NEXT GENERATION FIRE SUPPRESSION TECHNOLOGY PROGRAM: FY2002 PROGRESS

Richard G. Gann
Building and Fire Research Laboratory
National Institute of Standards and Technology
Gaithersburg, MD 20899 USA
Tel: (301) 975-6866; Fax: (301) 975-4052; e-mail: rggann@nist.gov

ABSTRACT

This paper summarizes the accomplishments and new knowledge from NGP research. The paper concludes with an indication of the program direction for FY2003 and beyond.

INTRODUCTION

The Department of Defense's Next Generation Fire Suppression Technology Program (NGP) has completed its fifth year of research. Initiated in 1997, the NGP goal is to

> "Develop and demonstrate technology for economically feasible, environmentally acceptable and user-safe processes, techniques, and fluids that meet the operational requirements currently satisfied by halon 1301 systems in aircraft."

Fires and explosions continue to be among the greatest threats to the safety of personnel and the survivability of military aircraft, ships, and land vehicles in peacetime and during combat operations. However, over the past five years, research to identify replacement fire suppressants has declined considerably, within the NGP, domestically and internationally, despite the continuing need. To date no commercial or military aircraft have had their halon 1301 systems replaced, while new systems are being installed in the cargo bays of commercial jetliners. Meanwhile, the international community is continuing to cast an eye on the necessity of maintaining the large halon 1301 reserves and even considering the requirement of a total phaseout. Thus, the demands on research to identify new approaches to aircraft fire suppression are unabated, nor have the demands on the new technologies lessened.

The NGP participants have generated unparalleled contributions to the published literature, all of which can be obtained via the NGP web site, which has moved to www.bfrl.nist.gov/866/NGP. Much of the most recent progress is being reported at this Conference.

TECHNICAL PROGRESS

NEW FLAME SUPPRESSION CHEMISTRY

The search continues for new fire suppressant chemicals. The list of criteria has evolved to the following:

- Fire suppression efficiency at least comparable to halon 1301 and higher than the hydrofluorocarbons (HFCs).
- Short atmospheric lifetime (current preference of the order of a month), to keep ODP and GWP values and any future unidentified environmental contamination to a minimum.

- Low toxicity relative to the concentration needed for suppression.
- Boiling point sufficiently low that an extinguishing concentration can be achieved quickly following discharge. An approximate theoretical upper limit is 80 °C, but slow evaporation or poor dispersion will reduce this significantly for some chemicals.

The families examined each produced additional knowledge of what makes a good suppressant, a list of most suitable members of that family, and criteria for future searches. Highlights include:

- Physically active suppressants. The most effective compounds identified were already known: lactic acid and $CH_3OC_4F_9$. The latter is four times more effective when introduced as a liquid aerosol, emphasizing the contribution of the heat of vaporization of the suppressant when the aerosol reaches the flame zone.
- Tropodegradable bromocarbons. The initial look was at brominated alkenes, and was performed in conjunction with the Advanced Agent Working Group. Four compounds did well in all screens. However, the one compound tested for cardiotoxicity produced effects on a test animal at a molar concentration of about 1 %. This showed that our ability to anticipate this use-limiting effect needs refinement. (See below.)
- Metal-containing compounds. Some iron, manganese, and tin compounds showed very high flame inhibition effectiveness on premixed flames and highly strained diffusion flames (Figure 1), but were unimpressive on cup burner flames. These condensed phase compounds would most likely be used with solid propellant gas generators.
- Phosphorus-containing compounds. NGP research established that the phosphorus atom imparts good flame suppression efficiency to a compound and that the binding state of the phosphorus is unimportant. Due to their high boiling points, these compounds would need to be dispersed as aerosols or be used with SPGGs.

The NGP has used this updated knowledge to conduct a review of the world of chemicals to identify those chemical families still ripe for examination in the NGP. For each type of chemical functionality, assessments were made of the extent of prior fire suppression studies and the potential for success in any (further) study. Expected flame suppression efficiency, atmospheric persistence, boiling point, and toxicity were again the main screening criteria.

