providing just the agent inerting concentration is achieved. The discharge rate should be slowed significantly. Using multiple agent cylinders, restricting nozzles, or reducing the piping diameter would provide simple, yet sub-optimal solution. Optimal agent flows could be provided by other means, such as "smart" valves which open as agent pressure decreases.

### 3.3 Model Comparison to SPGG Experiments

All SPGG model calculations assumed plug flow mixing in the nacelle, consistent with the measured concentration curves as described in Section 2.1.3.

Figure 32 shows the transient SPGG canister pressure for 1.1 kg of propellant (0.2 kg of FS-20 and 0.9 kg of FS01-40), the critical agent mass for Run 3R, measured during the Primex concentration test 2c. The pressure sharply increased to 15 MPa in  $\approx 0.2$  s, rapidly declined to 2 MPa by  $\approx 1$  s after initiation, and then slowly increased to 10 MPa after 6.5 s. The pressure trace is characteristic of a hybrid system using a combination of



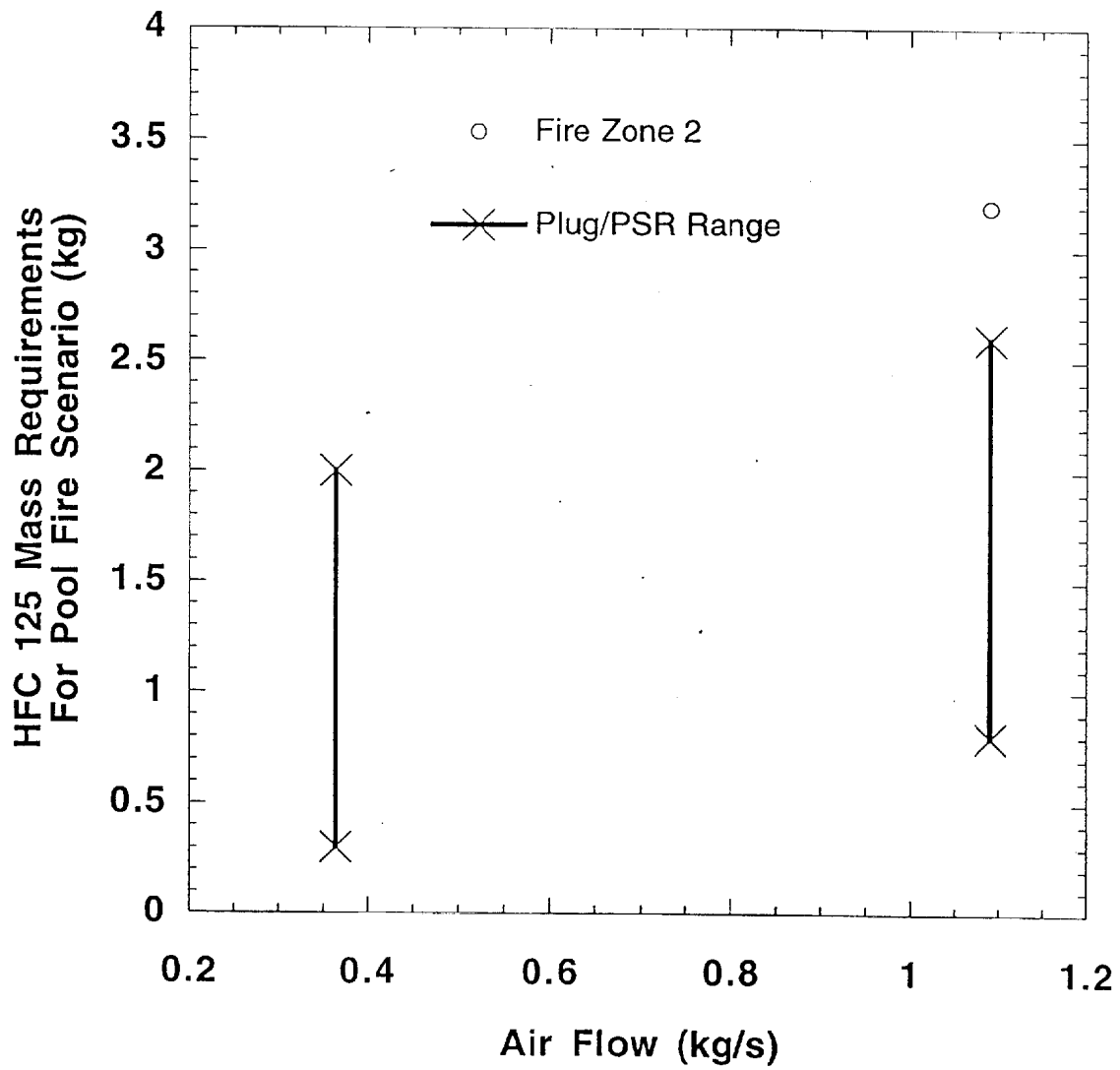


Figure 31. The HFC-125 mass requirements as a function of air flow for a spray/pool fire scenario.

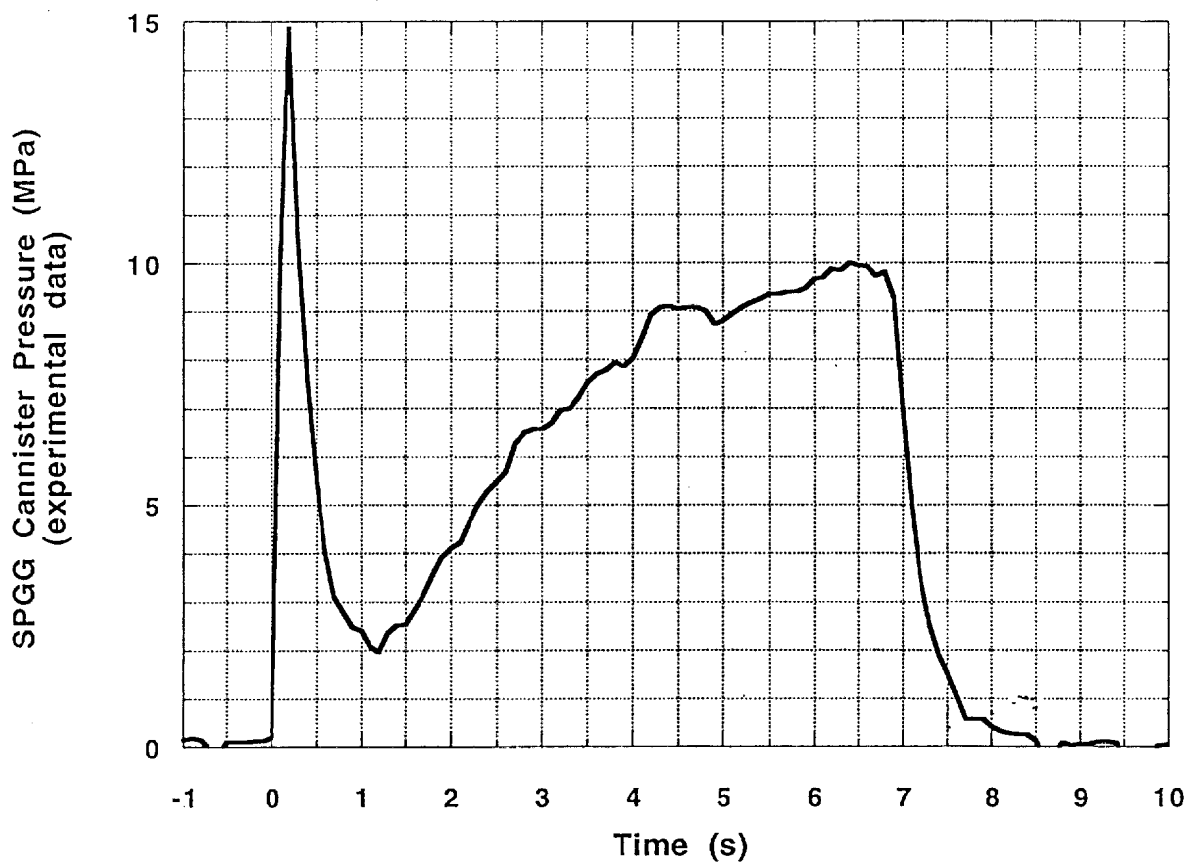


Figure 32. The SPGG canister pressure for 1.1 kg of propellant during Primex Concentration Test 2c as a function of time.

fast and slower reacting propellants. This information is used as model input to determine the agent mass flow.

Figure 33 shows the average  $O_2$  concentration calculated using the model. For comparison,  $O_2$  measurements at four radial locations each separated by  $90^\circ$ , are also shown. Figure 14 shows the relative location of each of the probes. Although, the duration of the model and measurements are similar, the measured  $O_2$  depletion was significantly lower than that predicted by the model. As described in Section 2.1.2.1, the  $O_2$  and  $CO_2$  measurements yielded agent concentrations which were irreconcilable, leading to the conclusion that at least one of the gas concentration measurements was flawed. The results in Figure 33 show that the predicted  $O_2$  concentration was extremely different than the measured profile. Possible problems with the Primex  $O_2$  gas analyzer are discussed in Section 2.1.2.1.

Figure 34 shows the average  $CO_2$  concentration as a function of time calculated using the model. For comparison,  $CO_2$  measurements at four radial locations each separated by  $90^\circ$  are also shown. Figure 14 shows the relative location of each of the probes. The average of the four measured traces is of the same order of magnitude as the model results. An initial sharp rise in  $CO_2$  concentration was measured by Probe 7, followed by a decrease. This followed the trends predicted by the model except for a 0.5 s time lag which was likely due to a combination of instrument time response (which was  $\approx 0.1$  s according to Primex) and agent dispersion in the sampling lines. For Probes 5 and 6, the rapid initial increase in  $CO_2$  concentrations were achieved 0.8 s later. A much larger delay was associated with Probe 4. The duration of the model and measurements by Probes 5 to 7 are similar. The  $CO_2$  profile is related to the volumetric flow of the SPGG effluent. Interpretation of the measured local agent concentrations associated with the SPGG tests were discussed in Section 2.2.2.

Figure 35 shows the model prediction for the transient volumetric flow. The model predicts a rapid 25% increase in volumetric flow to  $0.85 \text{ m}^3/\text{s}$ , a 10% decrease in flow over  $\approx 1$  s to  $0.7 \text{ m}^3/\text{s}$ , a slow steady increase for 6 s to  $0.8 \text{ m}^3/\text{s}$ , and finally a return to the initial nacelle flow. For comparison, Figure 35 also shows the measured velocity just upstream of Fire Zone 1. The measured velocity actually decreased, rather than increasing as expected with agent addition. There is also a discrepancy between the steady-state measured and calculated air velocities as described in detail in Section 2.1.1.1. Because the velocity data is unreliable, the volumetric flow is shown in Figure 35 rather than the average velocity. Careful velocity measurements need to be re-conducted and the flow field needs to be better characterized to confirm the importance of flow straining in flame suppression by SPGG as suggested by the results in Tables 6 and 7.

