NIST Technical Note 1451

FY2002 Annual Report
Next Generation Fire Suppression Technology Program (NGP)

Richard G. Gann

National Institute of Standards and Technology
Technology Administration, U.S. Department of Commerce

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NEXT GENERATION FIRE SUPPRESSION TECHNOLOGY PROGRAM

FY2002 ANNUAL REPORT

Next Generation Fire Suppression Technology Program (NGP)

[PP-1059]

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Technical Program Manager
January, 2003

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ABSTRACT

The Department of Defense's Next Generation Fire Suppression Technology Program (NGP) has completed its sixth year of research with a goal 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.

Research to complete a suite of suppressant screening tests has been completed. Research on new flame suppression chemistry, new and improved aerosol suppressants, improved suppressant delivery, and viability of new suppressant technologies has produced substantive results.

The NGP is supported by the DoD Strategic Environmental Research and Development Program (SERDP).

Keywords: fire research, fire suppression, halon, aircraft

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I. INTRODUCTION

Initiated in 1997, the Department of Defense's Next Generation Fire Suppression Technology Program (NGP) has completed its sixth year of research with considerable accomplishment. Supported by the DoD Strategic Environmental Research and Development Program (SERDP), 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 both in peacetime and during combat operations. Production of halon 1301 (CF_3Br), long the fire suppressant of choice, had ceased as of January 1, 1994 due to its high ozone depleting potential (ODP). By 1997 the DoD had identified the best available replacement for halon 1301 in aircraft, HFC-125 (C_2H_5F) [1], but it requires two to three times the mass and storage volume and contributes to global warming. The new Program was to identify fire suppression technologies with reduced compromises.

While research to identify replacement suppressants for engine nacelle and dry bay fires has declined considerably over the past five years, the demand for new approaches is unabated. New aircraft are in various stages of design. No commercial or military aircraft have yet had their halon 1301 systems replaced, while new systems are being installed in the cargo bays of commercial jetliners. The international community is questioning the necessity of maintaining the large halon 1301 reserves and even considering the requirement of a total phaseout.

The demands on the new technologies remain daunting. These need to be of low mass and volume and compatible with the host aircraft design. New chemicals must have high suppression efficiency and perform well in evaluations of ODP, global warming potential, atmospheric lifetime, reignition quenching, residue level, electrical conductivity, corrosivity to metals, polymeric materials compatibility, long-term storage stability, toxicity of the chemical and its combustion and decomposition products, speed of dispersion, and occupational safety.

The systematic NGP search for new suppressant chemicals and technologies for assured, efficient delivery is continuing to produce new results. During the past year, an Independent Review Panel found the NGP program to be "technically strong and targeted realistically" and "resulting in research output in quality and quantity far above what is considered typical for the resources available and applied," with "much of the research output having high potential for near term use in design of fire protection systems for aircraft." They made a number of suggestions for tuning the Program, all of which will be implemented by FY2003.

The NGP participants continue to generate unparalleled contributions to the published literature, all of which can be obtained via the NGP web site: www.bfrl.nist.gov/866/NGP. The following pages highlight the new knowledge gained from the NGP research and the progress made towards the NGP Goal. The uncertainties in the reported data are discussed in the individual research reports. Recent publications are listed at the end of each research topic. A concluding section forecasts where the research will proceed from this time forward. An appendix lists the NGP projects to date.

II. TECHNICAL PROGRESS

A. NEW FLAME SUPPRESSION CHEMISTRY

In prior years, the NGP had developed a new understanding of how efficient chemicals interact with flames and eventually suppress them. This is summarized as follows:

> Flame propagation results from the fast reactions of key species (H and O atoms, OH radicals) with vaporized fuel molecules. These species exist at concentrations far above those expected from thermal equilibrium at flame temperatures. Chemically active agents catalytically reduce the radical concentrations toward equilibrium levels. While this process slows the flame, it does not extinguish it. The suppressant also increases the heat capacity of the fuel/air mixture, reducing the flame temperature and thus the flame reaction rates below the level needed to sustain combustion. These two effects are synergistic. The need for both effects suggests that the lower limit for a suppression concentration may be at about 1 % by volume**.**

With this knowledge and given the availability of HFC-125, the NGP had developed a list of criteria to guide the search:

1. Fire suppression efficiency at least comparable to halon 1301 (about 3 % by volume) and certainly higher than the hydrofluorocarbons (HFCs).
2. Short atmospheric lifetime (current preference of the order of a month), to keep ozone depletion potential (ODP), global warming potential (GWP) and any future unidentified environmental contamination issues to a minimum.
3. Boiling point sufficiently low that for gaseous agents, an extinguishing concentration can be achieved within a specified time following discharge. An approximate theoretical upper limit is near 30 °C if the minimum temperature in flight is -40 °C.
4. Low toxicity relative to the concentration needed for suppression.

The NGP has systematically examined (and continues to examine) many of the most promising chemical families. While this search has produced additional knowledge of what makes a good suppressant, we have to date not identified a likely successor to halon 1301 for in-flight aircraft fires.

1. Low Boiling Point Compounds

The third criterion is the subject of NGP activity. There is some uncertainty as to the typical low ambient temperature experienced during in-flight fire suppression; -40 °C has been used thus far. A project has been commissioned for FY2003 to examine reports of the in-flight deployment of halon 1301, with an eye toward identifying a realistic value. In an additional effort to identify compounds with low boiling points, a search of the chemical literature is underway for all compounds with boiling points under 35 °C that contain bromine, iodine and/or phosphorus.

2. Prediction of Cardiotoxicity

There is also research activity on the toxicity criterion. Many of the most promising alternative chemicals are in the category of tropodegradable bromocarbons. As the name implies, these are compounds that contain a bromine atom for efficient fire suppression (criterion 1) and a chemical feature that enables the molecule to meet criterion 2. One of the most appealing bromoethers ($CF_3CBr{=}CH_2$) did well in all screens, but its LOAEL (lowest observed acute exposure level) for cardiac arrhythmia in laboratory dogs was found to be 1 % (volume), a concentration well below the extinguishing level of about 3 %. [For reference, halon 1301 has a LOAEL value of 7.5 % by volume.] These tests are expensive (at least $70 k) and require significant mass of a test chemical that may not be in commercial production. Thus, we have reprogrammed resources to improve our ability to estimate the cardiotoxicity of halogenated compounds from their chemical composition and structure.

Unfortunately, there are no recognized quantitative structure-activity relationships (QSARs) for estimating LOAEL values for members of the chemical families that comprise tropodegradable bromocarbons. A re-examination of the field has led to a focus on two approaches: partition coefficients and *in vitro* toxicity tests.

Partition Coefficients. A wide range of compounds, including halogenated and unhalogenated alkanes, alkenes, and ethers are known to induce cardiac arrhythmia. The mechanism is not known. A hypothesis is that the effect results not from chemical (reactivity based) toxicity, but from the absorption into or adsorption onto heart nerve and muscle cells and cell membranes. The pharmaceutical industry and environmental scientist use octanol-water partition coefficient in QSAR analysis for rational drug design (absorption, bioavailability, hydrophobic drug-receptor interactions, metabolism and toxicity) and estimating the environmental fate of chemicals. The property being assessed is molecular hydrophobicity, the disaffinity for the polar environment of water in favor of the far less polar octanol.

Partition coefficients are determined experimentally using reverse phase chromatographic methods. The measured property is the equilibrium constant for the concentrations of the chemical in the two liquids, K_{OW}. Compounds of known K_{OW} are used to determine relationships between measured chromatographic retention times and partition coefficients. For an unknown compound, a determination then requires only a few mg sample.

Values of K_{OW} may also be calculated from the contributions of molecular fragment-based terms plus correction factors. The algorithms can give different results, so some experience is needed to select or develop an appropriate version for the particular chemicals under consideration. Two of the most commonly used algorithms are from Molinspiration Cheminformatics (http://www.molinspiration.com) and Syracuse Research Corporation (http://esc.syrres.com)). An indication of the disparity as well as trends in the predicted values for the two calculation methods can be seen in Table 1.

Table 1. Comparison of Calculated and Measured Values of Log K_{OW} of Selected Halocarbons

Compound	Log K_{OW} * (calculated)	Log K_{OW} ** (calculated)	Log K_{OW} (measured)	LOAEL (vol. %)
CF_3Br (halon 1301)	1.833	1.591	1.86	7.4
$CHBrF_2$	1.849	0.98	NA	3.9
CH_2=$CBrCF_3$	2.141	2.49	NA	1.0
CF_2ClBr (halon 1211)	2.175	1.905	2.1	1.0
CF_3I	2.219	2.007	NA	0.4
C_3HF_7	2.349			10.5

* Molinspiration Cheminformatics algorithm
** Syracuse Research Corporation algorithm

It is probable that the use of calculated partition coefficient values to develop predictions of trends in LOAEL performance may work best when only applied to narrowly defined groups of compounds (for instance bromofluoro-alkenes) and even then only used as a tentative predictor of LOAEL value. This limitation is shown when comparing the last two lines of Table 1. The calculated Log K_{OW} value for C_3HF_7 suggests a LOAEL lower than that any of the other compounds, which is clearly not the case.

For calculated and/or experimental partition coefficients to be employed to select fire suppressant compounds for further evaluation, greater assurance in the relationship to cardiac sensitization LOAEL values is needed. The next step in our examination of this approach will be to expand the above table to include the experimental determination of K_{OW} values for the halons, HFCs, current candidate compounds and alternate fire suppressants. Medical anesthetics, which are chemically related to the above fire suppressants, will also be examined. Preference will be given to those compounds for which LOAEL values for cardiac sensitization have been determined. Additional work will further evaluate the merits of the various types of partition coefficients (water/octanol, water/membrane, etc.). Success will enable intelligent selection of compounds for synthesis in the quantities needed for further study.