The following families were identified as the most promising:

- N compounds: amines nitriles
- P Compounds: *acids* *esters* *nitriles* *halides*
- S Compounds: sulfides mercaptans sulfoxides
- Metal Compounds: *manganese* *tin*
- Halogenated Organics: alkenes (I) *fluoroethers (Br,* I*)*

Those families in italics are the highest priorities for examination. It was expected that substantial fluorination would be needed to obtain the desired low boiling points. In an additional effort to identify compounds with low boiling points, a search of *Chemical Abstracts* was instituted for all compounds with boiling points under 25 °C that contain bromine, iodine and/or phosphorus. The results will be available soon.

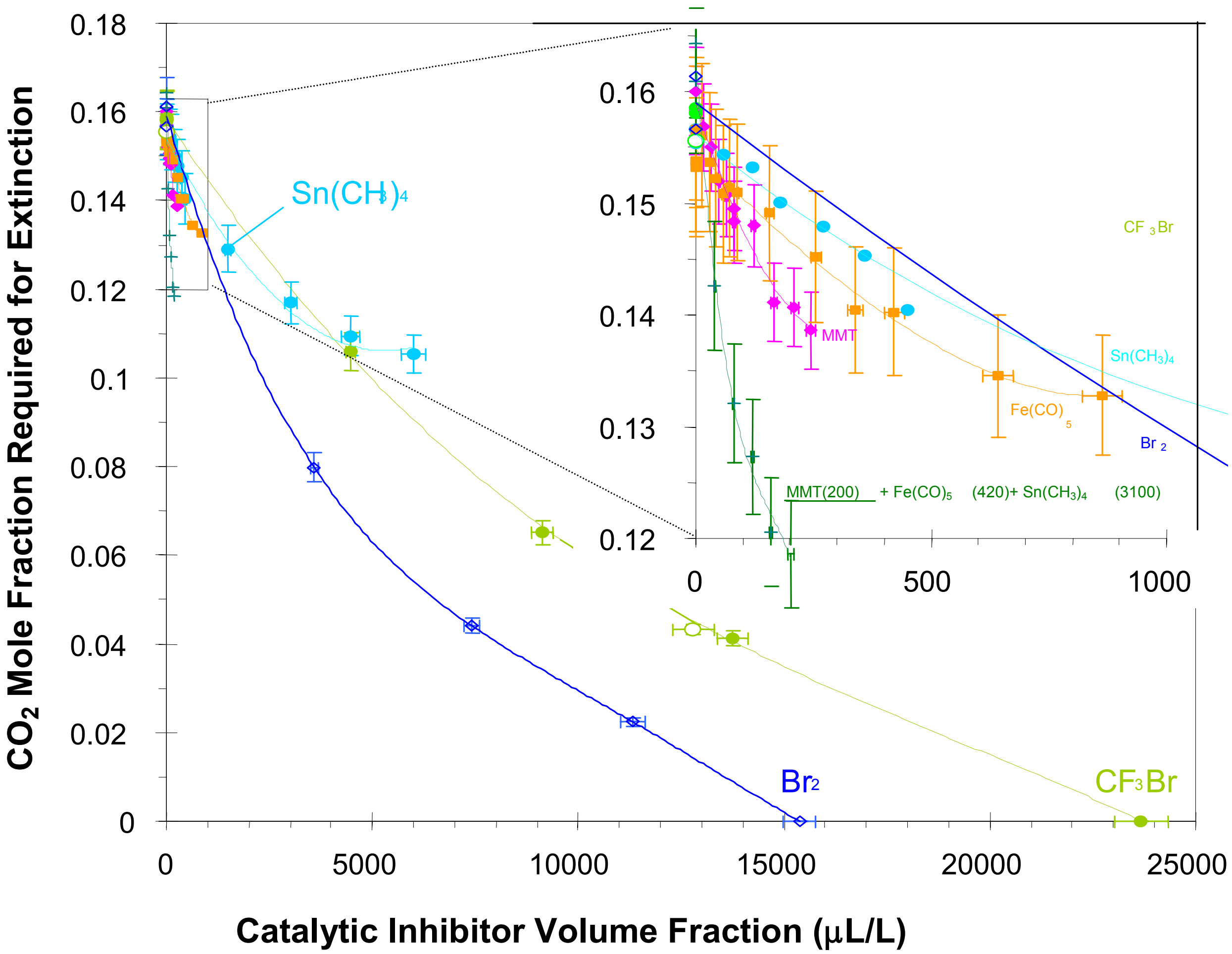

Figure 1. Mole fraction of CO$_2$ required for methane-air cup burner flame extinction as a function of catalytic inhibitor mole fraction, CF$_3$Br, Br$_2$, Fe(CO)$_5$, (Sn(CH$_3$)$_4$, MMT [(CH$_3$C$_5$H$_4$Mn(CO)$_3$], or a blend of the last three (insert shows data with expanded x- and y-axes). The termination of the curves at high CO$_2$ mole fraction indicates the limit of suppression effectiveness.