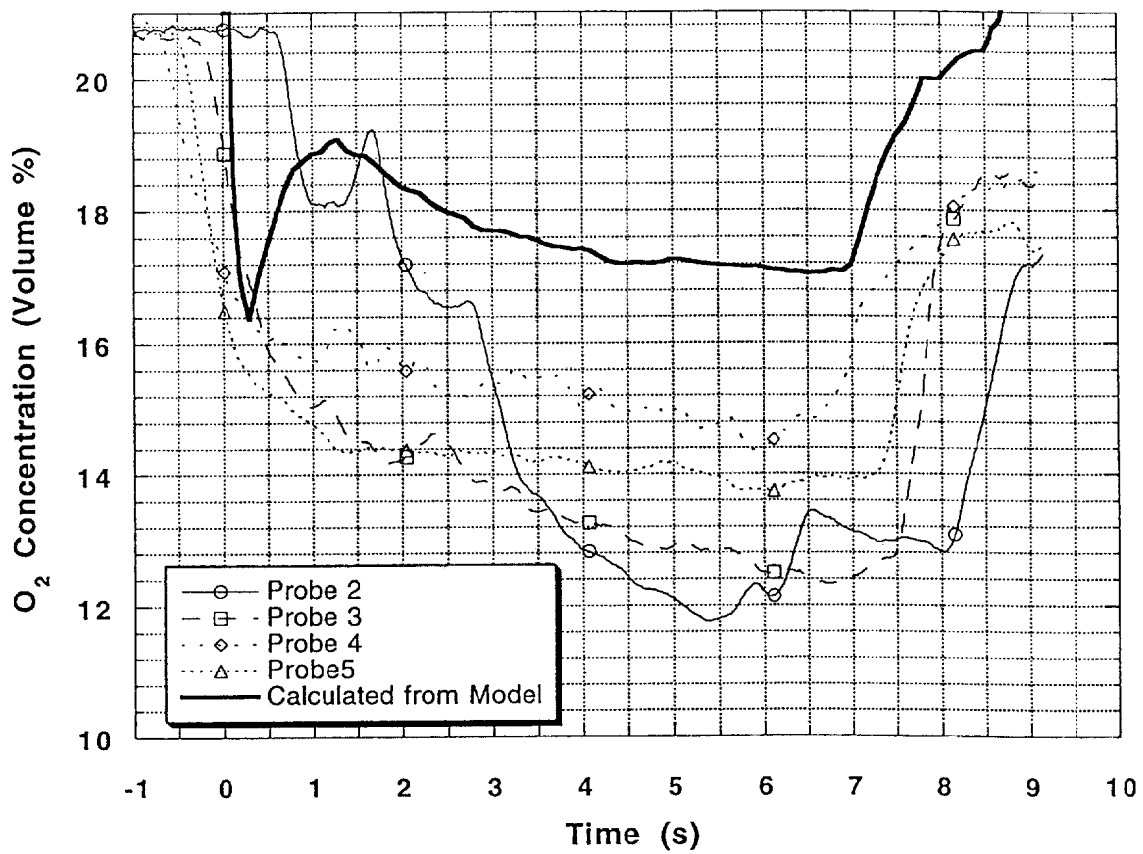


Figure 33. The calculated and measured O<sub>2</sub> concentration during Primex Concentration Test 2c as a function of time.

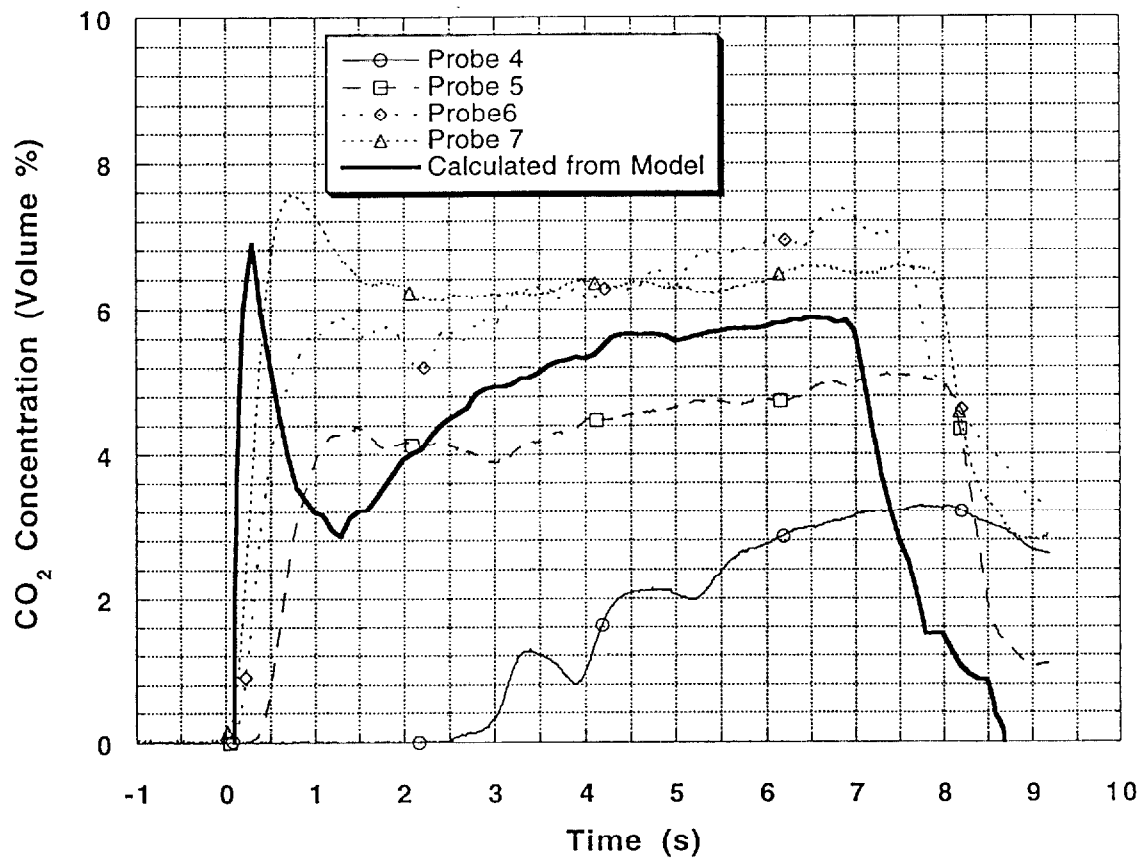
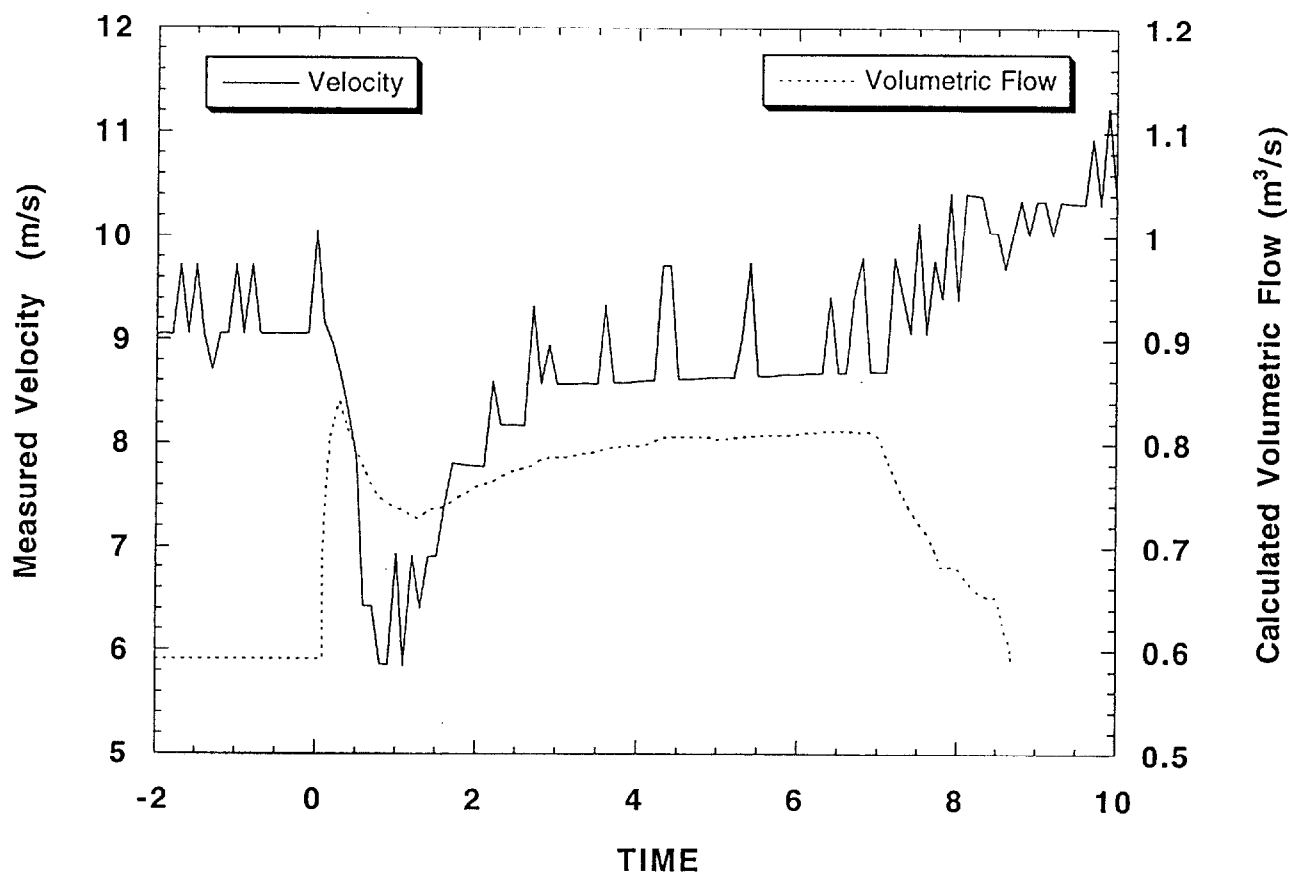


Figure 34. The calculated and measured CO<sub>2</sub> concentration during Primex Concentration Test 2c as a function of time.



**Figure 35.** The calculated transient volumetric flow and the measured velocity in the downstream axial direction during Primex Concentration Test 2c as a function of time.

Figure 36 shows the temperature predicted by the model at the agent nozzle outlet (labeled isentropic expansion) and after mixing with the air in the nacelle (labeled plug flow mixing). The outlet temperature is predicted to be moderately high (350°C to 500°C), but decreases to rather low values ( $\approx 200^\circ\text{C}$ ) when the agent is perfectly mixed with the ventilation air. The measured temperature at Fire Zone 1 was within 50°C of the model prediction as shown in Figure 36. The temperature measured inside of the SPGG manifold (in Figure 36) took on values as high as 1200°C. This temperature should be considered in terms of hardware design.

Figure 37 shows the calculated gas phase agent and water concentration in the nacelle. The profile is proportional to the CO<sub>2</sub> profile shown in Figure 35 and resembles the pressure input trace.

The SPGG model results presented here should be considered preliminary. If a better understanding of the suppression requirements for a particular SPGG formulation were available, then analysis similar to those for the halogenated agents could be accomplished increasing the level of confidence in the simple NIST model.