***In Vitro* Screening Methods.** While no *in vitro* method exists for evaluating the cardiac sensitization properties of compounds there is strong interest in this area by pharmaceutical companies. One example is development of micro-scale *in vitro* testing systems based on human or animal cardiomyocytes. These systems are expected to outperform generic cell systems when cardiac cells are the target of the tested chemical. The results should also be directly relatable to the abnormal clinical ECG patterns that define drug-induced arrhythmia. The NGP is evaluating its possible role in this field.

3. Fluoroalkyl Phosphorus Compounds

Work is continuing in our effort to assess whether there are members of this family with estimated acceptably low toxicity, ODP, and GWP that could be used as replacements for halon 1301. Of the eight compounds initially targeted for synthesis (Table 2), about 7 g of seven of them were ultimately delivered for testing. Some general observations are:

- Fluorine substitution does yield compounds of lower boiling point, as expected.
- Several compounds exhibited instability on exposure to air and may either be hydrolyzing due to reaction with the ambient humidity and/or reacting with oxygen. A compound is listed as not air reactive if no heating of the glass vial container occurred on opening, and no flame or white fumes were observed on exposure of the compound to air.

For measuring the extinguishment concentration of these high boiling chemicals, the cup burner (Figure 2) was modified to pre-heat the incoming air, to nebulize the chemicals and to dilute the chemical before it entered the flame zone. This prevented condensation of test compounds on the cup-burners inner glass surfaces. The apparatus can now address compounds with boiling points from at least –57 °C (halon 1301) to 130 °C. Extinguishment data for these compounds are listed along with boiling point information and air reactivity observations in Table 2. The extinguishment data are upper limits due to the small quantity of chemical available.

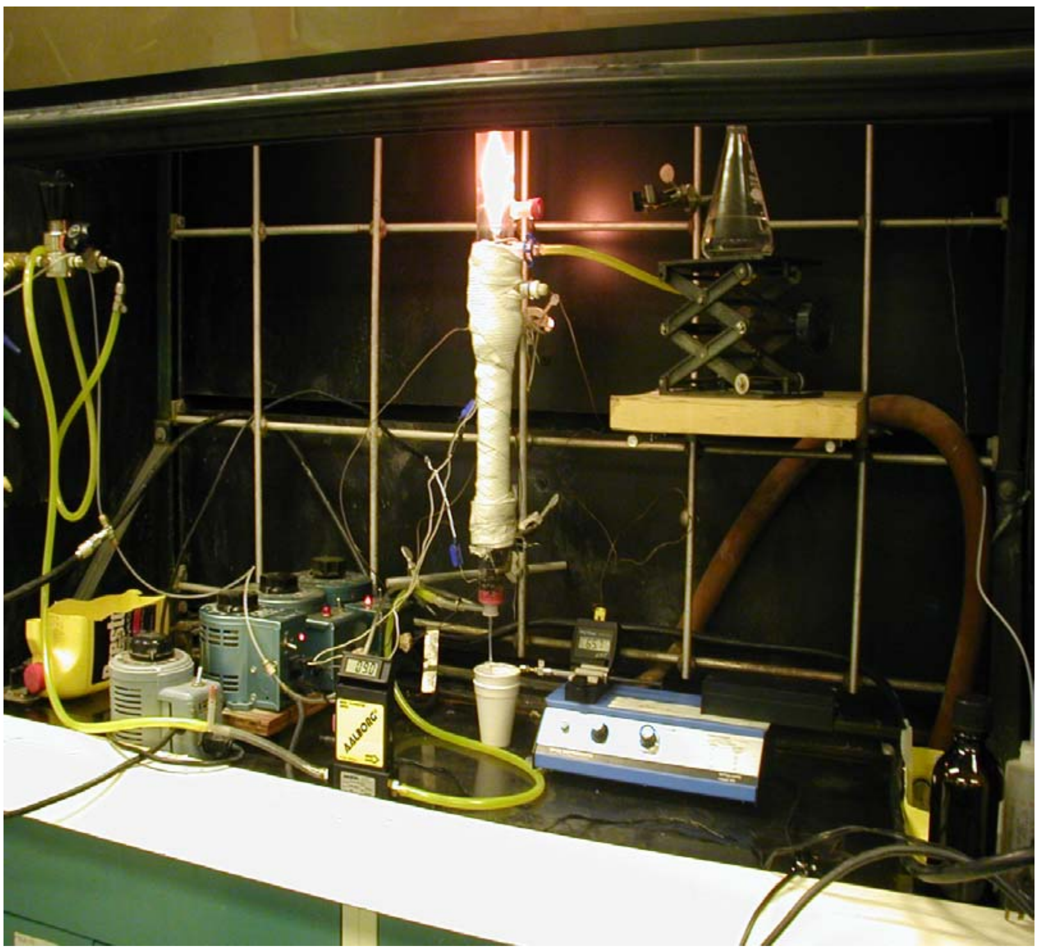
Table 2. Fluoroalkyl Phosphorus Compound Cup Burner Results

ID	Compound	Boiling Point (°C)	Extinguishment (vol. %)	Air Reactivity, Ignition
1	$O=P(CF_3)_3$	32	No extinguishment @ 5 %	Not air reactive - no ignition
2	$P(OCH_3)(CF_3)_2$	55	Spontaneously ignites in air – Not tested	Ignites spontaneously
3	$P(OCH_2CF_3)_3$	131	3.1 %	Not air reactive - no ignition
4	$O=P(OCH_3)(CF_3)_2$	42	4.6 %	Some reactivity - no ignition
5	$P(OCH_2CF_3)_2CF_3$	112	3.0 %	Some reactivity - no ignition
6	$P(OCH_2CF_3)(CF3)_2$	~90	1.8 %	Very reactive, no spontaneous ignition
7	$O=P(OCH2CF_3)(CF_3)_2$	>130	No extinguishment @5 %	Not air reactive - no ignition
8	$O=P(OCF_3)_3$	32	Not tested	Not yet synthesized

Phosphonates (P^{+5} oxidation state, compounds 1, 4, 7). The limited data suggest that phosphonates may need sufficient hydrogen atoms in their structures to break down in the flame zone and become chemically active flame suppressants. Only compound 4 approaches the needed boiling point range. If the trade-off is between high fluorination to reduce the boiling point and moderate hydrogenation for efficient fire suppression, there may not be much further promise in this family of compounds.

Phosphines (P^{+3} oxidation state, compounds 2, 3, 5, 6). None of these compounds has a sufficiently low boiling point to be of practical value for aircraft application, and high volatility (high fluorination) compounds tend toward spontaneous flammability. Thus, this family shows little promise. For other uses, identification of the decomposition products of compound 6 might point the way to dramatically better phosphorus-based extinguishants.

Figure 1. Cup Burner with Nebulizer



4. Agent Stability During Long-term Storage

Under the Technology Development Plan[1] an assessment was performed as to the potential for degradation of a number of candidate suppressants during four-year exposure to metal storage bottle materials. For all compounds there were some metals for which the exposures at temperatures up to 150 °C and 4.13 MPa showed no ill effects. CF_3I manifested the most serious interactions; those samples, stored for an additional five years at ca. 23 °C, have now been re-examined under the NGP.

Metal coupons made from one of four test metals (C4130 alloy steel, Ti-15-3-3-3 titanium alloy, Nitronic 40 stainless steel, and Inconel 625 nickel alloy) had been inserted into polytetrafluoroethylene-lined stainless steel cylinders. The coupons had roughly the same surface area as the inside of the cylinders to simulate the agent contact area if the cylinder had been made of that metal. Some cylinders were left without metal coupons as a control. In addition to the test metals, half of the cylinders received metal coupons made of copper (type CDA 110), since copper reacts with iodine to form the nearly insoluble cuprous iodide. While some cylinders contained only dry materials, some cylinders received 100 µL of distilled water. The cylinders were then filled with a mixture of CF_3I vapor and nitrogen to a pressure of 4.13 MPa as measured at 23 ˚C. During the initial testing period, from 1993 to 1997, each cylinder was stored at its assigned temperature of either 100 ˚C, 150 ˚C, or ambient temperature (approximately 23 ˚C). Fourier transform infrared (FTIR) spectroscopy was used to analyze the cylinder contents at various times during the storage. The spectra were analyzed for the magnitude of the CF_3I peak and examined for new peaks that would also indicate degradation of the agent.

No significant changes were found in the CF_3I concentration and no new peaks were found, indicating stability during the five-year period at ambient temperature. [Note that the combination of copper and Nitronic 40 had already resulted in a complete breakdown of CF_3I during storage at 150 ˚C.]

Recent Publications: New Flame Suppression Chemistry

Mather, J.D., and Tapscott, R.E., “Tropodegradable Bromocarbon Extinguishants – Compound Selection and Testing Issues,” *Proceedings of the 2002 Halon Options Technical Working Conference*, NIST Special Publication 984 (CD), National Institute of Standards and Technology, Gaithersburg, MD, 2002.

Tapscott, R.E., Shreeve, J.M. and Mather, J.D., “Fluoroalkyl Phosphorus Fire Extinguishing Agents,” *Proceedings of the 2002 Halon Options Technical Working Conference*, NIST Special Publication 984 (CD), National Institute of Standards and Technology, Gaithersburg, MD, 2002.