Study of the fluoroalkyl-phosphorus compounds is currently underway, with eight selected for synthesis and testing. To minimize inhalation toxicity, these have no halogen-to-phosphorus bonds. The compounds are:

$O{=}P(CF_3)_3$
$O{=}P(OCF_3)_3$
$P(OCH_2CF_3)_3$
$O{=}P(OCH_3)(CF_3)_2$
$O{=}P(OCH_2CF_3)(CF_3)_2$
$P(OCH_2CF_3)_2CF_3$
$P(OCH_3)(CF_3)_2$
$P(OCH_2CF_3)(CF_3)_2$

These represent some of the lowest boiling points for phosphorus-containing compounds, with the first having the highest volatility of any non-flammable chemical in the family, 32 ºC. The cup burner extinguishment concentration for $P(OCH_2CF_3)_3$ was found to be 1.9 % by volume.

We are also continuing our examination of the tropodegradable halocarbons, now concentrating on the brominated ethers. Some of these are used as surgical anesthetics, but thus have high boiling points for ease of handling and administration. Therefore, the candidate ethers will need to be synthesized. Cup burner extinguishment values for two ethers, $CH_2BrO(CF_3)_3$ and CH_2BrOCF_2H, are close to that for halon 1301 and the atmospheric lifetimes should be very short. The boiling points are 40 °C and 70 °C, respectively.

However, before extensive resources are expended in synthesizing new bromocarbons, it is first necessary to find out if we can improve our ability to estimate the cardiotoxicity of such compounds. We will summarize the compound attributes and physical properties that could be used in predictions of cardiac sensitization; review anesthesiology research to identify and collate relevant test data, quantitative structure-activity relationships (QSAR) and any attributes that might be employed in evaluating the cardiac sensitization properties of a series of brominated fluorocarbons; and search for possible *in vitro* methods applicable to the low resource assessment of the cardiac sensitization potential of a candidate halon replacement chemical or a series of such chemicals.

Another factor affecting the use of brominated compounds is their atmospheric lifetimes. Brominated species must not rise to the stratosphere. A sure way to prevent this transport is for the compound to be degraded in the lower atmosphere. The NGP has completed a methodology for estimating the reactivity of halocarbons with atmospheric OH, the major tropospheric elimination pathway.

NGP research had discovered that while metal-containing compounds could be effective flame inhibitors, they might not be effective *in any form* in quenching practical flames. Now, a clear picture has emerged concerning the potential and limitations of metallic agents as fire suppressants in unoccupied areas.

- Computer modeling of inhibited flames showed that the metal must have intermediate species with thermodynamic properties such that the stable di-hydroxide intermediate can be formed, and the equilibrium concentration of this species must be large so that it can remove H atoms from the flame chemistry.
- The first measurements of particle formation in cup burner flames inhibited by the metallic agent $Fe(CO)_5$ (Figure 2) showed that particle formation acts as a sink for the active metal species, preventing them from reaching the flame zone in which they are required to suppress the flame. Thus, condensation of one or more of the metal-containing species must not occur. Analysis of previously published results for the antimony- halogen system showed a strong loss of effectiveness above a certain mole fraction, also likely caused by particle formation from antimony oxide. This phenomenon even occurs for the alkali metal compounds (which are highly effective on practical flames) where condensation to either liquid hydroxide or a salt (*e.g.*, NaCl) can detract from their efficiency.