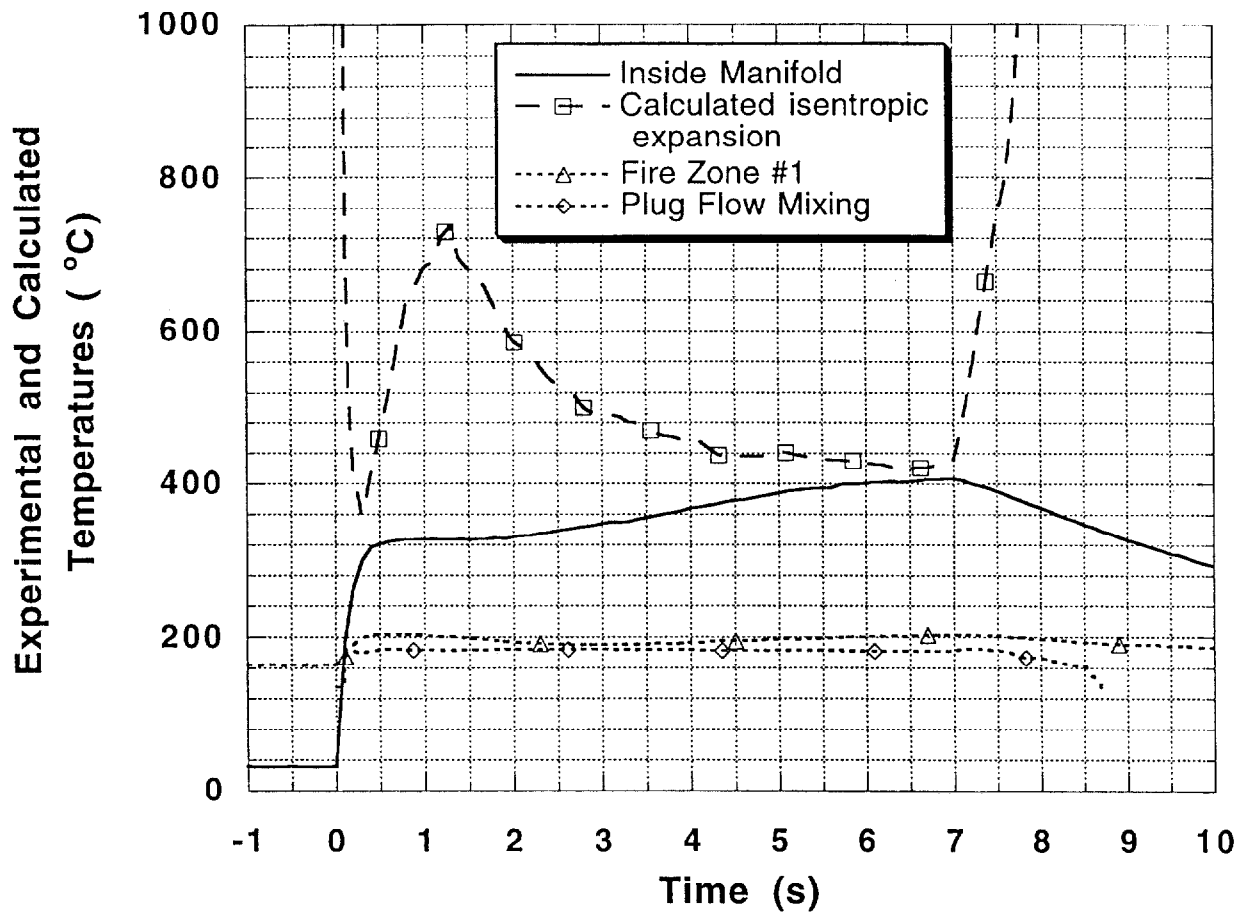


Figure 36.

The calculated average temperature at the nozzle outlet and when perfectly-mixed for Primex Concentration Test 2c as a function of time. The measured temperature in the SPGG manifold and in Fire Zone 1 are also shown.



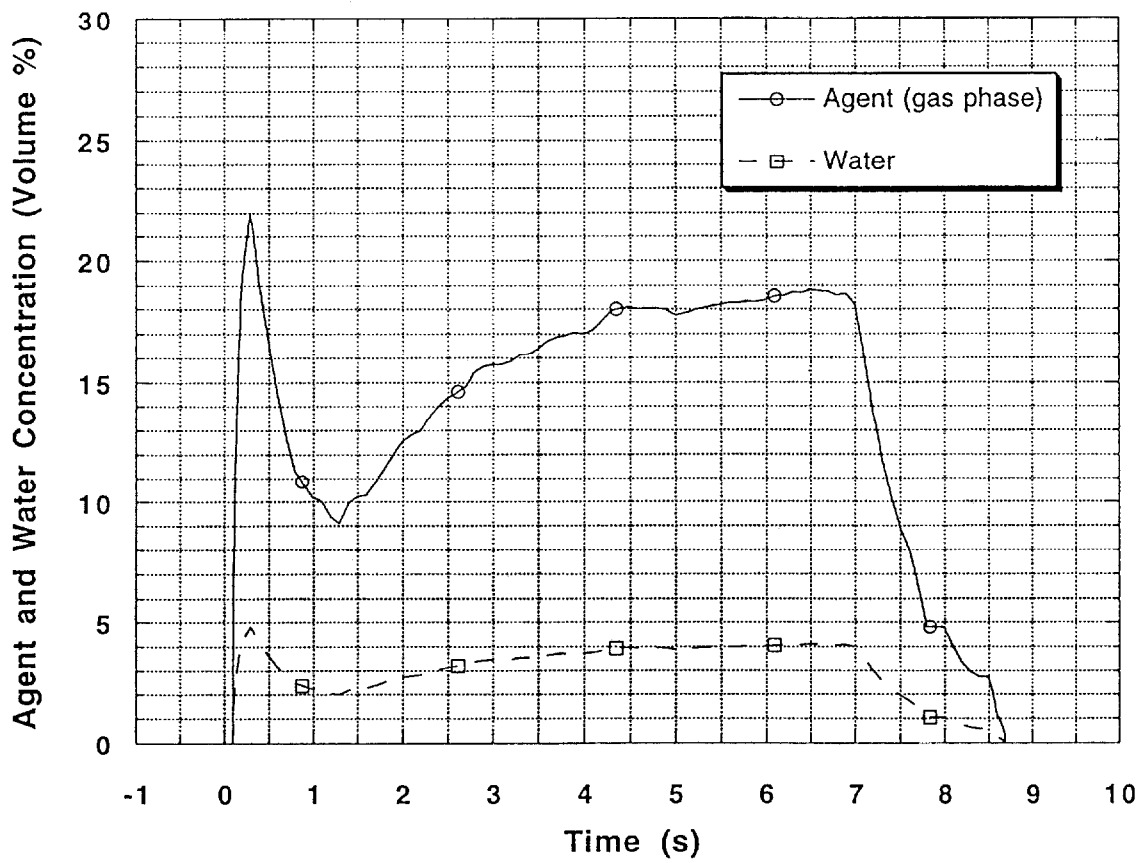


Figure 37. The calculated gas phase average agent mixture and H<sub>2</sub>O concentrations during Primex Concentration Test 2c as a function of time.

#### 4. CONCLUSIONS AND RECOMMENDATIONS

Our conclusions are summarized as follows:

- \* The SPGG effluent was significantly more effective than HFC-125 and similar in performance to halon 1301 in suppressing spray fires.
- \* The SPGG effluent was significantly more effective than HFC-125 and halon 1301 in preventing hot-surface re-ignition, a scenario which dominated agent mass requirements for the compressed halogenated liquids. The SPGG formulation which contained a significant percentage of  $K_2CO_3$  particulate was particularly effective for re-ignition protection. Even the filtered Primex SPGG apparently produced enough particulate to prevent hot-surface re-ignition. Agents which contain  $K_2CO_3$  and perhaps other types of particulate offer a mass efficient approach to re-ignition protection.
- \* Just as every halogenated agent has different properties which affect its suppression effectiveness, every propellant formulation should be thought of as a distinct agent. Given its constituents and their effectiveness, it is possible to estimate the suppression effectiveness of the SPGG effluent mixtures and to optimize the SPGG formulation.

The Primex SPGG effluent was filtered, removing much of the  $K_2CO_3$  particulate. The suppression effectiveness of this formulation would have performed significantly better, if the particulates had not been filtered.

- \* The increased temperature associated with SPGG was measured to be very small near the fire zones, resulting in negligible effect on agent requirements. In nacelle regions close to the agent nozzle exit, the temperature of the SPGG effluent/air mixture could stabilize a fire, leading to small increases in agent concentration requirements depending on ambient conditions and local heat transfer.
- \* Experiments in a full-scale system involve the interaction of many complex phenomena and it is not possible to control or even fully characterize key experimental parameters. Unrecognized parameters may also effect experimental outcome. Therefore, any conclusions regarding mechanisms of flame extinction by SPGG or halogenated liquids during the full-scale testing should be viewed as preliminary.

From the available data, the mechanisms of flame extinction by SPGG were largely due to effects beyond those associated with thermal and chemical effects as exemplified by extinction of simple cup burner flames, such as flame

straining effects. Questions regarding the accuracy of the local velocity measurements preclude stating this with certainty.

- \* For the halogenated agents, the Zone 2 spray fires were more difficult to extinguish than the Zone 1 spray fires which were directly downstream of one of the branches of the agent nozzle. This was due to poor agent transport to this region as well as other factors which are poorly understood. These other factors stabilized the fire in Zone 2 leading to larger agent concentrations than expected to achieve suppression.
- \* A simple model for SPGG delivery was developed. Assuming plug type flow, the transient average agent concentrations were calculated in the nacelle and compared to measurements. The results give reasonable agreement.

Our recommendations for future research are:

- \* **Further research is needed to optimize agent delivery and distribution.**

Calculations show that the HFC-125 mass requirements could be decreased by a factor of four if agent delivery and distribution were optimized. Significant reduction of agent mass requirements for all agents (including SPGG and compressed halogenated liquids) could be realized through improved design of agent delivery rates and agent distribution. Such a strategy would involve maintaining agent inerting concentrations for an appropriate duration. This could be accomplished through modifications in agent hardware, such as the agent delivery tube length, tube diameter, and valving.

- \* **The fire suppression effectiveness and ignition prevention effectiveness of SPGG and other agents should be tested in bench-scale experiments.**

Suppression using SPGG effluent is a developing technology. Its performance in this program proves that it has great potential. More SPGG testing is needed to better understand its performance and possible limitations. Experience with halogenated agents suggests that the effectiveness of SPGG agents and their mechanisms of flame extinction can be understood under controlled and well-characterized bench-scale conditions. Testing in a carefully designed reduced-scale device would remove the complexity associated with aspects of agent mixing and uncertainties in agent concentration distribution which complicates interpretation

of full-scale results. The relation between agent temperature and required agent concentration should be determined. Bench-scale testing offers the possibility of optimizing propellant formulations and delivery strategies at lower cost than full-scale testing. Simple bench-scale experiments on ignition suppression with inert, halogenated, powder and SPGG compounds would be helpful in predicting ignition phenomena in engine nacelles. The suppression effectiveness of  $K_2CO_3$  should be investigated. In particular, the peak flammability limits of  $K_2CO_3$  and its effectiveness in suppressing diffusion flames should be determined.

**\* Use of powder agents should be reconsidered.**

SPGG with its  $K_2CO_3$  particulate appears to be a very effective suppressant of re-ignition. Other powder containing agents may offer very effective re-ignition protection at extremely low cost. If SPGG is allowed for fire protection of engine nacelles, then the use of powders such as mono-ammonium phosphate or sodium bicarbonate might be re-considered. Suppression testing also shows that powders are very effective fire suppressants, even more effective than halon 1301 on a mass basis. Powders may offer very effective re-ignition protection at extremely low cost.

**\* Reliable, fast response gas analysis instruments should be developed.**

Such instruments are needed to measure agent concentration for possible SPGG certification purposes as well as other newly developing agents. If the Primex instruments are to be used in the future, further work needs to be conducted to insure that they are reliable. Inconsistencies in the gas measurements suggest that bench-scale testing and calibration of these instruments under nacelle-like conditions are necessary. Fast, reliable instruments are critical for the development of advanced agents.

Agent concentrations determined using gas sampling depends on sampling conditions. As different agents are approved for fire protection, a variety of instruments with possibly different flow requirements may be used for certification purposes. Thus, specification of agent concentrations for certification of agent fire protection systems for aircraft applications (such as MIL-E 22285 for halon 1301 systems) should stipulate instrument/system time response. This may include the instrument time response and the lengths, diameters, and flows within a sampling line which impacts agent dispersion and system time response.