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B. IMPROVED SUPPRESSANT DELIVERY

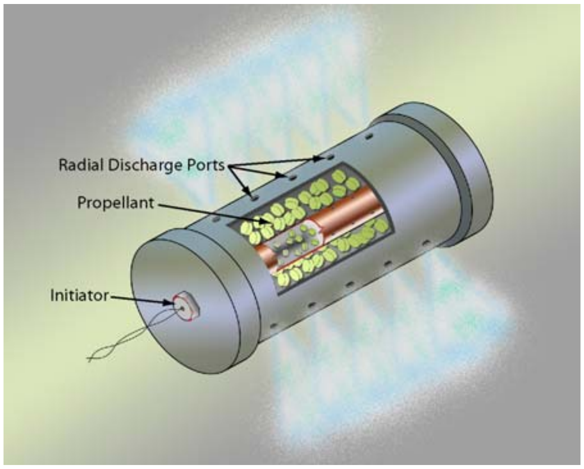
1. Solid Propellant Fire Extinguishers

NGP research is developing new types of solid propellant gas generators (SPGGs) 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 modification of the solid propellant, inclusion of additives in the propellant formulations, and entrainment of a chemically active additive into the gas stream. There are two different design categories (Figure 2):

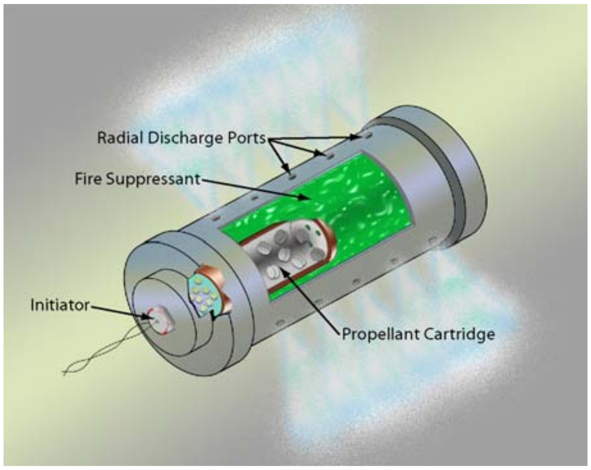
- Solid propellant Gas Generators (SPGGs), in which the coolant or chemical additive is incorporated directly into the solid propellant composition, and
- Hybrid Fire Extinguishers (HFEs), in which the coolant or chemical additive comprises an auxiliary "hybrid" fluid that is discharged with the propellant effluent.

Propellant/Additive Development. Direct incorporation of coolant compounds into the propellant composition was shown to be an effective means for reducing exhaust temperatures. However, while the effect of coolant level upon ballistic performance is consistent within a given family of compositions, this trend is not consistent for different propellant families. These findings suggest that the benefits of decreased exhaust temperatures are often offset by a decrease in the burn rate of the propellant, which in turn relates to a decrease in the rate of suppressant delivery.

Figure 2. Solid Propellant Fire Extinguishers

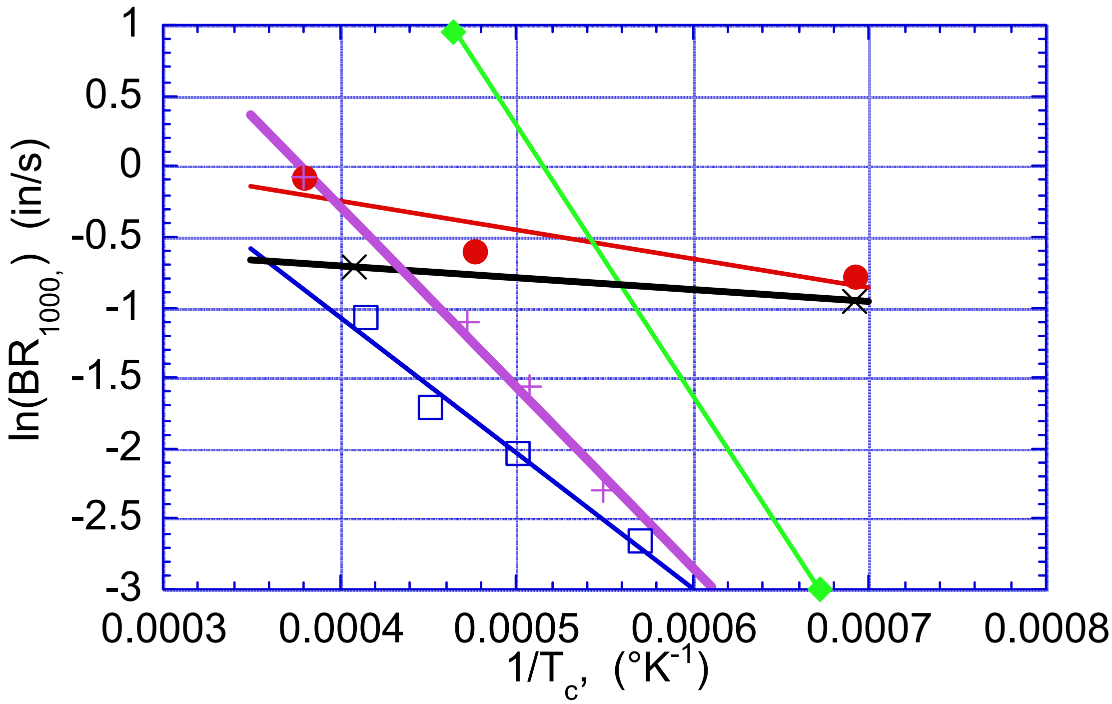


SPGG



HFE

Figure 3. Relationship Between Propellant Burn Rate and Exhaust Temperature



Propellant formulations incorporating the new high nitrogen compound BTATZ ($C_4H_4N_{14}$) (Table 3) appear to provide increased means for reducing propellant combustion temperatures while maintaining agent delivery rates at levels sufficient for rapid flame extinction. Preliminary ballistic testing (Figure 4) indicates that burn rates may be maintained within workable constraints at the same time that exhaust temperatures are reduced as much as 30 % below current baseline levels.

The preparation of BTATZ has progressed to the kg scale, with a purity of 97 % to 99 %. Scale-up work on propellant batches approaching the 10 L scale has proven successful. Further safety data on BTATZ shows acceptable friction and impact sensitivity but some sensitivity to electrostatic initiation. When formulated into a molding powder with poly(ethylacrylate), electrostatic sensitivity is still a concern, even when 0.5 % carbon black is added. However, when pressed into pellets or deposited as a thin layer the material meets the criteria set for routine handling of energetics.

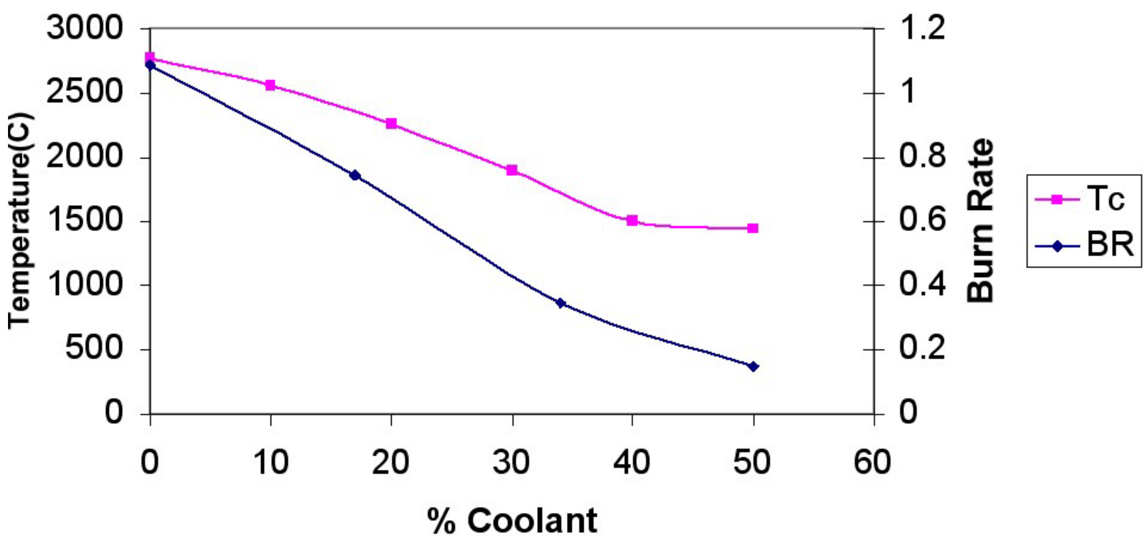
Chemical additives (or their precursor) were blended directly into the propellant for SPGG (or HFE) delivery, or the additive (or precursor) was blended directly into the hybrid fluid for HFE delivery. Several compositions were developed such that a common composition "family" evolved having different levels of additive.

Table 3. Propellant Physical Properties

Descriptors	Major Constituents[a]	T_c (K)	Gas (mol/100g)	Theoretical Density (g/cc)	BR_{1000} (in/s)
BTATZ KP	BTATZ-5AT KP	1961	4.12	1.72	1.31
BTSN-00	BTATZ $Sr(NO_3)_2$	2774	2.27	2.38	1.09
BTSN-10	BTATZ $Sr(NO_3)_2$	2562	2.12	2.43	TBD
BTSN-20	BTATZ $Sr(NO_3)_2$	2258	2.00	2.49	0.75[b]
BTSN-30	BTATZ $Sr(NO_3)_2$	1890	1.89	2.55	TBD
BTSN-40	BTATZ $Sr(NO_3)_2$	1503	1.79	2.61	0.35[c]
BTSN-50	BTATZ $Sr(NO_3)_2$	1444	1.54	2.67	0.15
Aerojet-04	5AT $Sr(NO_3)_2$ $MgCO_3$ K_2CO_3	1445	1.61	2.54	0.56
Aerojet-05	5AT $Sr(NO_3)_2$ $MgCO_3$ K_2CO_3	1444	1.81	2.54	0.55
Aerojet-06	5AT $Sr(NO_3)_2$ $MgCO_3$ KNO_3	1445	1.78	2.36	0.41

(a) The balance remaining in each formulation is made up of coolant, binder, opacifier and process aid.
(b) Reported burn rate corresponds to 17% coolant composition.
(c) Reported burn rate corresponds to 34% coolant composition.