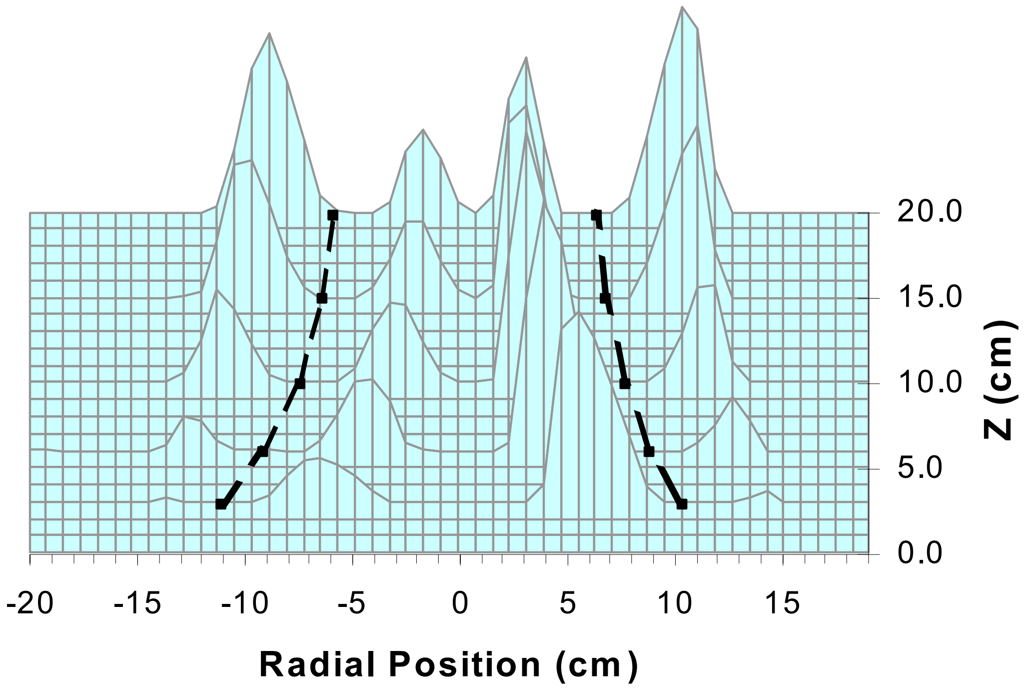

Figure 2. Scattering cross section as a function of radial position in flame and height above cup-burner rim, with 200 μL/L of $Fe(CO)_5$ added to the air stream, and a CO_2 volume fraction of 8 %. Dotted lines show flame location of the uninhibited flame.

NEW AND IMPROVED AEROSOL SUPPRESSANTS

FY2001 brought to a close the NGP investigation of the properties of droplets that enhance their flame suppression efficiency. Research with NASA-funded collaborators led to a validated model for the inhibitory effects of small drops (< 5 μm) and water vapor on premixed flames. The model includes elementary combustion chemistry and multicomponent molecular transport. It predicts a small-drop limiting behavior for premixed flames similar to that previously observed for non-premixed counterflow flames and consistent with other NGP modeling predictions.

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IMPROVED SUPPRESSANT DELIVERY

Solid Propellant Fire Extinguishers

NGP research is developing new systems that have both reduced combustion temperatures and increased flame suppression efficiency, which in turn will enable freedom of selection of the momentum of the suppressant stream. The approaches include:

1. Modification of the solid propellant. NGP research had co-developed a new propellant compound, BTATZ ($C_4H_4N_{14}$); prototype formulations incorporating it reduced discharge temperatures by 20 %. Process improvements in its preparation (to the 0.5 kg scale) now enable more extensive use in testing, including re-formulation with additional coolants.

2. Inclusion of additives in the propellant formulations of the Solid Propellant Gas Generators (SPGGs).
3. Entrainment of a chemically active additive into the exiting gas stream of a Hybrid Fire Extinguishers (HFE).

Following last year's demonstration that some chemical additives enhanced the efficiency of an otherwise inert gas generator, additional experiments were performed to quantify the benefit. Additives to either the propellant (SPGG) or the fluid (HFE) were evaluated for fire suppression effectiveness using a 1 MW JP-8 flame in a forced air stream. All discharge times were maintained at ≈200 ms for ease of comparison. The test results summarized in Figure 3 represent the amount of agent needed to extinguish the fire at least two out of three times.

There is clear efficiency improvement with the blends of inert gases with chemically active additives in both systems. Tests with $KHCO_3$ and $NaHCO_3$ added into the HFE fluid produced results similar (based on moles of K or Na) to those with active agents (KI, K_2CO_3) added into the propellant. Active hybrid systems were also tested using potassium acetate/water blends, and using CF_3. The former delivered performance comparable to HFC-227/active-agent blends, and reduces toxic and corrosive HF. The CF_3I system was the most effective HFE system tested, but was observed to produce significant quantities of I_2 vapor during suppression testing.