- \* **Further research is needed to characterize worst-case fire conditions in an engine nacelle.**

Each of the three fire scenarios investigated (a spray fire, a spray fire and fuel spray on a hot surface, and a spray/pool fire) yielded strikingly different results. Studies to date have selected fire configurations and test conditions on an *ad-hoc* basis. To evaluate fire protection strategies and decide on the desired level of safety, information is required on a number of issues including the impact of various realistic baffle geometries on flame stability (for both re-ignition and suppression protection), fuel configuration effects (i.e., is the fuel a spray, a puddle, or a combination), fuel load effects, fire placement relative to warm surfaces, and the spatial extent of the fuel. For example, it may be reasonable to select fire locations for full-scale suppression testing based on agent distribution measurements. It would be interesting to conduct SPGG suppression tests with a fuel puddle behind a baffle, which is a challenging location for the halogenated agents. Also, a fuel puddle between baffles directly downstream of the high momentum SPGG may also be a challenging situation as the SPGG momentum disperses the fuel.

In addition, key experimental parameters which influence the critical agent mass required for suppression should be varied to represent possible in-flight fire conditions. In this test program, these parameters were the preburn time before agent delivery, selected as 20 s, and the fuel flow duration after flame extinction, selected as 8 s. Selection of other values would have significantly changed the measured critical agent masses. Yet, these parameters were not necessarily based on worst case conditions, nor even realistic conditions. Nor have worst case conditions been characterized for fire placement or configuration. Many of these issues could be investigated in reduced-scale experiments. Knowledge from such studies could be used to construct a reduced-scale suppression screen which realistically simulates fire conditions in an engine nacelle.

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**APPENDIX**

**TEST PLAN:**  
**SPGG ASSESSMENT PROGRAM**

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## Executive Summary

- For the past 30 years, Halon has been widely used in aircraft fire suppression systems because of its ability to efficiently extinguish fires. Unfortunately, the properties that enable Halon to be such an effective extinguishant also cause it to be a significant Ozone Depleting Chemical (ODC). Due to increased environmental awareness and international legislation, the production of Halon ceased in January 1994. Existing stockpiles of Halon will not meet the Department of Defense's critical fire suppression needs indefinitely, and a crucial need for a Halon replacement exists. The Halon Replacement Program for Aviation was undertaken in 1992 with the objective of identifying a conventional replacement agent from a given list of 10 potential candidates. That program identified HFC-125 as the baseline Halon replacement, but preliminary data from the development of design equations indicated potential penalties in terms of overall system weight. Consequently, other alternatives must be researched to meet the survivability and safety needs of current and future weapon systems. One such alternative is the Solid Propellant Gas Generator (SPGG). The primary objective of this program is to build upon SPGG testing conducted by the Navy and assess the application of SPGG technology to the engine bays of advanced aircraft through simulated fire testing. The particular focus of this program will be the engine nacelle of the F-22. Analysis of the data acquired will provide guidance for the development and design of an engine nacelle fire suppressing gas generator system. Additional analyses will address the potential application of SPGG technology to specific aircraft platforms such as the F-15 and C-17 based upon an understanding of and investigation into the extinguishing mechanisms important to the gas generator.

## 1.0 INTRODUCTION

The Clean Air Act Amendments (CAAA) of 1990 and US Environmental Protection Agency (EPA) rules limit US consumption and production of ozone depleting substances (ODS). These actions carry out the United States' obligations under the "Montreal Protocol on Substances that Deplete the Ozone Layer", an international treaty ratified by the Senate in December 1988 limiting global production and consumption of such chemicals. Subsequent international and national legislation has dictated the phase-out of ODS production, and industrial production ceased in January 1994. These restrictions were established because the atmospheric chlorine loading caused by these chemicals depletes the earth's protective stratospheric ozone layer, and stratospheric ozone depletion is predicted to have a significant adverse global impact on human health, climate, and natural environmental systems.

Some of the most important of the ODS chemicals are the halons, especially Halon 1301. Halons are important because they are used as the primary fire-extinguishing chemical in the engine nacelles and dry bays of most military and civilian aircraft. Halons have been used since the late 1940s, and after many years of operational experience, Halon 1301 (CF<sub>3</sub>Br) emerged as the favored agent for aircraft. This is due primarily to the wide range of applications to which Halon 1301 is suited; however, increasing environmental concerns with ozone depletion have resulted in the mandate to discontinue its use.

In 1992, a decision was made by the US Air Force to develop a "non-ozone depleting solution" for on-board aircraft fire extinguishing by 1995. This timeline was dictated by the program schedule of the F-22 fighter and the hope that the alternative solution could be considered for implementation on the production aircraft. A program for evaluating and identifying alternative extinguishing agents that would be commercially available was developed by the Air Force's Wright Laboratory. This program - The Halon Replacement Program for Aviation - was subsequently expanded in scope to include the requirements of all US military and commercial aircraft engine nacelle and dry bay applications and was sponsored by the US Air Force, Navy, Army, and Federal Aviation Administration. The objective of this program was to find a near-term chemical "drop-in" replacement agent for halon.

The Halon Replacement Program for Aviation consisted of three phases. Phase I was the Operational Parameters Study; Phase II, the Operational Comparison of Selected Agents; and Phase III, the Establishment of Design Criteria Methodologies. As the result of a decision made at the end of Phase II, HFC-125 was selected as the most promising replacement agent with which to proceed to Phase III. Phase III is now complete and the design methodologies have been developed, but the final documentation is still not ready for release.

There are several important considerations in replacing halon in aircraft fire protection systems. The most obvious among these is the weight and volume of the agent and of the delivery equipment. Unfortunately, HFC-125 is not as effective as halon at suppressing fires and therefore, larger volumes and weights of this agent may be required. Since there are severe weight and space limitations on aircraft systems, engineers may be forced to compromise fire

suppression capability in order to meet a restriction on system weight. This could result in a significant decrease in aircraft and pilot survivability.

Fortunately, while the Halon Replacement Program for Aviation was being conducted, research progressed on other fire suppression technologies, such as the Solid Propellant Gas Generator (SPGG). Recently, this concept has shown promise as a lightweight halon alternative. The SPGG concept uses technology designed for the inflation of automobile airbags, relying on the controlled burning of solid reactants to produce inert gases such as H<sub>2</sub>O, CO<sub>2</sub>, and N<sub>2</sub>. The Naval Air Systems Command (NAVAIR) has already conducted testing to evaluate the applicability of these devices for fire suppression in engine nacelles and dry bays. As a result of this testing, NAVAIR currently plans to implement gas generators on the V-22 and the F/A-18 E/F. Additionally, the Air Force's Wright Laboratory has conducted a 6.2 Exploratory Development effort investigating the extinguishing merits of the SPGG. Now the time has come for the Air Force to take advantage of the aggressive Navy testing and look for similar near-term applications of SPGG technology.

As a result, the F-22 has been chosen as an Air Force platform for the investigation of the SPGG technology because it is a fighter configuration similar to the Navy F/A-18 and it has a clearly defined requirement for non-ozone depleting fire suppression. At the same time, other fighter and transport aircraft such as the F-15, C-17, and KC-135 will require halon-free fire suppression systems, and every effort should be made to consider these aircraft in the generation of any test data. Careful consideration of test methodologies and the development of an understanding of the SPGG extinguishment mechanism will be important for this task - creating the potential to transition the technology to other aircraft with minimal additional testing. Furthermore, special effort will be directed toward the investigation of unresolved technical issues regarding SPGG. These issues include: (1) uninsulated bleed air ducts and hot surface reignition, (2) cold temperature discharge, (3) ventilated pool fire scenarios, and (4) chemically active (vs. inert) gas generation.

In response to the scenario described above, a test program is being introduced to resolve the technical issues related to SPGG and evaluate the applicability of SPGG for the fire suppression requirements of the F-22. The emphasis of this program will be on engine nacelle fire protection. The feasibility of dry bay testing will be evaluated in terms of cost and schedule. In conducting this program, it will be particularly important to coordinate with the Navy and assess their data for lessons learned and potential application to other aircraft platforms.

## **2.0 FACILITIES DESCRIPTION**

The Aircraft Engine Nacelle Fire Test Simulator (AENFTS or AEN) located at Wright-Patterson Air Force Base, OH is a ground test facility designed to simulate the fire hazards which exist in the annular compartment around an aircraft engine. This facility has been used to test the effectiveness of different methods of engine nacelle fire prevention, detection and extinguishment. The AENFTS includes air delivery and conditioning equipment designed to

simulate engine compartment ventilation air flow, a test section within which fire testing may be safely conducted, and an exhaust system which can cool the combustion products and scrub them sufficiently to allow their release into the atmosphere. Electrical heaters are used to provide a hot surface area on the inserted engine core simulation surface. In addition, a gas-fired heating system is available to provide simulated engine bleed-air to the test section. Up to 1500°F and 220 psia air may be provided at flow rates up to one pound per second at the exit of the heater.

The current test fixture (Figure A-1 in Appendix A) simulates a full 360° airflow field. Cross-sectional Area can be adjusted by using 24", 30", or 36" diameter internal inserts that represent the engine casing. The outer diameter remains constant at 48". A generic clutter configuration, composed of longitudinal and circumferential flanges, can be used around the fire zone to act as a flame holder. In addition, removable clutter can be used upstream to hinder agent distribution.

An electric heater platen provides the capability to create an "engine hot spot" at the downstream end of the engine core. The platen is approximately 30" long, with a 100° arc on the insert surface. The temperature is "set point" controlled at up to 1500°F.

Extinguishing agents are delivered to the nacelle fire from a cylindrically-shaped, high pressure bottle which is equipped to either heat or chill the test agent. The bottle is also designed for variable volume to accommodate the various quantities of agent desired. Heating the agent is accomplished with several electric band-type heating units mounted around the outside of the cylinder. The heaters are "set point" controlled and are effective for heating and maintaining the agent up to 200°F. For cooling, the bottle is equipped with a flat-sided "jacket" enclosure which is filled with dry ice. The temperature of dry ice is -127°F. Therefore, in order to maintain the cold temperature at a known fixed point such as -55°F, the band heaters are utilized to hold the desired temperature.

The volume of the agent chamber is controlled by a floating piston which can be placed and maintained at any vertical location in the agent bottle. Spacer rings are used above the piston to maintain the piston location. The test agent is charged and delivered from the bottom of the vertically mounted cylinder, which can accommodate from 1 ounce to 24.5 pounds of agent. The charging gas is typically nitrogen.

Air delivery and conditioning allows for the simulation of test pressure conditions of atmospheric, above atmospheric, and below atmospheric pressures. In addition, the capability to control the heating and cooling of the air is provided. The inlet air supply originates from two sources: (1) an air blower with a maximum capacity of 8,780 SCFM (11.2 pounds per second) and (2) a high pressure blow-down system with a storage capacity of 8,800 pounds of air at 2,000 psig. A flow control and vent by-pass system is used to control airflow to the engine nacelle. Standard commercial-type controllers are used to control the blower airflow. The airflow controller system consists of a differential pressure/current transmitter, controller, current/pneumatic transducer, and a 24-inch butterfly valve with pneumatic actuator and positioner.

The air exhaust subsystem includes those components downstream of the nacelle transition. Major components include the 24-inch piping from the nacelle outlet to the 10 and 24-inch butterfly valves, the 10-inch butterfly valve at the ejector inlet, the 24-inch atmospheric throttling butterfly valve, the ejector, the adaptive piping for the 10 and 24-inch pipe merging and enlarging to the 48-inch pipe, a water quencher/sump section, the 48-inch exhaust stack, a scrubber bypass valve, the scrubber with recirculating water pump, scrubber-to-fan ducting (42-inch), and a centrifugal exhaust fan with outlet ducting. A water treatment system, which is located at ground level at the north end of the building, accepts liquids pumped from the quench/sump section and also liquids which drain or overflow from the scrubber. In addition, combustibles are separated from the water/chemical solution through a series of baffles in the water treatment tank where quality is sensed for monitoring in the control room. Accumulated combustibles are manually drained into the facility waste fuel sump, and the water/chemical solution is recirculated until the water quality is on the verge of being chemically unacceptable, at which time the solution is expelled into the base sanitary sewer system. A schematic of the overall facility is included in Appendix A (Figure A-2).