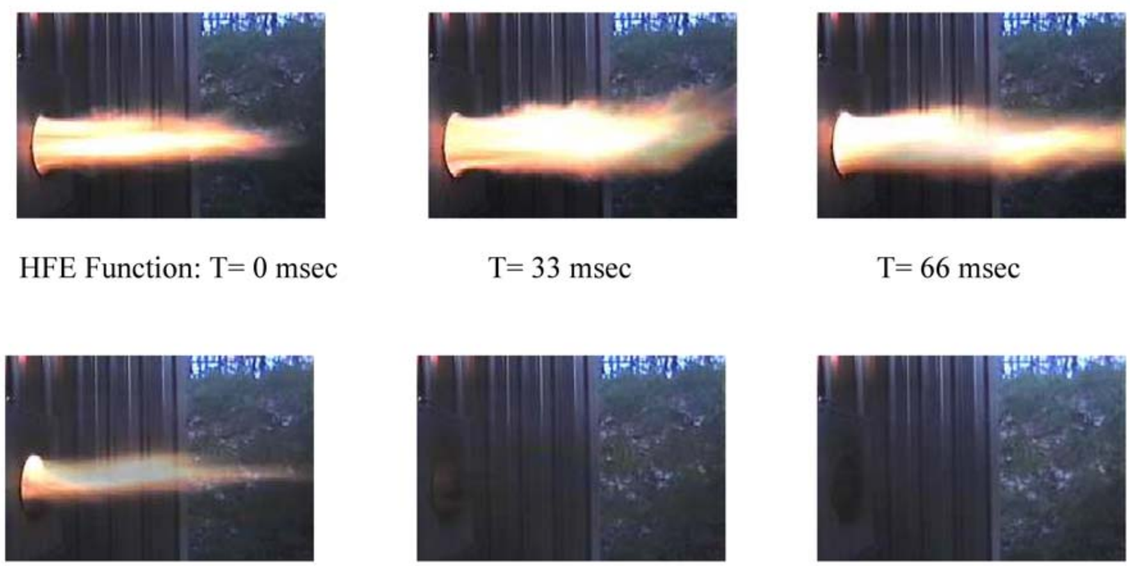
Figure 4: Plot of Adiabatic Agent Temperature and Burn Rate vs. Coolant Level



Fire Suppression Testing. The mid-scale Fire Test Fixture (FTF) developed by Aerojet was used to test the effectiveness of various agents. The fuel was JP-8, the air flow was 450 g/s, and the equivalence ratio was 0.5, resulting in a flame temperature of ca. 1000 K and ca. 700 kW intensity. The residence time through the fire zone of the fixture was calculated to be 1.2 s and the discharge time of the SPGG and HFE units was ca. 100-200 ms. Typical flame extinguishment times were shorter, generally ca. 100 ms (Figure 5). The results of testing are summarized in Table 4.

The presence of chemically active additives greatly enhances the fire suppression efficiency of both SPGG and HFE devices (Figure 6). AEROJET-04 was the most effective solid propellant composition tested. This composition incorporates potassium carbonate in its discharge, and is ca. 3x more effective per unit mass than the inert baseline FS01-40. Testing with compositions of lower loading levels of active agent resulted in less effective performance. This indicates that the additive loading in AEROJET-04 is at or below the saturation level reported in sub-scale testing with numerous other chemically active suppressants. Variation in propellant ballistics was examined at several different temperatures and was shown to be on the order of 13 % from 25 °C to 75 °C.

Figure 5. Fire Out Sequence (Aerojet-04/HFC-227 HFE)



HFE Function: T= 0 msec | T= 33 msec | T= 66 msec

T= 99 msec | T= 132 msec | T=165 msec

Fire testing using hybrid fire extinguisher (HFE) configurations showed that “cold soaked” CF_3I hybrids and other high-boiling agents perform well at low temperatures, their low vapor pressures offset by the heating and pressurizing power of the solid propellant driven HFE. FS01-40/Novec-1230 HFEs were as effective as FS01-40/HFC-227 HFEs on a mass basis. Hence other factors (e.g., atmospheric lifetime) may provide the discrimination between their use.

HFE testing with aqueous agents provided additional insight into necessary levels of active agent required to effect suppression. Tests using an inert propellant configuration with pure water were found to require higher agent loads than the same propellant plus HFC-227. Testing with FS01-40/water/potassium acetate HFEs showed a 36 % reduction in the mass needed for flame extinguishment.

This NGP solid propellant technology forms the basis for fire protection products currently installed on both the Navy F/A-18 E/F and V-22 aircraft. Advanced fire protection products incorporating improvements supported by this NGP project are currently being examined by each branch of the U.S. military as well as other government organizations.

Figure 6. Performance Summary of Fire Testing

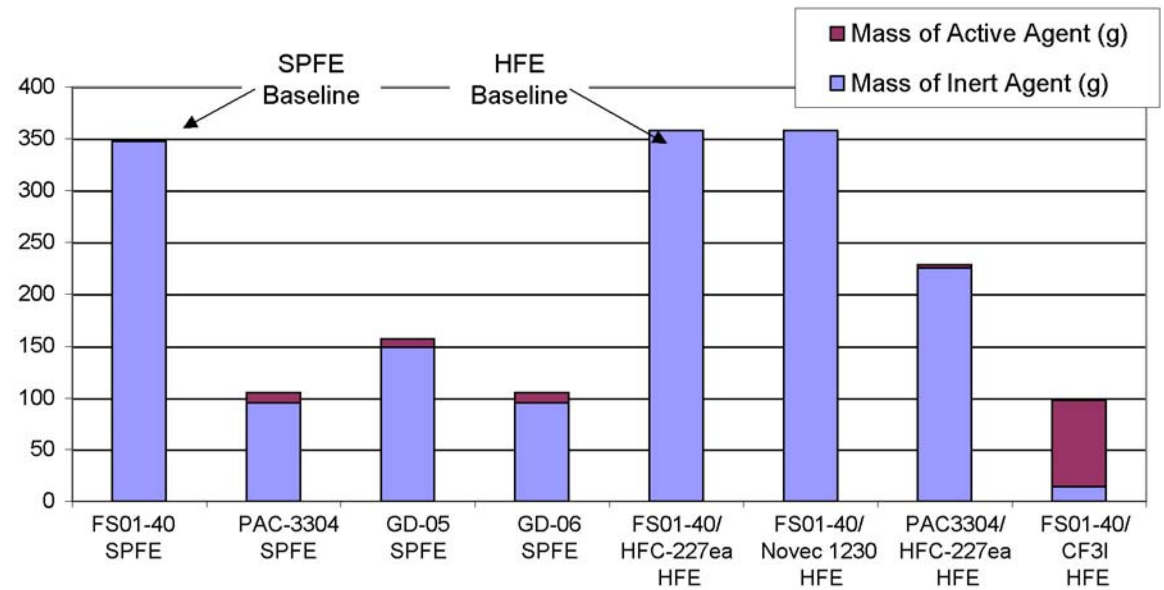


Table 4. Suppression Effectiveness Summary

Agent	Active Additive	Gas Fraction[a]	MW (g/mol)	Mole Active/ 100 g Discharge	GG Load (g)	Discharge Mass (g)	Mole Active Discharged	Average m-dot (g/s)
SPGG RESULTS								
FS01-40	-	50 %	30	0	347	173.5	0	868
A-02	KI	50 %	30	0.26 (K)	157	78.5	0.199	393
A-04	K_2CO_3	50 %	30	0.29 (K)	105	52.5	0.152	263
A-05	K_2CO_3	50 %	30	0.15 (K)	157	78.5	0.110	393
A-06[b]	K_2CO_3	50 %	30	0.29 (K)	105	52.5	0.152	263
HFE RESULTS								
FS01-40/ HFC-227	-	95 %	170	0	358	340.1	0	1701
A-02/ HFC-227	KI	95 %	170	0.019 (K)	228	216.6	0.040	1083
A-04/ HFC-227	K_2CO_3	95 %	170	0.021 (K)	228	216.6	0.046	1083
FS01-40/ HFC-227 $KHCO_3$	$KHCO_3$	95 %	170	0.021 (K)	265	252	0.052	1260
FS01-40/ HFC-227 $NaHCO_3$	$NaHCO_3$	95 %	170	0.021 (Na)	228	216.6	0.039	1083
FS01-40/ CF_3I	CF_3I	95 %	196	0.46 (I)	98	93	0.43	450
A-02/ Water[c]	KI	95 %	18	0.019 (K)	>358	-	-	-
A-04/ Water[c]	K_2CO_3	95 %	18	0.021 (K)	>358	-	-	-
FS01-40/ Water KOAc	KOAc	95 %	30	0.46 (K)	228	216.6	0.96	1083
FS01-40/ HFE-7100[c]	-	95 %	250	0	>358	-	-	-
FS01-40/ Novec 1230	-	95 %	316	0	358	340.1	0	1701

[a] Assuming all of the Hybrid fluid is vaporized.

[b] KNO_3 as additive in propellant blend rather than K_2CO_3. Upon combustion K_2CO_3 is produced.