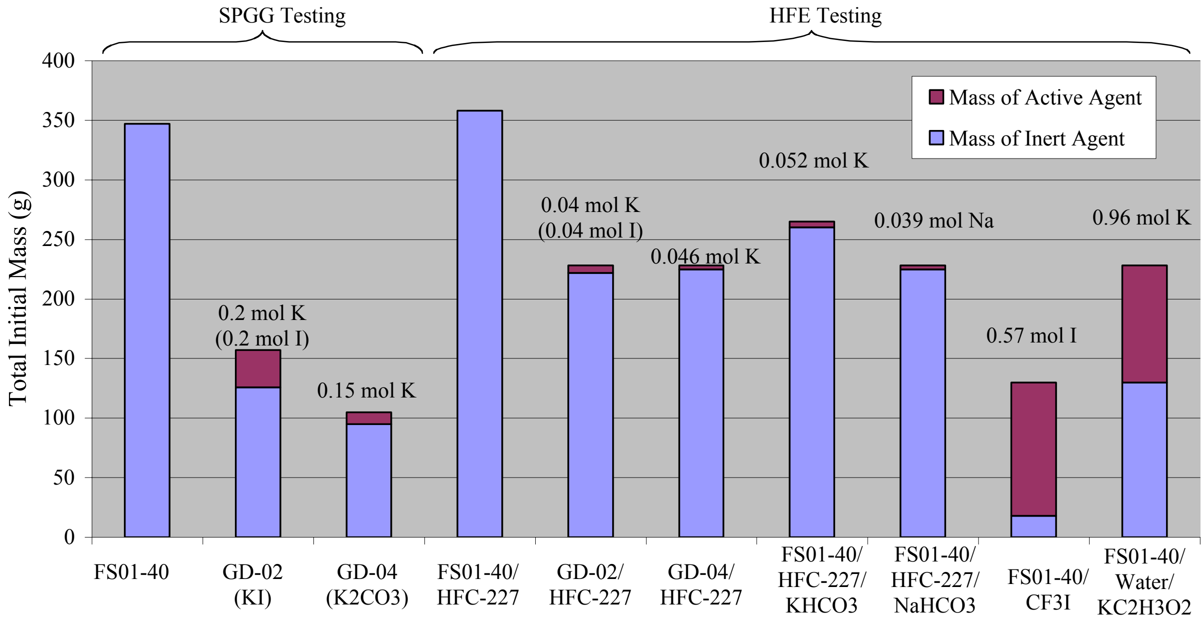

Figure 3. Summary of SPGG and HFE Fire Effectiveness Testing

Dispersion of Suppressants at Low Temperature

In a space where the fire could be anywhere, efficient dispersal of a suppressant throughout the volume is essential. Halon 1301 (T_b = -58 °C, flash vaporizes and distributes well, even at the lowest temperatures (*ca*. -40 °C) it experiences in in-flight aircraft. Earlier research indicated that high boiling fluids (*e.g.*, CF_3I, -22 °C) might not disperse well. This could reduce the upper boiling point limit for screening chemicals for further consideration.

The initial experiments involved examination of CF_3I discharges in a simulated engine nacelle under different thermal conditions (Table 1). As in a real engine nacelle, ribs induced turbulence. The agent bottle was charged with $\approx$1 kg of CF_3I and then pressurized with N_2 to 4.12 MPa at room temperature. The simulator mass air flow was the same in all tests.

Table 1. Experimental matrix for cold temperature agent dispersion

Test Condition	Nominal Initial Conditions of Vessel	Nominal Conditions of Vessel before Discharge	Nominal Simulator Temperature (ºC)
1[§]	22 ºC and 4.12 MPa	–40 ºC at prevailing P	–40
2	22 ºC and 4.12 MPa	22 ºC and 4.12 MPa	22
3	22 ºC and 4.12 MPa	22 ºC and 4.12 MPa	–40

[§] Tests were performed in an environmental test chamber.

For Test Condition 1, during the crucial initial 10 s the concentration of suppressant is much lower than when the temperature differential is higher (Figure 4). Liquid CF_3I droplets disappeared with the first 2 s and most of the fluid pooled at the bottom of the chamber, then evaporated slowly over many seconds. Heating the storage container to room temperature improved but did not correct the problem.