For the purpose of this program, an F-22 engine nacelle simulator was designed and fabricated to be more representative of the geometry and operating conditions found in the engine nacelle of the F-22. The on-site contractor, Systems Research Laboratory (SRL), designed the simulator and ASC/AMFP, the Developmental Modification and Manufacturing Facility, performed the fabrication tasks. The design of the simulator was based on data obtained from Boeing, Pratt & Whitney, and the F-22 System Program Office (SPO). The fabricated simulator is realistic in terms of clutter, engine/airframe components, geometry, temperatures, and airflow. Upon fabrication, the F-22 simulator was integrated into the test section of the existing AEN facility. A schematic of the F-22 test section is located in Appendix A (Figure A-3). This new test section retains all the features of the existing facility but special care has been taken to provide for more realistic heating of engine surfaces. An engine core heater was integrated into the simulator and it is capable of heating the entire surface of the engine core to set point temperatures less than and equal to 1000 °F. Additionally, a bleed air duct heater was included to provide additional heating over a smaller area. This bleed air duct heater can be set point controlled up to 1500 °F.

### **3.0 TEST OBJECTIVES**

The primary objective of this research and development test program is to gain a better understanding of unresolved technical issues related to SPGG and assess the application of SPGG to an advanced fighter engine nacelle. In making this assessment of SPGG, performance will be evaluated in terms of mass (quantity of agent) and concentration required to extinguish a given fire condition. Both strictly inert and chemically active SPGG devices will be tested and their performance will be measured relative to the performance of Halon 1301 and HFC-125. Data will be analyzed with the intent of gaining insight into the extinguishing mechanism of the gas generator in order to provide sound guidance regarding the design and application of SPGG for engine nacelle fire protection. Additional analyses will provide for the validation and



verification of the design equations developed for use of HFC-125 during the Halon Replacement Program for Aviation.

## 4.0 TEST APPROACH

### 4.1 Performance Metric

The basic performance metric of this testing will be the quantity of agent or gas generator chemicals required to extinguish the fire. Unfortunately, it is very difficult to converge on this parameter directly during the test. To address this problem, a bracketing procedure was devised which uses an iterative process to narrow down the amount of agent required to extinguish a fire. This bracketing procedure was developed for Phase IIIB of the Halon Replacement Program for Aviation. A next generation, more efficient bracketing procedure was used in a follow-on test program known as the Broad Methodology test program. The implementation of this procedure streamlined the agent bracketing process, and required the completion of 5 successful extinguishments at each weight to establish an "Upper Limit" of extinguishment performance. If 5 successive tests at a given weight are successful extinguishments, the procedure calculates the next weight as half the difference between the Upper Limit just established, and the highest unsuccessful weight. When the calculated next weight is within 10 percent of the current test weight, it is said that convergence has been reached, and the test run is finished. A schematic illustrating the logic of the bracketing procedure may be found in Figure B-1 of Appendix B.

This bracketing procedure will be employed in this program during the development of the Halon and HFC-125 baselines; however, it may not be advantageous to use this procedure when testing the gas generator systems because these systems have multiple parameters which may be adjusted when attempting to determine the quantity of agent required to extinguish a fire. For instance, the burn time of the gas generator propellant and the firing sequence of the gas generator units (if considering multiple 1 pound units fired through a manifold) may be varied in addition to varying the mass quantity of the propellant. Because of the complex interaction between the variable parameters of the gas generator, a method for converging to the minimum quantity of agent required to extinguish the fire will not be specified and the vendors of the gas generator technology will be permitted to devise their own method of determining the required quantity of agent. However, the vendors must have their test methods approved by the government prior to testing.

### 4.2 Test Parameters

Phase I of the Halon Replacement Program for Aviation determined that the following parameters had the greatest impact on the extinguishment of engine nacelle fires:

- a. Surface Temperature (*variable*)
- b. Air Temperature (*variable*)
- c. Fuel Temperature (*variable*)

- d. Fuel Type (*fixed*)
- e. Cross Sectional Area (*fixed*) (area = 7.7 ft<sup>2</sup> and volume = 85 ft<sup>3</sup>)
- f. Pre-Burn Time (*variable*)

However, other parameters will be of interest in this test program, including:

- g. Airflow Rate (*variable*)
- h. Configuration/Clutter (*fixed*)
- i. Agent Distribution/Discharge Location (*fixed*)
- j. Fire Location (*variable*)
- h. Agent Temperature (*variable*)
- j. Fuel Post Dump Time (*fixed*)

Values or ranges for these parameters will be established based on representative operational environments encountered by the F-22 in a typical mission profile. For this program, the fixed - "*fixed*" - and variable - "*variable*" - parameters have been indicated

### 4.3 Test Phases

A simple three phase test approach will be used in this program. The first phase (Phase I: Simulator Check Out and Reignition Assessment) will involve simple simulator check out and fire characterization studies. The second phase (Phase II: Baseline Fire Definition) will involve the determination of a "worst case" baseline fire condition and a baseline ventilated pool fire condition. Following the second phase, the SPGG units will be tested and sized against the "worst case" baseline fire in the third phase (Phase III: SPGG Testing). However, the worst case condition for HFC-125 may not necessarily be the worst case for SPGG. Therefore, following the sizing of the SPGG units against the "worst case" baseline condition, a final series of tests will be conducted in which SPGG units will be tested against additional fire scenarios involving: (1) cold temperature conditions and (2) baffle stabilized pool fires. Each phase will be discussed in detail:

#### 4.3.1 Phase I: Simulator Check Out and Reignition Assessment

The objective of Phase I is to empirically assess the fires generated in the new engine nacelle test fixture and determine what fuel nozzle, fuel flow rate, and fuel spray direction to use throughout the test program. The issue of Hot Surface Reignition will be addressed and an attempt will be made to define a test condition which may be used to evaluate the consistency/repeatability of the simulator.

#### Phase I Exit Criteria

1. Selection of Fuel Nozzle, Fuel Flow Rate, and Fuel Spray Direction
2. Completion of Assessment of Reignition within the Nacelle Fixture
3. Development of Test to Evaluate Consistency/Repeatability of Simulated Fires

**Selection of Fuel Nozzle, Fuel Flow Rate, and Fuel Spray Direction:** To select the fuel nozzle, fuel flow rate and fuel spray direction, fires will be generated at the two fire locations within the nacelle and different nozzles, flow rates and spray directions will be tried in various combinations. The fuel nozzle, flow rate and spray direction will be empirically selected to produce the most robust fires based on the following criteria:

VISUAL INFORMATION: Absence of soot and smoke, ease of fire ignition

TEMPERATURE DATA: Highest average thermocouple readings in the fire zone

**Reignition Assessment:** Hot surface reignition is a phenomena that is difficult to understand and control. During the Halon Replacement Program for Aviation, testing showed that significant quantities of agent (HFC-125) may be required to extinguish a fire and keep it out so that it does not reignite from hot surfaces following extinguishment. For this program, when extinguishing fires with agent, a reignition - re-light of a fire following extinguishment due to fuel being in contact with hot surfaces - will be classified as a FAILED TEST. If the fire is extinguished and reignition does not occur, the test will be deemed SUCCESSFUL. Given this definition of failure and success, it will be advantageous to gain an awareness of the conditions in which reignitions may be possible during the test program before attempting to extinguish fires with agent.

To make this assessment, fires will be investigated at the highest operating temperatures while varying preburn time and airflow velocity. The general procedure is to ignite fires under a consistent set of conditions and let the fire burn for a specified preburn time. After the preburn time expires, the fuel flow will be stopped until the fire is extinguished. Following extinguishment, the fuel will be reapplied for 8 seconds. The time of fire extinguishment and re-application of fuel will be based on the engineer's judgment of fire extinguishment. Each test combination of preburn time and airflow rate will be repeated 5 times and the number of reignitions will be recorded. The test matrix and procedures for this testing may be found in Table C-1 in Appendix C.

**Consistency/Repeatability of Simulated Fires:** Before entering Phase II and attempting to define the "worst case" baseline fire condition, it will be desirable to define a test condition which can be used to ensure the repeatability/consistency of the simulated fires throughout the test program. The repeatability/consistency of the simulated fires will be determined by verifying that the same quantity of agent extinguishes the same fire condition at various times during the test program. If a quantity of agent that is "expected" to extinguish the fire does extinguish the fire, and if a quantity of agent "not expected" to extinguish the fire does not extinguish the fire, then it will be *assumed* that the simulated fire conditions are repeatable and consistent across the entire operating range of the simulator.

To determine the parameters of the repeatability/consistency test, a curve of Percentage of Fires Out versus Quantity of Agent (HFC-125) will be generated for the fire conditions indicated in Table C-2 in Appendix C. Each quantity of agent will be tested against the fire condition 10 times and the number of failures and successes will be recorded. The percentage of fires out will be the number of successful extinguishments divided by the total number of tests - in this case 10. From this curve, a quantity of agent with a high probability of extinguishing the fire will be selected and a quantity of agent with a low probability of extinguishing the fire will be selected. These two quantities of agent will be tested against the defined fire condition every 3-4 days. Each quantity of agent will be tested against the fire condition 5 times, i.e. 5 tests at the high quantity of agent and 5 tests at the low quantity of agent. If the quantity of agent with a high probability of extinguishing the fire successfully extinguishes the fire for the majority of the five tests and the quantity of agent with the low probability fails to extinguish the fire for the majority of the five tests, it will be assumed that the simulator is operating in a repeatable manner across the range of fire conditions.

#### 4.3.2 Phase II: Baseline Fire Definition

The objective of Phase II is to define a “worst case” fire condition against which the SPGG devices may be tested. The “worst case” condition will be selected from a matrix of conditions representative of actual operating conditions found in the engine nacelle of the F-22. The data collected, agent weight and concentration, will be compared to predictions determined from design equations developed during the Halon Replacement Program for Aviation. A ventilated pool fire condition and cold temperature condition will also be defined based on the performance of HFC-125.

#### Phase II Exit Criteria

1. Definition of baseline, “worst case,” fire condition from a matrix of fire conditions
2. Generation of HFC-125 and Halon 1301 data for this condition
3. Generation of HFC-125 concentration data for the conditions in the matrix
4. Comparison of concentration data to predictions from design equations
5. Definition of a ventilated pool fire condition using HFC-125
6. Definition of a cold temperature test condition using HFC-125

**Baseline, “Worst Case,” Fire Condition Definition:** The “worst case” fire condition will be selected from a test matrix of 18 fire conditions. This matrix of fire conditions is based upon actual flight conditions of the F-22 and it may be found in Table D-1 in Appendix D.

(NOTE: The original intent of Phase II was to select the “worst case” fire condition from a matrix generated by Design of Experiments, but Boeing, the contractor responsible for

the engine nacelle fire protection of the F-22, had concerns with the Design of Experiments matrix because it contained unrealistic combinations of test parameters, i.e. combinations of parameters that did not correspond to actual flight conditions. As a result, Boeing was invited to provide a matrix of acceptable fire conditions from which the “worst case” condition would be selected. The matrix delivered by Boeing is the matrix contained in Table D-1. Unfortunately, the matrix provided by Boeing did not contain any preburn times. As a result, a uniform preburn time of 20 seconds was selected for each run of the matrix. 20 seconds was selected because the design equations derived from the Halon Replacement Program for Aviation are only recommended for use with preburn times less than or equal to 20 seconds. Although this approach allows for the testing of realistic operating conditions, the ability to do refined Design of Experiments analysis is lost and a single level for preburn time has been applied to all runs of the matrix thereby removing the ability to assess the impact of this important parameter.)