[c] Fire was not able to be extinguished using same amount of agent as FS01-40/HFC-227 HFE.

2. Dispersion of Suppressants at Low Temperature

Based on prior TDP and NGP work, there is reason to believe that fluid suppressants with boiling points considerably higher than that of halon 1301 (-58 °C) might not disperse efficiently throughout the volume of a cold nacelle or dry bay (*ca*. -40 °C; see above). Experiments using fluids with differing boiling points are continuing to explore the temperature regime where difficulty might be encountered.

The initial experiments involved examination of CF_3I (boiling point of -22 °C) discharges in a simulated engine nacelle (Figure 7) under different thermal conditions: a low temperature of -40 ºC and an ambient temperature of 22 ºC. The measurements were made using two UV/VIS fiber-optic spectrometers. The initial time (t = 0) in Figure 8 corresponds to the initiation of the agent release. The data indicate two findings:

- Inefficient dispersion should be expected when discharging a suppressant fluid into a system whose temperature is well below the fluid boiling point. In the low temperature release shown here, much of the liquid deposited on the nacelle floor and evaporated over many seconds.
- Basing the design mass of agent for an engine nacelle on room temperature test data could lead to significant underestimation of the mass needed for in-flight fire suppression.

Similar examination of compounds with other boiling points will complete this effort in the coming year.

Figure 7. Schematic of the Simulated Engine Nacelle Test Facility

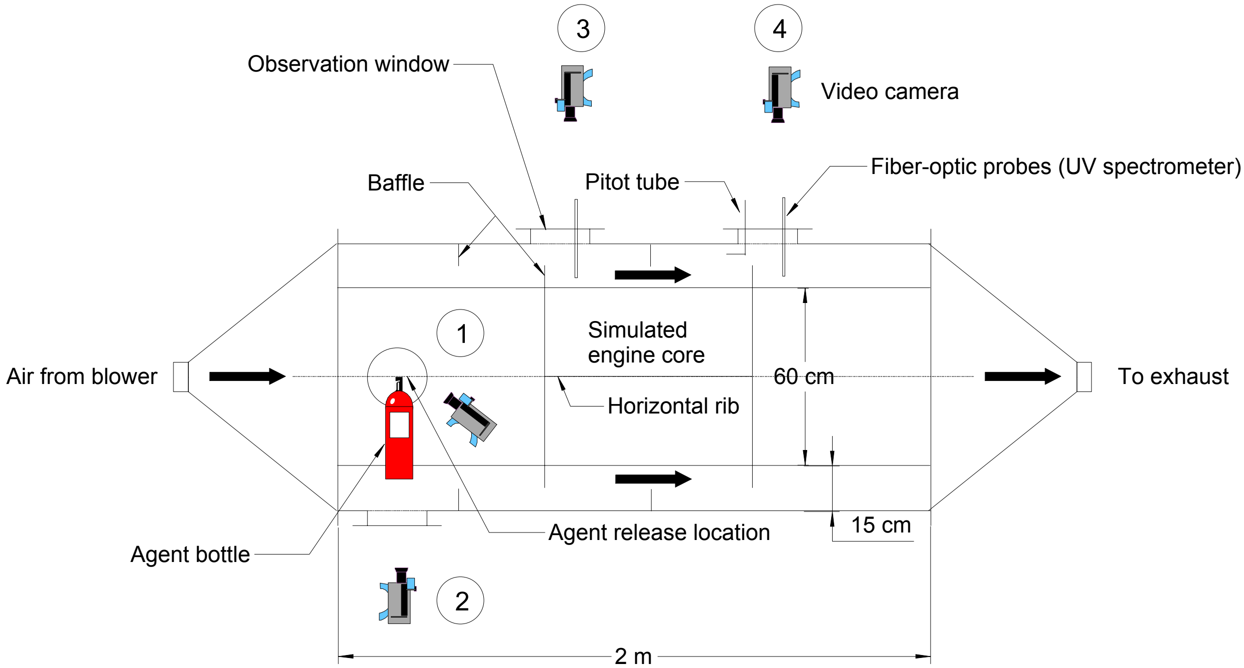
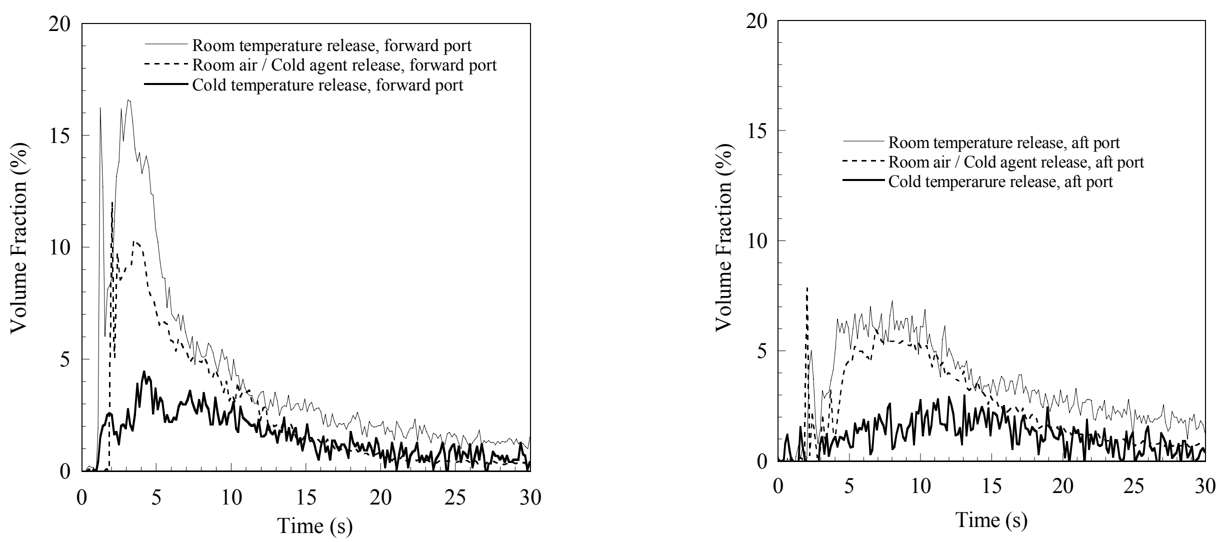


Figure 8. Concentration Profiles of CF_3I in the Engine Nacelle Simulator



3. Suppressant Dynamics in Engine Nacelles

Guidance on preferred locations for and styling of suppressant discharge can best be developed from validated computer modeling of the process. The computational fluid dynamic (CFD) model will include gaseous and aerosol suppressant flow, a fire, and fire extinguishment in cluttered environments. Several flow facilities are being used concurrently to provide both input and validation data in a timely manner.

Droplet Flow Around Obstacles. Existing apparatus was re-oriented horizontally to enable collection of liquid agent that drips off of the obstacle and to prevent liquid droplets downstream of the obstacle from falling back upstream into the oncoming stream (Figure 9). The agent used in this phase of the study was water. The flow field, seeded with fine water droplets (*ca.* 1 μm diameter) to enable characterization using a three-dimensional particle image velocimetry (PIV) system, was also recorded with a digital movie camera. Measurements were carried out with two obstacles:

- an aluminum cylinder of 32 mm diameter (larger than the turbulence length scale) and 305 mm length (Figure 10), with measurements made at both 296 K and 423 K, and
- a body-centered cube (BCC) arrangement of wooden spheres and connecting posts (Figure 11), whose flow blockage fraction was about 0.64.