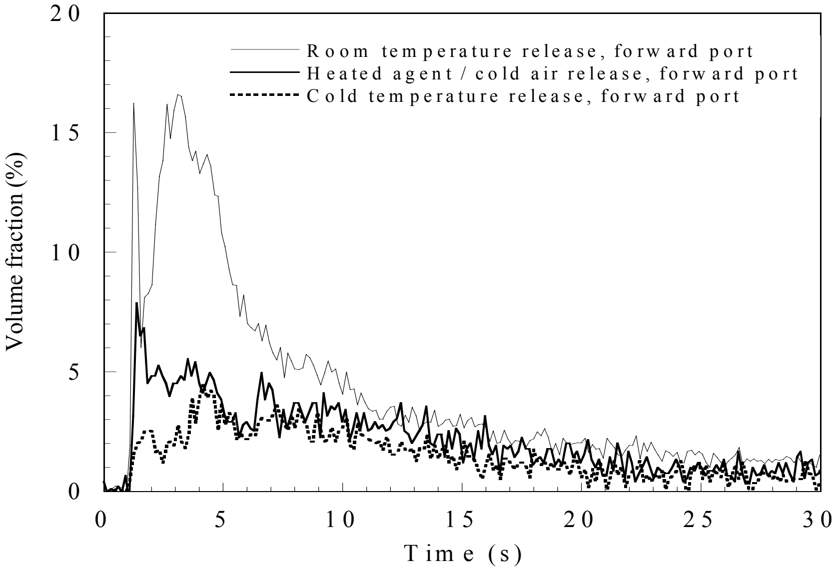

Figure 4. Concentration profiles of CF_3I at the forward measurement location.

Suppressant Dynamics in Engine Nacelles

The NGP is developing a validated computer model of the dispersion of a suppressant in the variety of engine nacelle geometries under diverse flight conditions in order to provide guidance on preferred location(s) and styling of suppressant discharge. The computational fluid dynamic (CFD) model will include gaseous and aerosol suppressant flow, a fire, and fire extinguishment in cluttered environments. Experiments are providing both input and validation data.

Sensitivity studies of the base-case model for air flow through a smooth nacelle show that the results are not sensitive to mesh size except near the walls from lack of resolution. An assumption of zero cross-stream turbulent velocities produced results in better agreement than did an assumption of isotropic turbulent flow, in agreement with experimental observations. Calculations with two wall functions showed no impact on the solution for this application.

Experimental drag and turbulence intensity data have been developed in order to add the effects of nacelle clutter to the calculations. Obstacle tubes of three diameters (3 mm, 13 mm, and 32 mm) were placed, in turn, in a straightened air flow, and the flow field upstream and downstream of the obstruction was characterized using 3-D particle image velocimetry (PIV). The flow mean velocity of 4.5 m/s, corresponding to a Reynolds number of 3700, was representative of air speeds through aircraft engine nacelles.

A preliminary version of this case of a single cylinder in a cross flow was integrated into the VULCAN fire physics code, along with a more sophisticated turbulence model. Comparison of the CFD predictions to the PIV measurements indicated that qualitatively the location and size of the recirculation zone for the largest cylinder case were well captured. The modest differences indicate that the numerical predictions underestimate the extent of turbulent mixing behind the cylinder, consistent with a known k-ϵ model limitation highly recirculating flows.

The next experiments will inject two liquid fire suppressant agents (water, $T_b = 373$ K, and HFE-7100, $T_b = 334$ K) and study the change in droplet transport as the spray interacts with different obstacles. These agents were chosen because of the effectiveness of high boiling liquids to extract heat from a flame zone. The impingement and breakup of droplets on the 32 mm cylinder will also be measured. This cylinder will also be heated to study that effect on droplet vaporization and transport.

Fire suppression capability for VULCAN is also under development. Prototype simulations of the 2-D nacelle fixture have been run for two agents (N_2 and HFC-125) with and without a typical rib located downstream of the inlet. The flow and size of the rib and nacelle were chosen to be representative of the flow and geometry in an actual nacelle. Fire extinguishment occurs between 40 % and 60 % N_2 by volume without a rib. Cold flow cases with the rib geometry reveal a sharp increase in turbulent kinetic energy over the top of the step resulting in high values of turbulence intensity (75 % or greater). This detailed information will be used to parameterize the clutter model for regions around the ribs near the nacelle wall and also to determine the extra suppressant required for a fire stabilized on the downstream side of a rib. The results from these simulations will help provide guidance for the experimental test series of a full-scale nacelle simulator to be conducted in FY2003.