The test matrix in Table D-1 will be bracketed with HFC-125 using the bracketing procedure defined in Figure B-1. This approach will define a quantity (upper limit) of agent required to extinguish each run of the matrix. The “worst case” fire condition will be defined as the run of the matrix requiring the greatest quantity of HFC-125 for extinguishment. Recall that successful extinguishment is defined by putting the fire out without any subsequent reignition. For comparison purposes, this worst case run will also be bracketed with Halon 1301 and then it will become the baseline fire against which the SPGG units will be evaluated in Phase III. In this way, the performance of HFC-125, Halon 1301, and SPGG propellants from two vendors can be compared relative to the same fire condition.

**Concentration Measurement:** Before testing the SPGG units against the baseline fire in Phase III, additional data will be collected. This additional data includes concentration measurements for each run of the baseline matrix. The concentration data is crucial because it will indicate the quantity of agent at the fire zone and throughout the nacelle in terms of volumetric percent as a function of time. The matrix for conducting the concentration measurements is found in Table D-2 of Appendix D. This matrix contains the same test conditions indicated in the baseline matrix, but it also contains the fire condition for the simulator repeatability/consistency test condition. For each run of the matrix, concentrations will be measured when the extinguishing bottle is filled with the upper quantity of agent corresponding to that run as determined from the bracketing procedure. For the repeatability/consistency test condition, concentrations will be measured when the bottle is filled with the two test quantities of agent (the quantity expected to extinguish the fire and the quantity not expected to extinguish the fire) and an intermediate quantity. The concentrations measured will be directly compared to the predictions from the design equations developed during the Halon Replacement Program for Aviation. It is hoped that the concentrations measured will validate and verify these design equations. The design equation predictions may also be found in Table D-2.

There are two design equations of interest, one for weight of agent and one for concentration. These equations are indicated below:

$$(1) \text{ Weight\_HFC-125} = (1.62 + 0.0007168 * \text{Air\_Temperature} + \text{Fuel\_Constant})^2$$

$$\text{Fuel\_Constant for JP-8} = 0.3586$$

$$(2) \text{ Concentration} = 16.91 + 0.0148 * \text{Air\_Temperature} - 3.124 * \text{Internal\_Airflow} + 1.597 * \text{Weight\_HFC-125}$$

These two equations can be combined to create the following:

$$(3) \text{ Concentration} = 21.10 + 0.0185 * \text{Air\_Temperature} - 3.124 * \text{Internal\_Airflow} + 5.174 * \text{Fuel\_Constant} + 0.0023 * \text{Air\_Temperature} * \text{Fuel\_Constant} + 1.597 * \text{Fuel\_Constant}^2$$

From this, a bottle sizing equation can be used:

$$(4) \text{ Bottle\_Size\_Weight} = 0.366 * \text{Concentration} * \text{Volume} + 4.138 * \text{Concentration} * \text{Internal\_Airflow} * (1 / (1 - \text{Concentration}))$$

However, it is important to understand that these design equations are only intended for air temperatures in the range of 100 °F to 275 °F and for airflow rates of 0.9 lbm/s to 2.7 lbm/s. Additionally, these equations only recommended for use with low surface temperatures, i.e. less than 800 °F, and preburn times less than 20 seconds.

**Ventilated Pool Fire and Cold Temperature Test Conditions:** As stated in Section 4.3, the “worst case” baseline condition for HFC-125 may not be a worst case condition for SPGG. Consequently, two other test conditions will be defined against which the SPGG units may be evaluated. These two conditions are (1) a ventilated pool fire condition and a (2) cold temperature test condition. Each test condition will be bracketed with HFC-125 to define a limit of extinguishing performance as was done in determining the “worst case” baseline test condition. The conditions and procedures for conducting the ventilated pool fire test condition may be found in in Table D-3 in Appendix D.

For the cold temperature test condition, the SPGG units will be tested against Run 16 of the baseline matrix defined in Table D-1. The HFC-125 data for this test condition will have already been determined during the bracketing of the baseline matrix earlier in Phase II. Originally, a separate cold temperature test condition was to have been selected, but parameters selected for that test condition were very close to the conditions indicated in Run 16; therefore, in the interest of time, the SPGG units will be tested against Run 16 so that an additional test condition will not have to be defined.

### 4.3.3 Phase III: SPGG Testing

This phase will allow for approximately 55 total tests from each of two vendors of gas generator technology. In this phase, each vendor will size their gas generator system against the baseline fire condition and the performance of Halon 1301, HFC-125 and the

gas generators from the two vendors will be compared relative to the baseline fire condition. Additionally, the sized systems will be tested against the ventilated pool fire condition and cold temperature condition as defined in Phase II. Finally, measurements of O<sub>2</sub> and CO<sub>2</sub> concentration will be made for each vendor at the baseline fire condition.

### Phase III Exit Criteria

1. SPGG system sizing by two vendors against baseline test condition
2. Test data of sized system against cold temperature test condition and ventilated pool fire test condition
3. Generation of concentration data for both SPGG vendors
4. Data collection to contribute to analysis of SPGG extinguishing mechanism

**SPGG Sizing:** One vendor at a time, the SPGG systems will be sized against the baseline fire condition defined in Phase II. The vendors will determine how to size their individual systems against the fire condition, but the logic of their sizing procedures must be presented to and approved by the government prior to testing.

**Ventilated Pool Fire and Cold Temperature Test Conditions:** Following the sizing of the SPGG system against the baseline condition, the sized system will be tested against the ventilated pool fire condition and cold temperature condition defined in Phase II. (The cold temperature test condition corresponds to Run 16 of the baseline matrix.)

**Concentration Measurement:** Following the testing against the baseline test condition, the ventilated pool fire condition, and the cold temperature test condition, concentration measurements of O<sub>2</sub> and CO<sub>2</sub> will be taken.

## 5.0 INSTRUMENTATION REQUIREMENTS

The following are the general instrumentation requirements for the test program:

### **Temperature Measurement**

- Array of 5-10 sensors per fire zone
- Free Stream Air Temperature
- Temperature Near Fuel Nozzle

### **Pressure Measurement**

- Static pressure near agent release point
- Static sensor inside agent bottle
- Kistler pressure transducers downstream during SPGG tests

### **Velocity Measurement**

- Upstream and downstream of fire zone and at fire zone
- Pitot tube and thermocouple

**Video**

Viewports for external cameras  
 Internal camera

**Concentration Measurement**

Statham Analyzer/Halonizer for HFC-125 and Halon 1301  
 O2/CO2 Analyzer for SPGG

**6.0 OTHER FACILITY REQUIREMENTS**

This test program will employ the F-22 Engine Nacelle Fire Simulator indicated in Appendix A. The facility requirements are consistent with those indicated in Section 2.0: Facilities Description. The facility will be required to provide fuel conditioning, ignition sources, airflow conditioning, surface temperature conditioning, and agent conditioning consistent with the test conditions described in this plan. The instrumentation described in Section 5 will be required and the following parameter tolerances must be maintained:

<u>PARAMETER</u>	<u>TOLERANCE</u>
Engine Surface Temperature	± 10 °F
Bleed Air Duct Temperature	± 10 °F
Internal Airflow	± 0.02 lbm/s
Air Temperature	± 2 °F
Air Back Pressure	± 0.02 psia
Agent Quantity	± 0.01 lbs
Agent Bottle Spacer Length	± 0.25 inch
Agent Temperature	± 2.0 °F
Agent Bottle Pressure	± 5.0 psig
Fuel Temperature	± 2.0 °F
Flame Preburn Time	± 0.02 s
Fuel Nozzle Insertion Height	± 0.25 inch
Post Dump Fuel Flow Time	± 0.02 s

**7.0 SCHEDULE**

The schedule for this test plan is included in Appendix E.