Figure 9. Apparatus Schematic for Droplet-laden Turbulent Flow Field

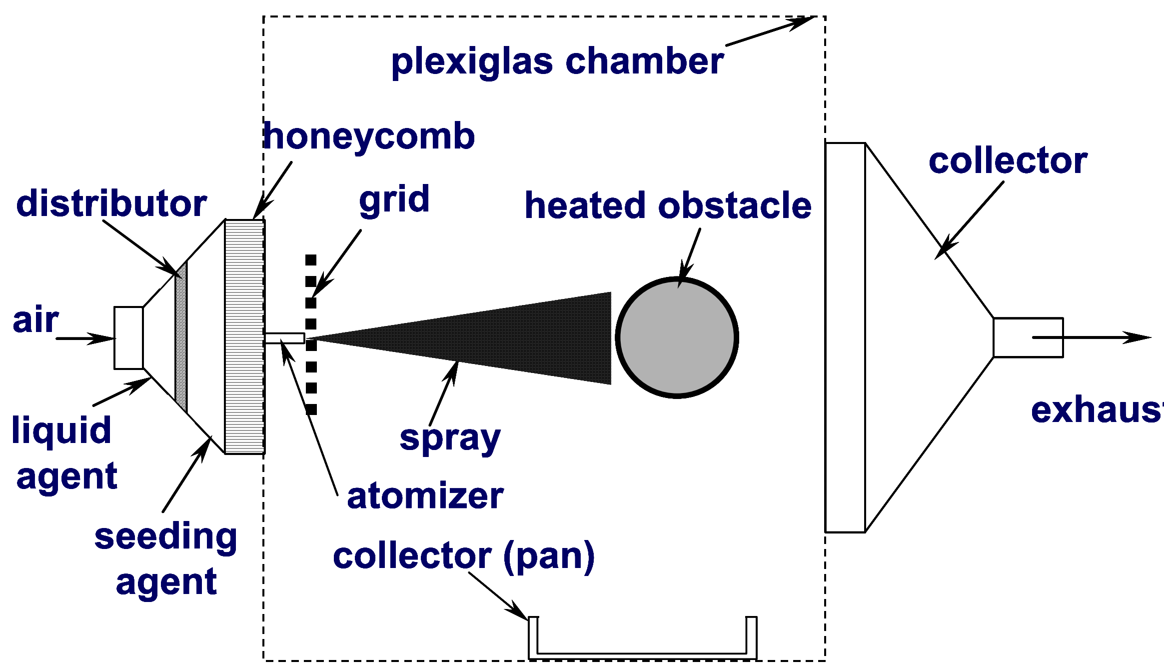


Figure 10. Heatable Cylinder. a: Schematic; b: Photograph

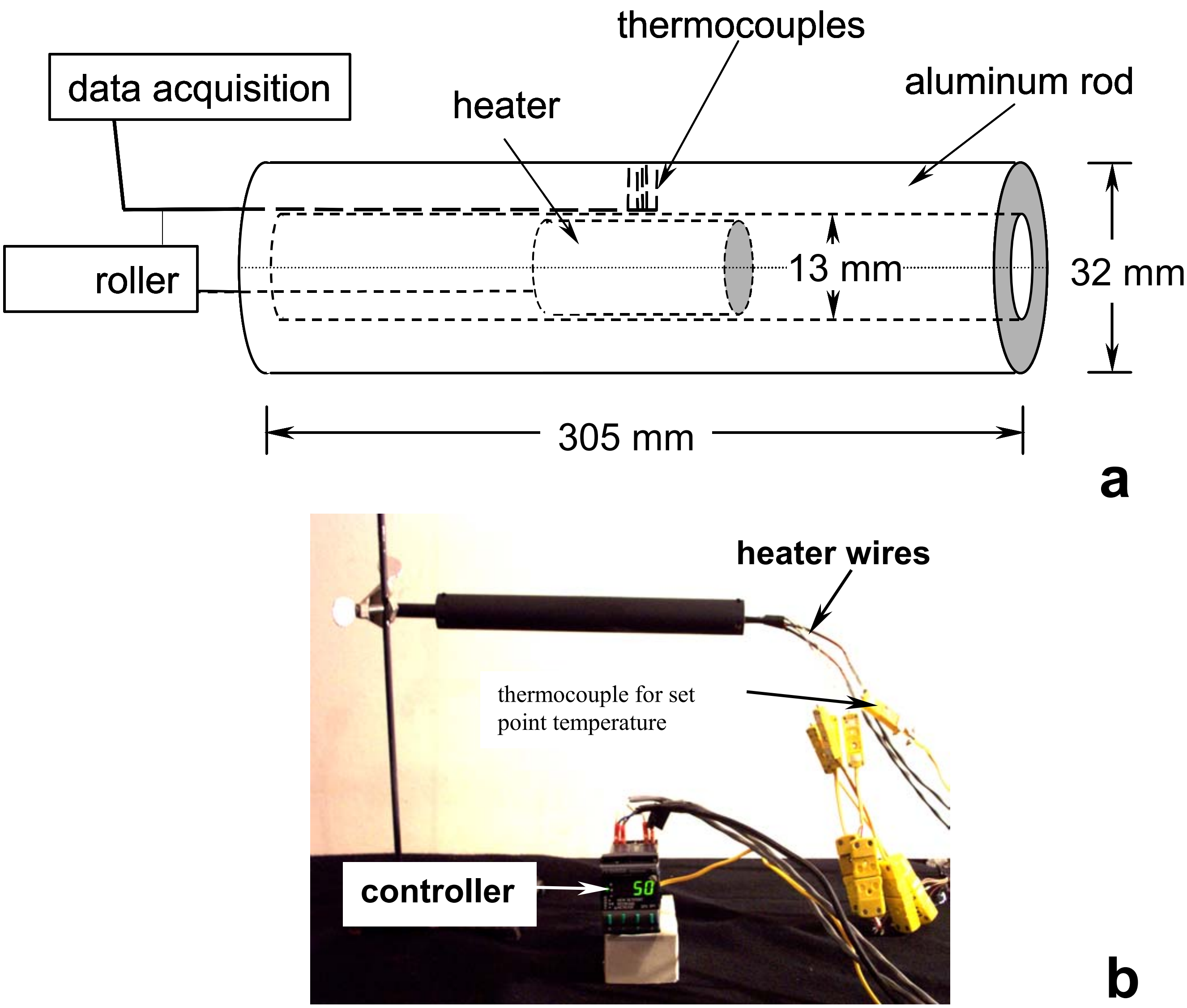
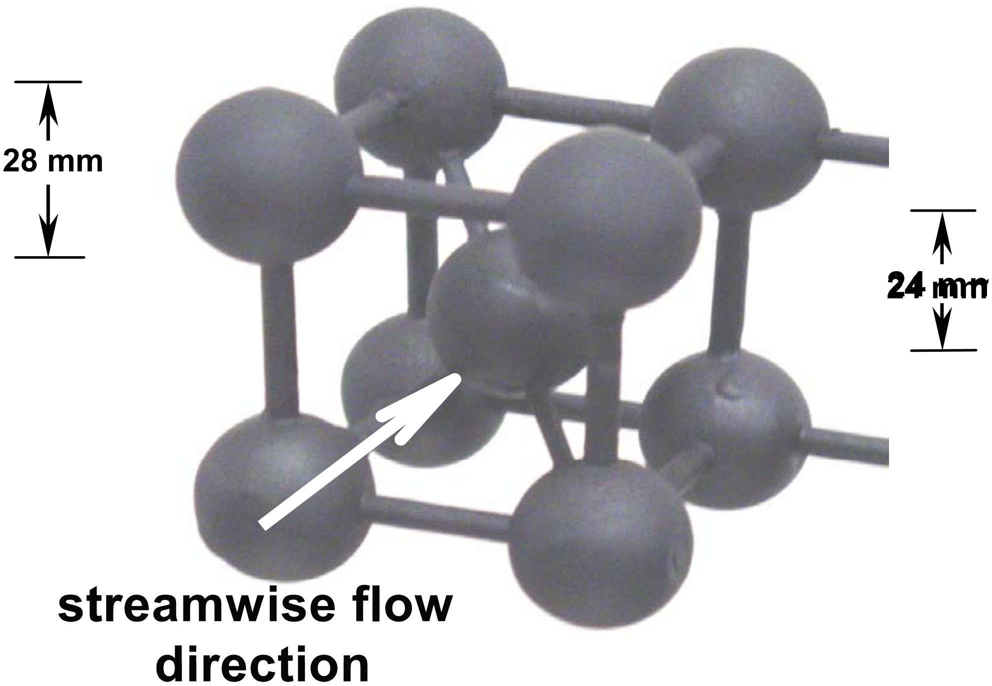


Figure 11. Schematic of Body-centered Cube Obstacle

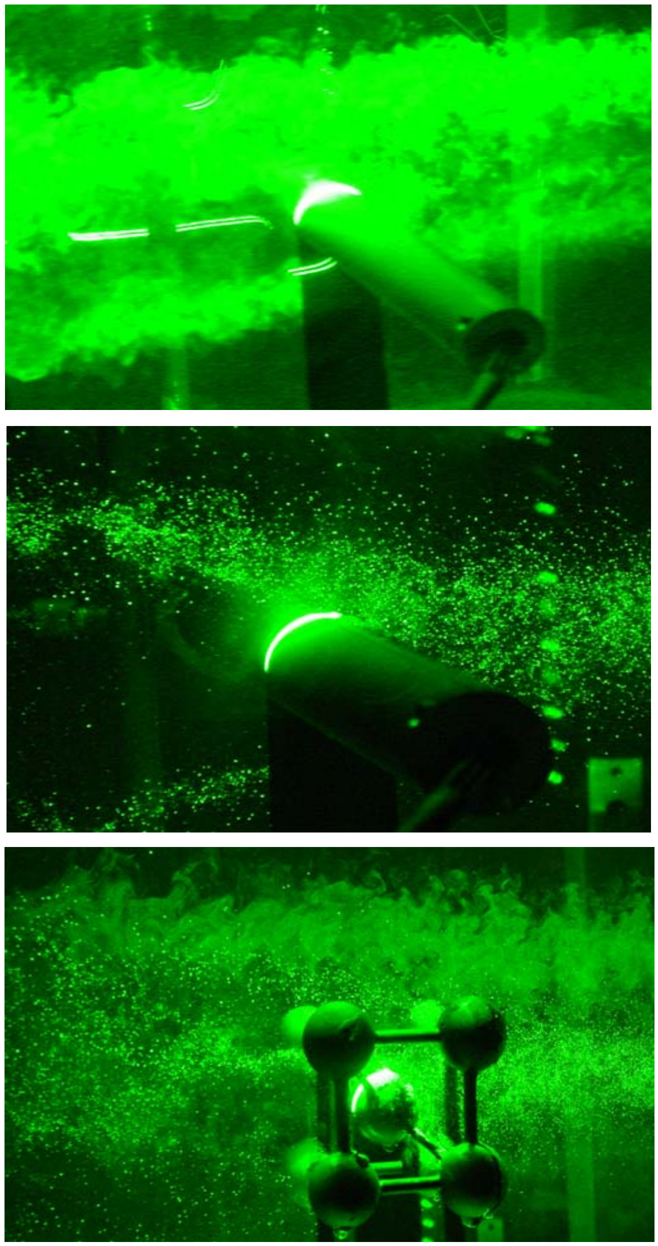


Photographs of the observed droplet transport are shown in Figure 12. The three components of droplet velocity for the flow over the unheated cylinder are presented in Figure 13. Comparison of the two cases with spray to the seed-only case indicates that the recirculation zone is larger for the spray cases. Larger size droplets require a longer distance to interact with the turbulent flow field, to reduce their higher momentum, and to be entrained into the recirculation zone, if at all.