Powder Panels for Dry Bay Fire Protection

The NGP is examining new concepts for an old alternative to the discharge of pressurized fluids or dry chemical fire extinguishing agents. Powder panels lining a dry bay can provide passive, lightweight, effective fire protection against ballistic impact by releasing powder into the fire zone to inert the space before the adjoining fuel spills into the space and is ignited by incendiaries. Previous powder panel testing has shown that only about one gram of a typical fire extinguishing powder could prevent a pool fire from igniting for over one minute. Today's panels are in essence the same designs that have existed for decades.

After compiling a list of powder panel materials and designs previously evaluated and those that have been integrated into aircraft designs, NGP staff used an experimental dry bay/fuel tank simulator to consider a number of variants.

- Front panel face (dry bay side): materials that exhibit brittle properties upon impact; intentional surface scoring of panels to enhance fracture characteristics.
- Back panel: thermoplastic materials were examined to determine if the fracture characteristics of the back panel influenced the front panel.
- Internal rib structure materials and designs: integral front and back walls and internal channels, honeycomb material, reduced number of ribs, maximized spacing, minimal panel thickness.

In each test, a light-gas gun was used to launch a 0.50 caliber hard steel ball projectile at a velocity of at least 670 m/s. These screening initial tests did not involve fluid in the fuel tank nor air flow. The powder was $KHCO_3$. The characteristics measured were panel fracture and material removal, the amount and dispersion of fire extinguishing powder released into the test article, and the time the powder remained suspended in the dry bay. Major results showed:

- The best of the new powder panel designs examined in this project offer the potential to be competitive with halon 1301 in a wider variety of dry bay designs. Figure 5 shows major performance benefits achievable with the enhanced design concepts.
- As expected, the front face material properties were of utmost importance. More brittle materials outperformed more ductile materials. Crack growth optimization helped.
- A strong synergism was found between the rib structure and the front face. Increasing the bond area between the face and ribs inhibited powder dispersion. Tradeoffs will be necessary between rib spacing and powder loading, as sufficient powder must be available at all potential impact sites.
- Three-piece powder panel designs outperformed easy-to-assemble double-wall extrusion designs, as built-in rib channels inhibited cracking.
- Channel designs allowed more powder to be released from the impact location than more segmented or cellular designs.
- Variation in the powder panel back face had less effect. In fact, limiting back face fracture might mitigate the chance of a dry bay fire by reducing fuel leakage and confining it to an area along which most of the powder is released.

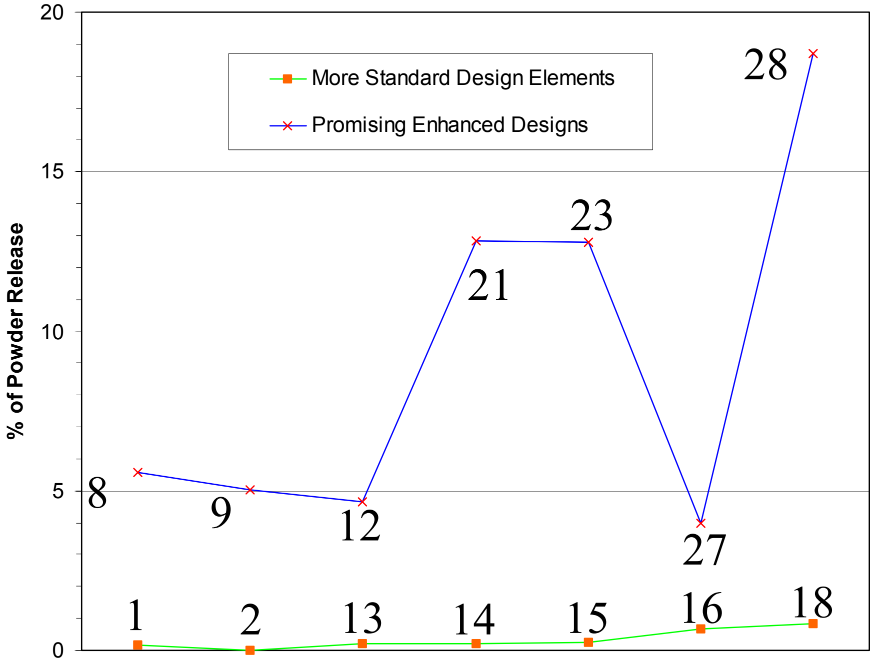

Figure 5. Effect on Suppressant Delivery of Standard Design Features and Enhanced Designs Showing 5x to 10x Greater Powder Release in the Latter