## APPENDIX A

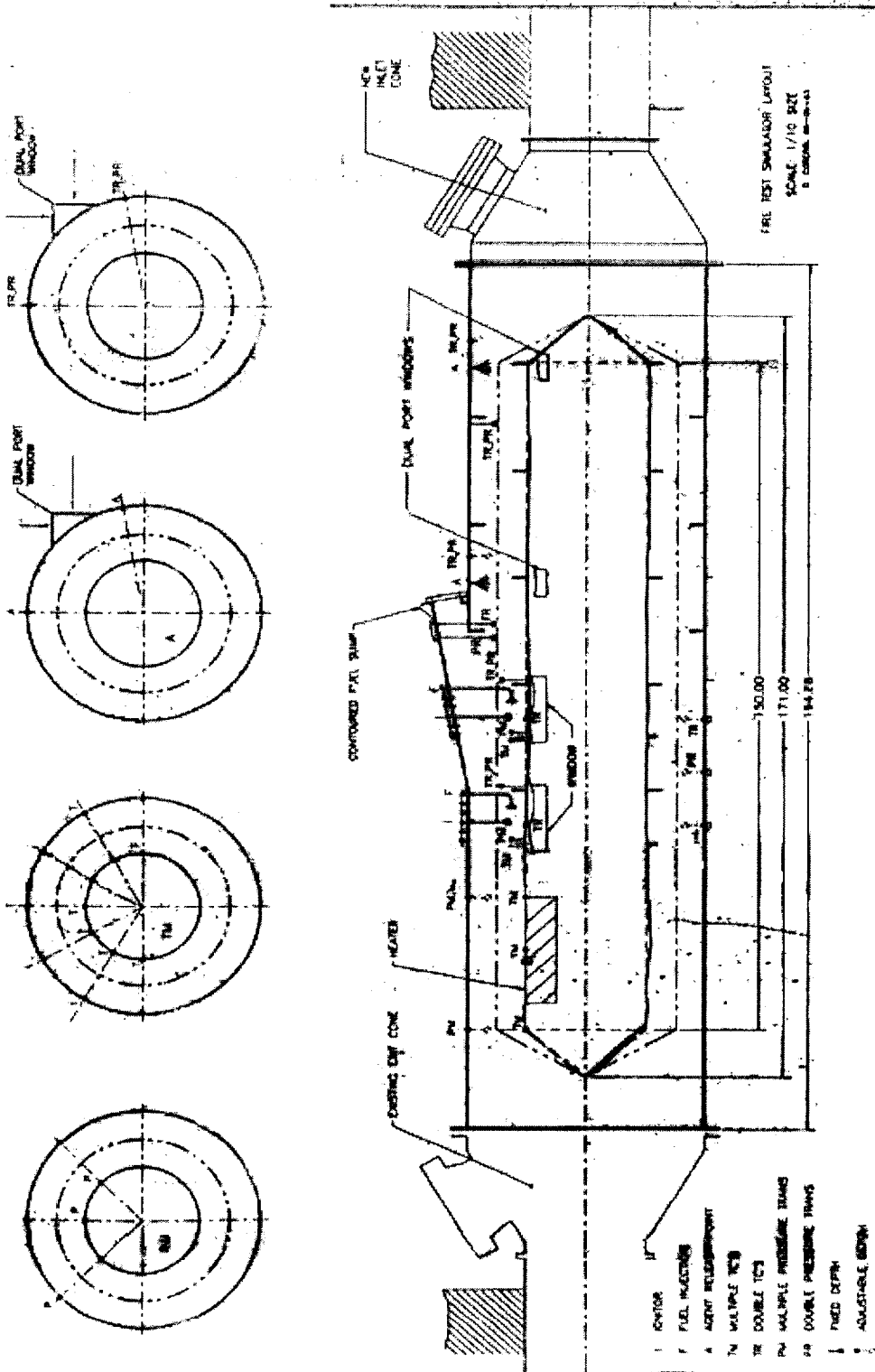


FIGURE A-1.1: Generic Test Fixture

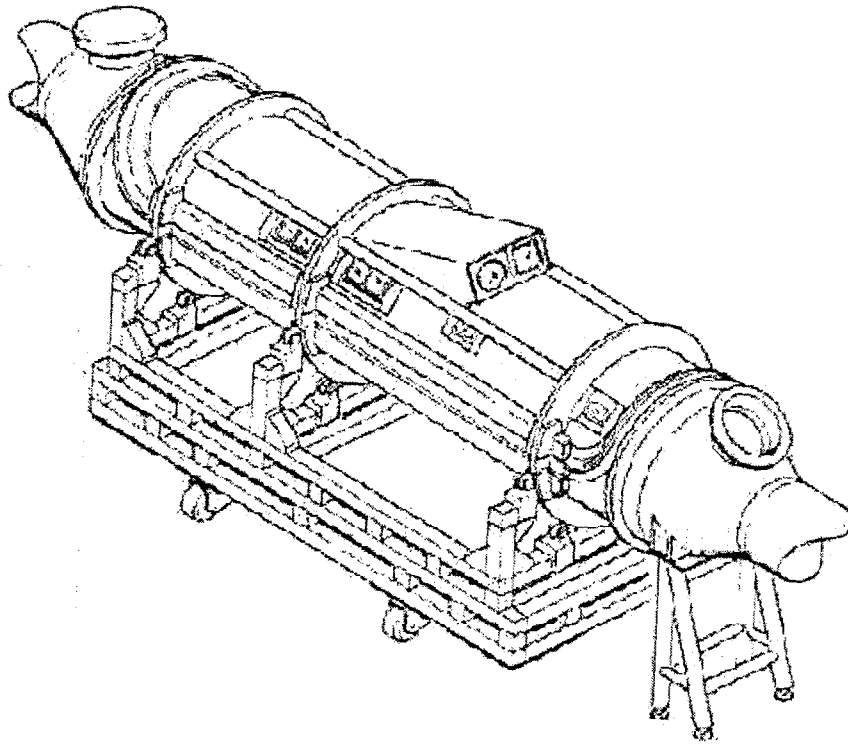


FIGURE A-1.2: Generic Test Section

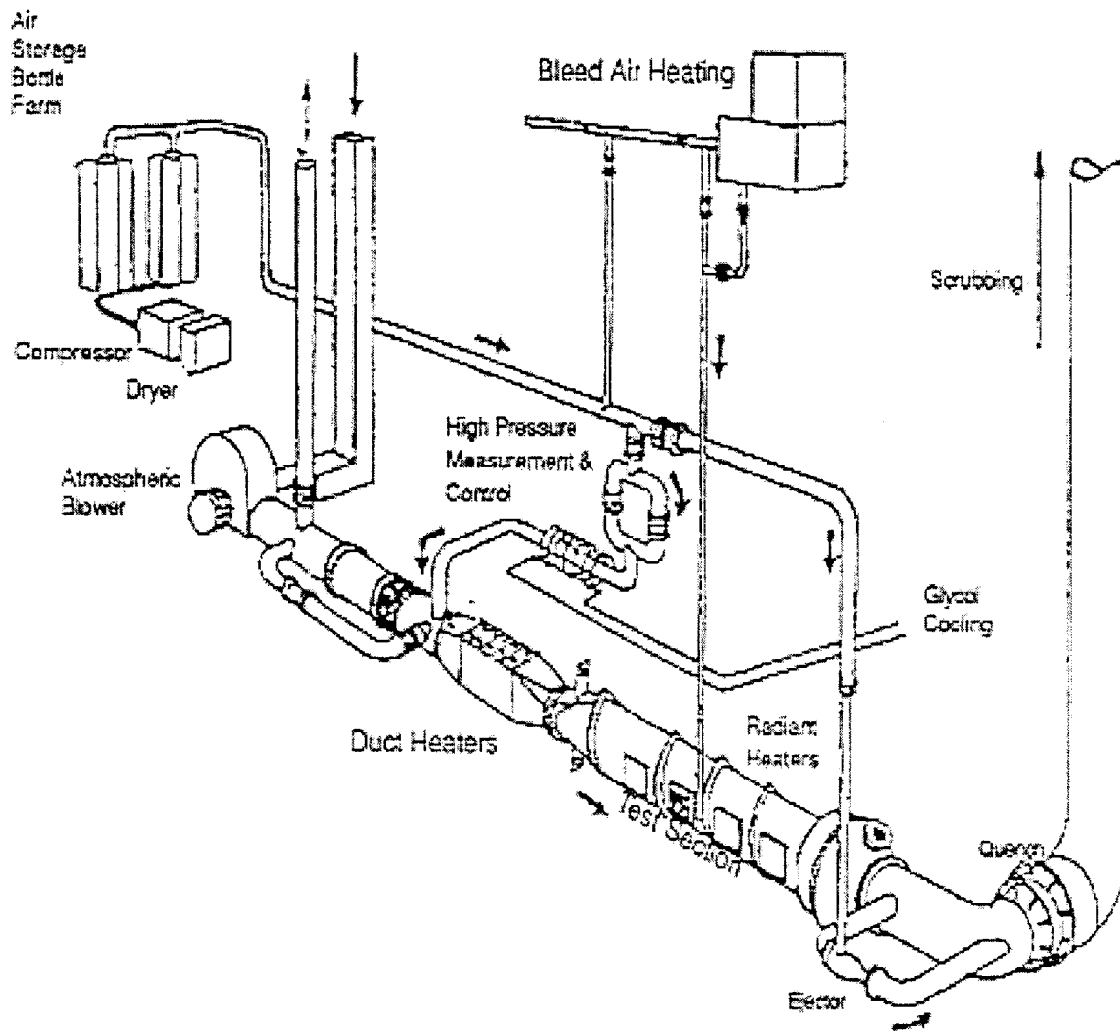
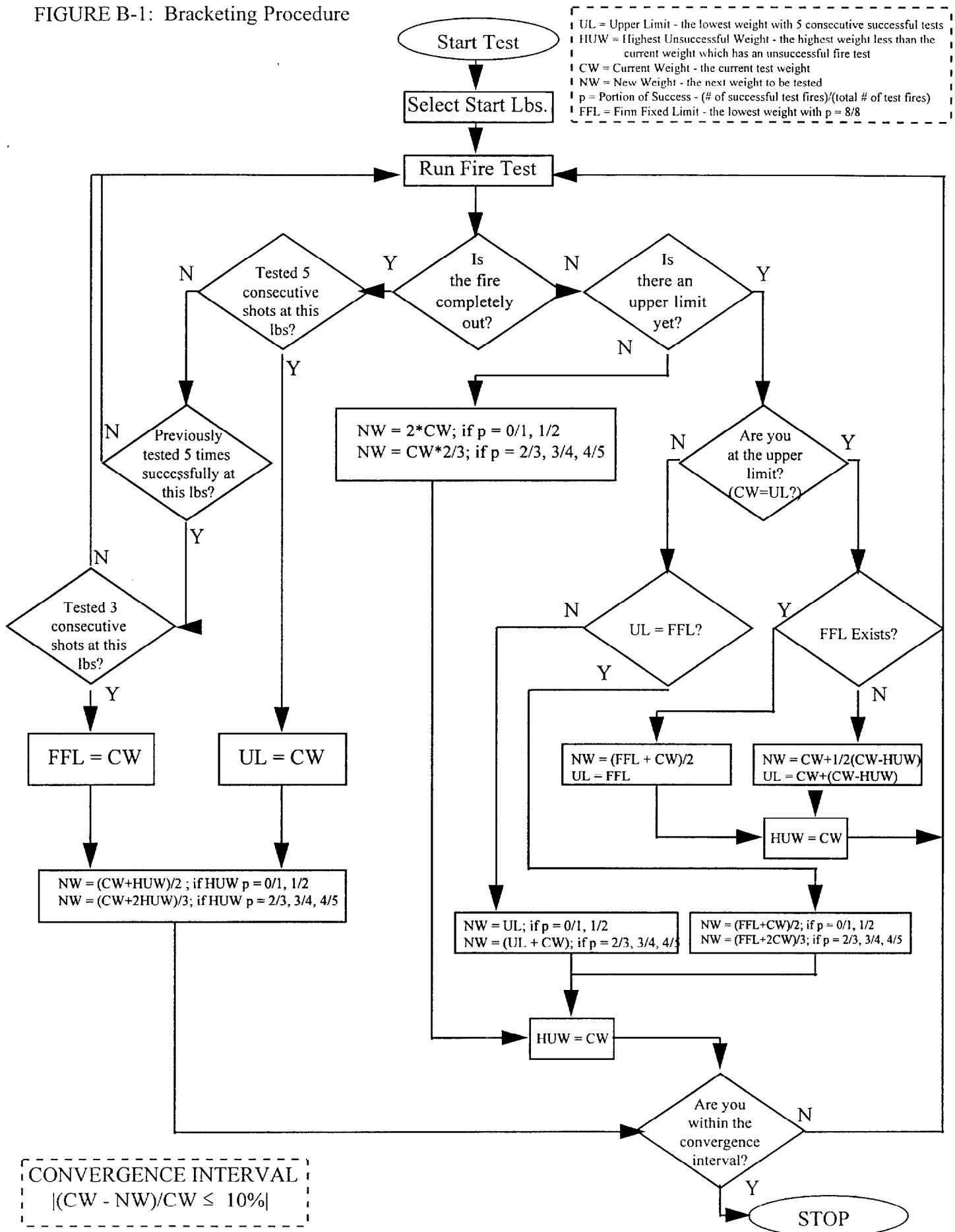


FIGURE A-2: Aircraft Engine Nacelle Fire Test Facility



## APPENDIX B

FIGURE B-1: Bracketing Procedure



## APPENDIX C



TABLE C-1: Reignition Assessment Matrix

Constant Parameters						
Surface Temp 600 deg F	Duct Temp 1130 deg F	Air Temp 275 deg F	Fuel Temp 275 deg F	Fuel Type JP-8	Fuel Flow Rate 0.15 GPM	Fire Location Location #1

**Series 1: Airflow = 2.4 lbm/sec**

Preburn Time	Test 1	Test 2	Test 3	Test 4	Test 5
0 s					
5 s					
10 s					
15 s					
20 s					
25 s					
30 s					
35 s					
40 s					
45 s					

**Series 2: Airflow = 1.5 lbm/sec**

Preburn Time	Test 1	Test 2	Test 3	Test 4	Test 5
0 s					
5 s					
10 s					
15 s					
20 s					
25 s					
30 s					
35 s					
40 s					
45 s					

**Series 3: Airflow = 0.6 lbm/sec**

Preburn Time	Test 1	Test 2	Test 3	Test 4	Test 5
0 s					
5 s					
10 s					
15 s					
20 s					
25 s					
30 s					
35 s					
40 s					
45 s					

**Reignition Assessment Matrix**

TEST PROCEDURES

1. Set Constant Test Parameters
2. Establish Desired Airflow
3. Ignite Fire
  - If preburn time = 0 seconds, do not ignite the fire, simply apply fuel for 8 seconds
4. Allow Fire to Burn for Specified Preburn Time
  - If preburn time = 0 seconds, there is no preburn time
5. After Fire Preburn Time is Expired, Stop Fuel Flow
6. Observe Fire for Extinguishment
  - Fire will extinguish itself when fuel is no longer present
7. After Fire is Extinguished, Initiate Fuel Spray for 8 Seconds (do not ignite the fuel)
  - Time of initiation of fuel spray is not specified, it is defined by the engineer's judgment when the fire is extinguished
8. Look for Reignition
  - If reignition occurs, record time of reignition and surface temperature at reignition
  - If reignition does not occur, record surface temperature when fuel was reapplied
9. Repeat Each Combination of Airflow and Preburn Time 5 Times

TABLE C-2: Simulator Repeatability/Consistency Test Conditions

**SIMULATOR CONSISTENCY ASSESSMENT TESTS**

TEST PARAMETERS

1. Engine Nacelle Surface Temperature	300 deg F
2. Bleed Air Duct Temperature	700 deg F
3. Air Temperature	125 deg F
4. Fuel Temperature	100 deg F
5. Airflow Rate	1.0 lbm/sec
6. Preburn Time	20 sec
7. Fuel Flow Rate	0.15 GPM
8. Fuel Type	JP-8
9. Agent	HFC-125
10. Agent Temperature	70 deg F