Dispersion of droplets/particles around the obstacle is dependent on its size. Fine droplets were entrained into the recirculation region behind the cylinder while the larger droplets impacted the cylinder surface, accumulated and dripped off, and/or rebounded and dispersed radially outward into the free stream. [The droplet size in the region around the cylinder will be measured in the next phase of the work using phase Doppler interferometry.] Even with nearly two thirds of the flow path blocked by the BCC, only about 5 % of the (large droplet) inlet water flow impacted the surfaces and dripped into the collector. An even lower fraction was observed for the cylinder. Nonetheless, significant spray cooling of the surface was observed for the heated cylinder.

The research is continuing with sprays of two additional fluids: HFE-7000 (boiling point of 307 K) and HFE-7100 (boiling point of 334 K). Phase Doppler interferometry will be used to obtain spatial profiles of the droplet size and velocity distributions, and number density, and allow comparison of the different liquid physical properties to droplet transport processes.

Figure 12. Photographs of Flow Fields Around Unheated Obstacles. a: Seed/Droplet-laden, Unheated Cylinder; b: Droplet-laden, Unheated Cylinder; c: Seed/Droplet-laden, Body-centered Cube. Flow is from Right to Left.

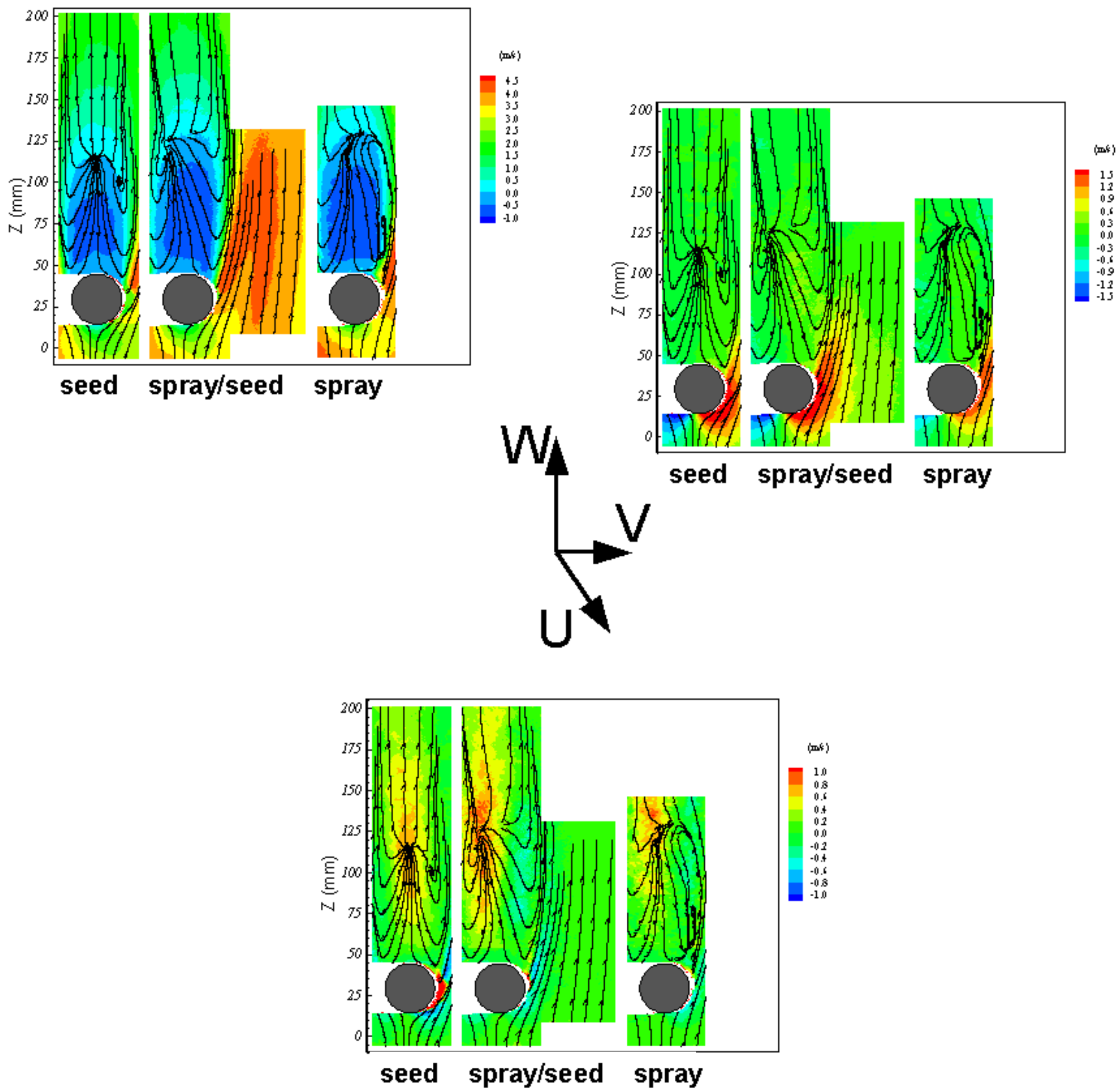


a

b

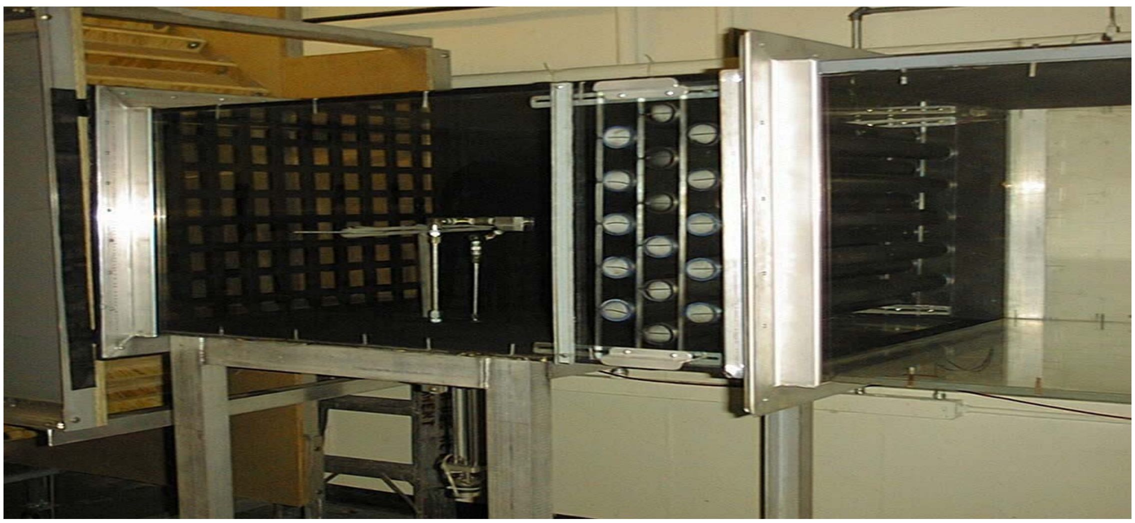
c

Figure 13. Variation of Mean Streamwise and Cross-stream Velocities with Downstream Distance for the Unheated Cylinder (Black Circles). The black contours represent traces of the in-plane velocity vectors.



Spray-Clutter Interactions. For the next step in complexity, we modified a low-speed flow visualization tunnel to investigate liquid fire suppressant spray dynamics in the presence of generic clutter (Figure 14). This included the fabrication of an additional flow section and installation of interchangeable turbulence-generation grids, a newly developed suppressant spray nozzle, and an adjustable array of three banks of cylindrical clutter elements. The new 1.23 m (4 ft.) section, mounted upstream of the existing 2.44 m (8 ft.) long test section, has two transparent surfaces, top and side, which enable optical measurement access to the spray and clutter elements. A top speed approaching 12 m/s (39.4 ft/s) has been achieved. New software will provide data on the energy spectrum, power spectral density, and signal autocorrelation.

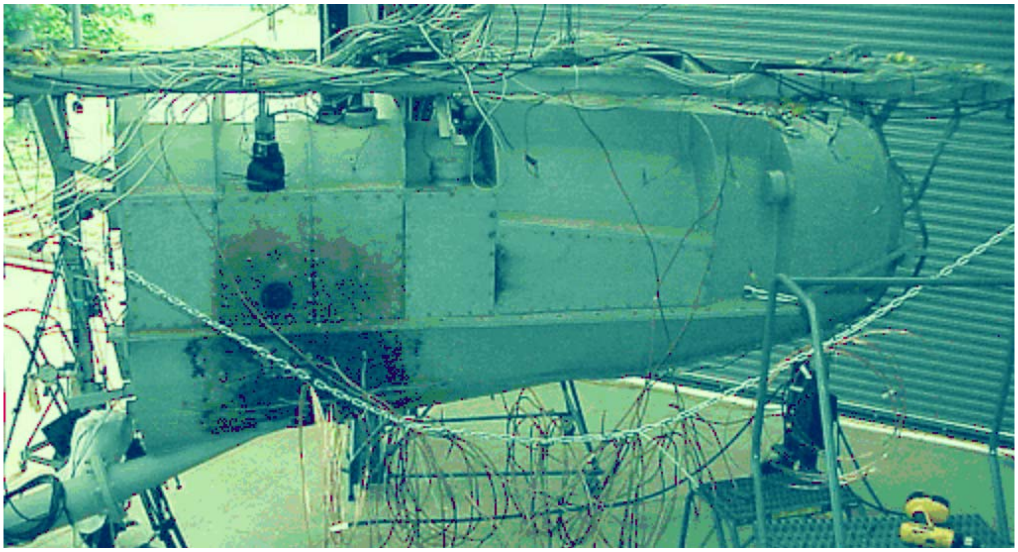
Figure 14: Suppressant Spray Flow Facility



Documentation of the dual-fluid spray nozzle has been completed using a three-dimensional particle dynamics anemometer (PDA). The dependency of data accuracy on optical configuration is not well documented, so the current measurements represent the state of the art. Flow visualization of the patterns in and around the clutter elements were then obtained.