VIABILITY OF NEW SUPPRESSANT TECHNOLOGIES

Benefit Assessment of Fire Protection System Changes

There are a large number of factors that must be considered when deciding which fire suppression system to select for a new platform or whether to retrofit the fire suppression system on a legacy platform. These include both objective cost factors and subjective value factors. Accordingly, the NGP has developed a methodology to quantify a fire suppression technology by its total, life cycle cost and to enable superimposing on this a subjective value system.

The example used in developing the methodology is a comparison of an existing halon 1301 system and a system of equivalent and altered performance to halon 1301 using an off-the-shelf-alternative, HFC-125. This methodology was developed to be applicable to both legacy platforms (for decision makers who must consider retrofit costs for existing platforms) and future platforms (for decision makers currently designing new platforms).

Significant uncertainties arise because of the need to use engineering estimates where data were not available, because of limited historical information over the life of the legacy aircraft, and because of the non-existence (in some cases) of a fielded HFC-125 system. Thus the figures are indicative, all in FY2000 dollars, rather than definitive.

Cost Analysis of Fire Suppression Systems for Cargo Aircraft. The total cost of ownership of the halon 1301 systems in the current fleet of an individual legacy aircraft platform is approximately 0.2 % of the total (life cycle) cost of the aircraft. It is estimated that the legacy cargo aircraft halon 1301 systems would save about four times this cost in avoided fire losses. The figures are roughly the same for a future cargo aircraft platform. The difference in total cost of the two systems is a modest fraction of the cost of the systems and is small compared to the total cost of owning and operating the aircraft.

Cost Analysis of Fire Suppression Systems for Fighter Aircraft. The total cost of ownership of the halon 1301 systems in the current fleet of an individual legacy aircraft platform and in a proposed fleet of future fighter aircraft is an even smaller fraction of the total cost of the aircraft, about 0.05 %. Either system would save about four times this cost in avoided fire losses.

Similar cost analyses are underway for engine nacelle protection in rotary wing aircraft and for dry bay applications for typical fighter, rotary-wing, and unmanned aircraft.

Changes in Cost Analysis for Altered Fire Suppression Performance. For either type of aircraft, the net cost change per single percent change in extinguishing effectiveness (*i.e.*, 91 % successful *vs.* 90 % in the field) of the fire system was approximately -$2 M. These estimates show that additional investment in optimizing fire suppression system performance pays off in assets (costs) saved.

WHAT LIES AHEAD?

From this point forward, NGP research will be focusing on two technical components:

- Evaluating the “world of chemistry” for new flame suppression chemicals that are operable in aircraft dry bays and engine nacelles. It is essential that as many candidates as possible are identified and screened as potential halon 1301 alternatives. It is equally important that chemical families with no potential be so designated, along with the reasons for the designation.
- Developing principles for optimizing suppressant storage and delivery. Both research and engineering experimentation have shown that there is much system effectiveness to be gained if the suppressant is deployed efficiently and much to be lost for a delivery design that is incompatible with the suppressant properties.

As these results near completion, a modest series of real-scale fire suppression tests will be conducted with the purpose of demonstrating the validity of the above findings.

Over the past five years, the NGP has solicited proposals for “outside the box” approaches to fire suppression. Some of these ideas broadened the thinking of the fire suppression community. A modest resumption of these solicitations is possible beginning in FY2003.

Much of the innovation in NGP projects has resulted from interactions among a large set of investigators in diverse but related aspects of fire suppression. The NGP plans to continue its enhanced support of the annual Halon Options Technical Working Conference as a principal forum for communication and collaboration. The NGP will seek to enhance the participation in its autumn Annual Research Meeting.

The prognosis for successfully meeting the revised NGP goal is excellent, given the technical infrastructure and cadre of experts advanced by the NGP. The Department of Defense will then need to set in place the engineering programs to develop the new technologies for implementation in its fleet of aircraft.

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