TEST OBJECTIVE

- Develop curve of Percentage of Fires Out versus Quantity of Agent for the above fire condition
- Use this test condition and the curve developed to ensure repeatability/consistency of the simulator
- Periodically (every 3-4 days) test this condition and a quantity of agent that has low probability of suppressing the fire and quantity of agent that has high probability of suppressing the fire
- Doing this will provide an indication that when we set fire conditions, we get the same fire
- The curve developed should be similar to the curve indicated below

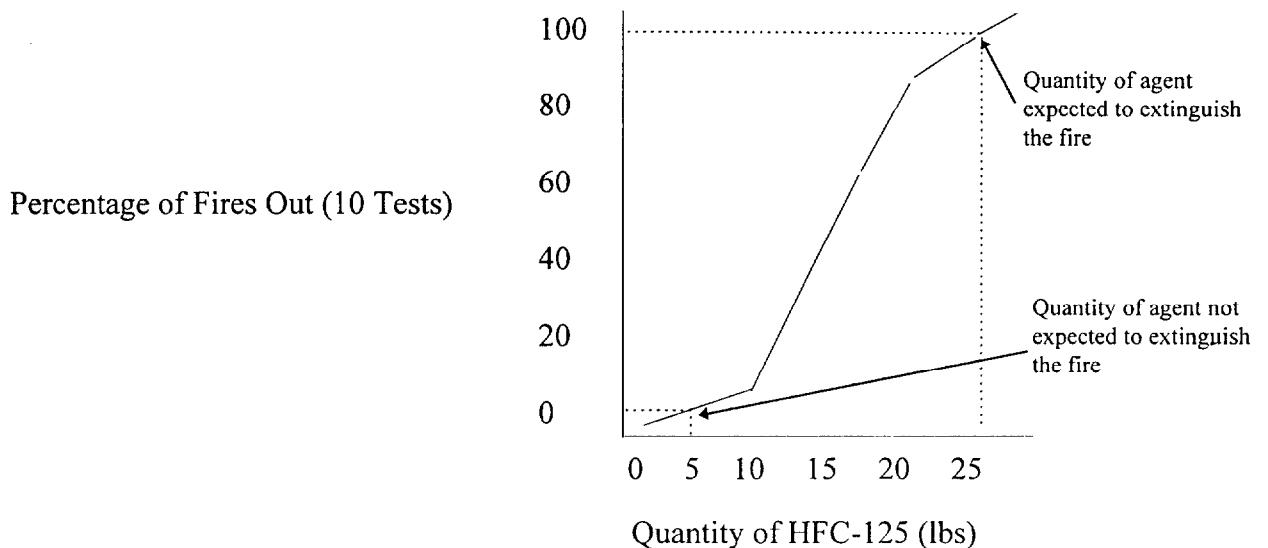


TABLE C-2: Simulator Repeatability/Consistency Test Conditions

TEST PROCEDURES

1. Set test conditions as described above
2. Conduct ten (10) extinguishing tests with the following quantities of HFC-125
  - a. 1 lbs
  - b. 3 lbs
  - c. 5 lbs
  - d. 7 lbs
  - e. 9 lbs
3. Let fuel flow for 8 seconds after agent is released
4. Record number of fires out and number of fires not out
5. If reignition occurs the fire is not out

NOTE: According to the design equations from the Halon Replacement Program, 7.24 lbs should put the fire out 8 or 9 out of 10 times

TABLE C-2: Simulator Repeatability/Consistency Test Conditions

SCHEDULE

- A total of 50 extinguishing tests are indicated: 10 at 5 different weights of agent
- At 20 tests per day - it is assumed it will take 2.5 days to complete these tests

## **APPENDIX D**

TABLE D-1: HFC-125 Baseline Matrix

RUN	FACTORS							
	LOCATION	SURFACE TEMP	DUCT TEMP	AIRFLOW RATE	AGENT TEMP	AIR TEMP	FUEL TEMP	PREBURN TIME
1	1	600	1130	2.4	170	275	325	20
2	1	600	1130	1.5	170	275	325	20
3	1	600	1130	0.8	170	275	325	20
4	1	350	850	2.4	70	132	165	20
5	1	350	1130	0.8	-40	-47	165	20
6	1	600	850	0.8	70	132	165	20
7	1	50	450	2.4	-40	-47	165	20
8	1	50	450	1.5	-40	-47	165	20
9	1	50	450	0.8	-40	-47	165	20
10	2	600	1130	2.4	170	275	325	20
11	2	600	1130	1.5	170	275	235	20
12	2	600	1130	0.8	170	275	325	20
13	2	350	850	2.4	70	132	165	20
14	2	600	1130	0.8	-40	-47	165	20
15	2	350	850	0.8	70	132	165	20
16	2	50	450	2.4	-40	-47	165	20
17	2	50	450	1.5	-40	-47	165	20
18	2	50	450	0.8	-40	-47	165	20

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NOTES

1. Bracket each run of the matrix with HFC-125 using the bracketing approach employed under the Halon Replacement Program
2. Assuming 25 tests for each run of the matrix: a total of 450 tests will be required to complete the matrix
3. Assume 20 tests can be completed each day - 22.5 days will be required to complete the matrix
4. Assume 40 tests will be conducted to check the repeatability of the simulator using the Simulator Consistency Fire Condition
5. Assume 20 tests can be completed each day - 2 days will be required to check the simulator consistency
6. Assume it will take 22.5 days to complete the matrix with simulator checking - APPROXIMATELY 5 WEEKS
7. Matrix was derived from actual operating conditions of the F-22

TABLE D-2: HFC-125 Design Equation Prediction

	Design Equation Parameters				Design Equation Value			Other Parameters					Actual Data	
	Air Temp	Airflow	Fuel Costant	Volume	Concentration (DE)	Mass (DE)	Mass (Bottle Size)	Location	Surface Temp	Duct Temp	Agent Temp	Fuel Temp	Preburn Time	Agent Weight
REPEAT	125.0	1.0	0.36	85.00	0.22	4.28	7.24	1	300.0	700.0	70.0	100.0	20.0	
1	275.0	2.4	0.36	85.00	0.21	4.73	8.28	1	600	1130	170	325	20.0	
2	275.0	1.5	0.36	85.00	0.24	4.73	8.34	1	600	1130	170	325	20.0	
3	275.0	0.6	0.36	85.00	0.27	4.73	8.06	1	600	1130	170	325	20.0	
4	132.0	2.4	0.36	85.00	0.18	4.30	7.11	1	350	850	70	165	20.0	
5	-47.0	0.6	0.36	85.00	0.20	3.78	6.12	1	350	1130	-40	165	20.0	
6	132.0	0.6	0.36	85.00	0.24	4.30	7.19	1	600	850	70	165	20.0	
7	-47.0	2.4	0.36	85.00	0.15	3.78	5.69	1	50	450	-40	165	20.0	
8	-47.0	1.5	0.36	85.00	0.18	3.78	6.05	1	50	450	-40	165	20.0	
9	-47.0	0.6	0.36	85.00	0.20	3.78	6.12	1	50	450	-40	165	20.0	
10	275.0	2.4	0.36	85.00	0.21	4.73	8.28	2	600	1130	170	325	20.0	
11	275.0	1.5	0.36	85.00	0.24	4.73	8.34	2	600	1130	170	235	20.0	
12	275.0	0.6	0.36	85.00	0.27	4.73	8.06	2	600	1130	170	325	20.0	
13	132.0	2.4	0.36	85.00	0.18	4.30	7.11	2	350	850	70	165	20.0	
14	-47.0	0.6	0.36	85.00	0.20	3.78	6.12	2	600	1130	-40	165	20.0	
15	132.0	0.6	0.36	85.00	0.24	4.30	7.19	2	350	850	70	165	20.0	
16	-47.0	2.4	0.36	85.00	0.15	3.78	5.69	2	50	450	-40	165	20.0	
17	-47.0	1.5	0.36	85.00	0.18	3.78	6.05	2	50	450	-40	165	20.0	
18	-47.0	0.6	0.36	85.00	0.20	3.78	6.12	2	50	450	-40	165	20.0	



TABLE D-3: Ventilated Pool Fire Test Condition

### VENTILATED POOL FIRE TEST

#### TEST PARAMETERS

1. Engine Nacelle Surface Temperature	350°F
2. Bleed Air Duct Temperature	850°F
3. Air Temperature	132°F
4. Fuel Temperature	165°F
5. Airflow Rate	2.4 lbm/sec
6. Preburn Time	20 sec
7. Fuel Flow Rate (Fuel = JP-8)	0.15 GPM
8. Fire Zone	2

#### TEST OBJECTIVE

- A baffle stabilized pool fire can be a very challenging fire condition to extinguish
- NIST SP 890: Vol. 2 - "Fire Suppression System Performance of Alternative Agents in Aircraft Engine and Dry Bay Laboratory Simulations" reports that a baffle stabilized pool fire may be more difficult to extinguish than a baffle stabilized spray fire
- Fire suppressive agents have not been extensively tested against pool fire conditions in large scale tests
- These tests will evaluate the difficulty in extinguishing a pool fire scenario
- HFC-125 will be evaluated against the pool fire condition using the bracketing procedure
- The SPGG systems as sized against the baseline fire condition will be evaluated against the pool fire condition
- Answer the following questions:
  1. Is a pool fire condition more challenging, less challenging, or as challenging to extinguish as a spray fire condition alone?
  2. Why or why not?

#### TEST PROCEDURES

1. Set indicated test conditions
2. Let fuel flow for 13 minutes, 20 seconds at 0.15 GPM
  - Allows 2 gallons of fuel to pool in the nacelle
3. Ignite fuel spray after 2 gallon pool is established
  - Continue fuel spray after ignition of fuel spray
4. Burn fire for 20 seconds
5. Discharge extinguisher
6. Allow fuel to spray for 8 seconds following agent discharge

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SUPPLEMENTARY NOTES

ABSTRACT (A 2000-CHARACTER OR LESS FACTUAL SUMMARY OF MOST SIGNIFICANT INFORMATION. IF DOCUMENT INCLUDES A SIGNIFICANT BIBLIOGRAPHY OR LITERATURE SURVEY, CITE IT HERE. SPELL OUT ACRONYMS ON FIRST REFERENCE.) (CONTINUE ON SEPARATE PAGE, IF NECESSARY.)

An analysis is presented on the full-scale suppression experiments conducted during 1996 and 1997 in the F22 engine nacelle fire simulator at Wright Patterson Air Force Base. Experiments investigated the relative effectiveness of halogenated agents and solid propellant gas generators (SPGG) in suppressing a series of spray fires with and without a fuel re-ignition source. Several agents were used tested including halon 1301, HFC-125, and two basic types of SPGG which included those that produced inert gases in conjunction with a fine solid particulate composed of K<sub>2</sub>CO<sub>3</sub>, and those that produced inert gases only.

A number of measurements were made during the suppression tests. Measurements included transient gas temperatures, re-ignition source temperature, cold-flow transient agent concentrations, and transient velocity measurements. This information was utilized to gain insight into the mechanisms of fire suppression with an emphasis on the differences associated with the different suppressant types.

A simple model for SPGG delivery is developed. Assuming plug type flow, average agent concentrations are calculated as a function of time in the nacelle and compared to measurements. The results give reasonable agreement.

KEY WORDS (MAXIMUM OF 9; 28 CHARACTERS AND SPACES EACH; SEPARATE WITH SEMICOLONS; ALPHABETIC ORDER; CAPITALIZE ONLY PROPER NAMES)

aerosol generators; aircraft safety; blowout velocity; fire suppression; flame extinguishment; flammability limits; halogenated compounds; ignition suppression; propellants

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