Nacelle Simulator. Figure 15 shows the full-scale F/A-18 E/F Nacelle Ground Test Fire Simulator that will be the eventual test bed for the predictions of suppressant dispersion. The air inlet source is seen in the lower left corner, with the air flowing into the bottom of the nacelle. There are two vents in the top and four exit holes in the front face. The various internal ventilation paths have been sized to provide the flow distributions predicted in an airflow analysis conducted by Northrop-Grumman. Therefore this simulator is designed for testing at one flight condition: the aircraft traveling at 0.55 M at sea level. Given this restriction, three flows were selected to correspond to high speed, high altitude cruise; loiter; and precision approach. These flows were derived from flight tests of the F/A-18 C/D, from which data for the E/F aircraft were scaled. Input/output air flow measurements were completed for each of these (without a fire). A simplified model was developed to estimate the overall flow and average pressures for any desired future test conditions. It is difficult to predict the pressure distribution inside the nacelle, and consideration will be given to an improved model.

Figure 15. F/A-18 E/F Nacelle Ground Test Fire Simulator, Port Side

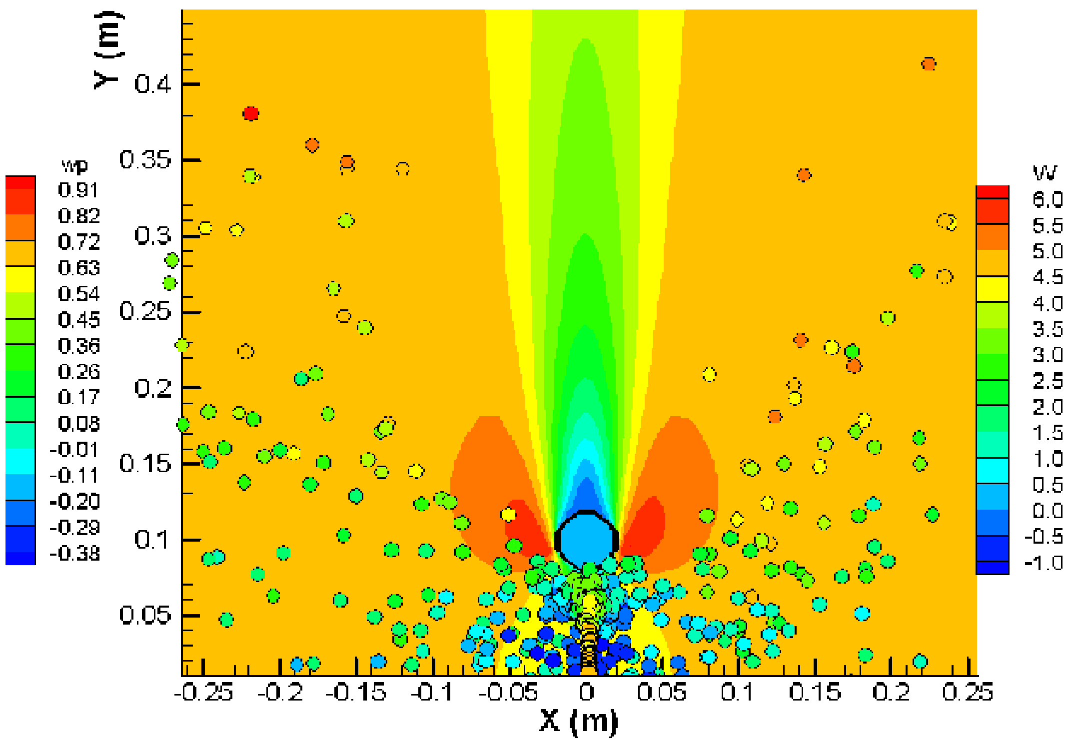


Wind Tunnel Data. NGP staff have compiled a large amount of data needed as input to the modeling of the Simulator:

- Wind tunnel turbulence data to characterize the tunnel for the clutter models and
- Coefficient of drag by momentum balance for all the three-dimensional clutter.

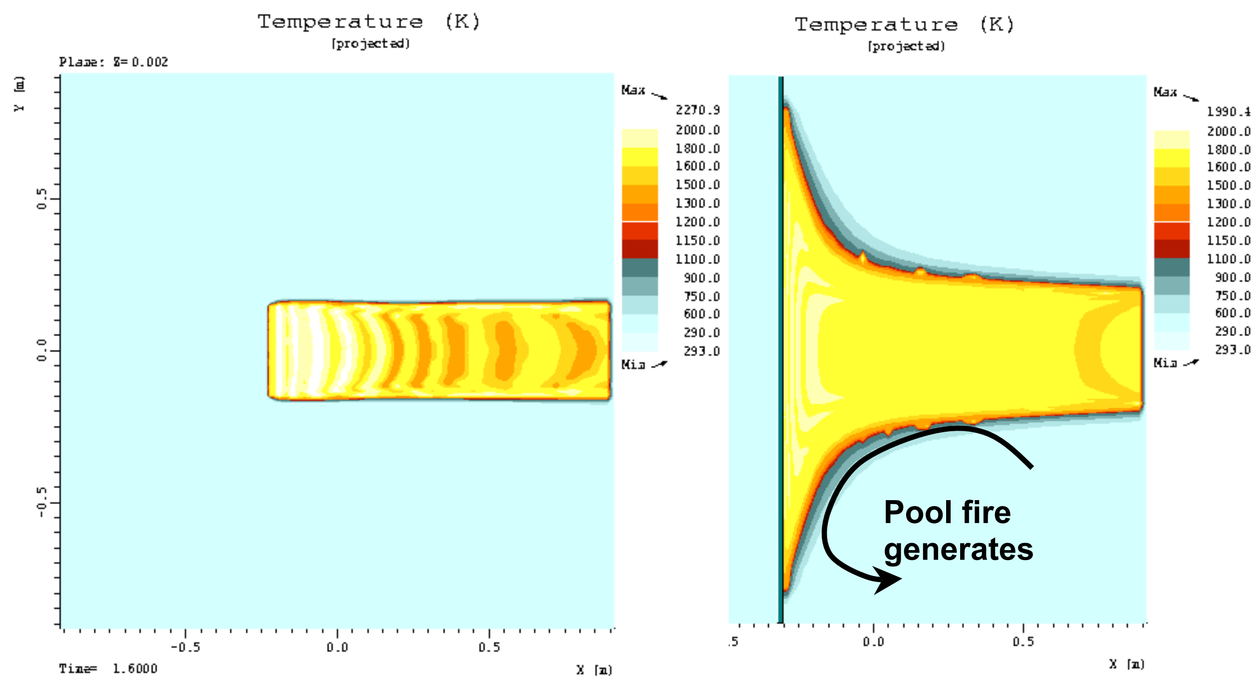
Computer Modeling and Simulation. A preliminary phenomenological model describing the interaction of sprays with objects in the flow has been formulated for use with the VULCAN spray model. The fate of particles impacting a surface is known to depend on the impact energy, and the impact model accounts empirically for energy lost in the impact, providing a post-impact kinetic energy for particles that bounce off or shatter on the surface. The model has been evaluated using HFE-7100 as the fluid (Figure 16). Initial particle velocities are slow, and droplet bouncing is the prevalent behavior. Because the inlet flow is turbulent, the particles deviate from the centerline, and post-bounce particles exhibit a range of transverse velocities including negative rebound. Because the mean flow is upward, drag causes the particles to accelerate. However, the rebound results in most particles exiting the sides of the domain, and the number of particles convected through the wake is observed to be small. Results different from those in Figure 16 are found in simulations for different initial droplet velocity and size distributions. Results range from droplets sticking to the cylinder to droplets shattering upon impact into smaller droplets.

Figure 16. Particle locations and velocities during the impingement of a 1 mm HFE-7100 droplet stream on a cylinder. [Actual number of droplets simulated is orders of magnitude greater than shown, and particle sizes are exaggerated for visibility.]



A numerical study of flow past a rib protruding from a wall was conducted to analyze the effectiveness of the subgrid clutter model. Results are used to evaluate clutter-induced changes in turbulent energy and its dissipation rate. Simulations were conducted with a pool fire near the end of the recirculation zone that exists behind the rib. Figure 17 shows temperature contours for the pool fire both with and without the rib. Results indicate that the fire is convected upstream through the recirculation zone and that the fire zone behind the rib is significantly wider than the pool itself because of the secondary flow generated by the pool fire. The existing VULCAN suppression model was used to simulate the suppression of this flame. Some changes were made in the VULCAN suppression model because the original version was too conservative and predicted suppressant requirements well in excess of requirements observed experimentally. This work has also identified necessary extensions to the clutter model to account for the flame stabilization effect. This work will continue to take advantage of empirical correlations for transport of suppressant into recirculation regions behind steps developed as part of earlier NIST (Gann, 1995) and NGP efforts (Takahashi et al, 1998).

Figure 17. Temperature Contours for a Pool Fire with (right) and without (left) a Small Rib (1/16 of the Wind Tunnel Height). The Rib Acts to Create Recirculation Zones that Stabilize the Flame and Draw it Upstream.



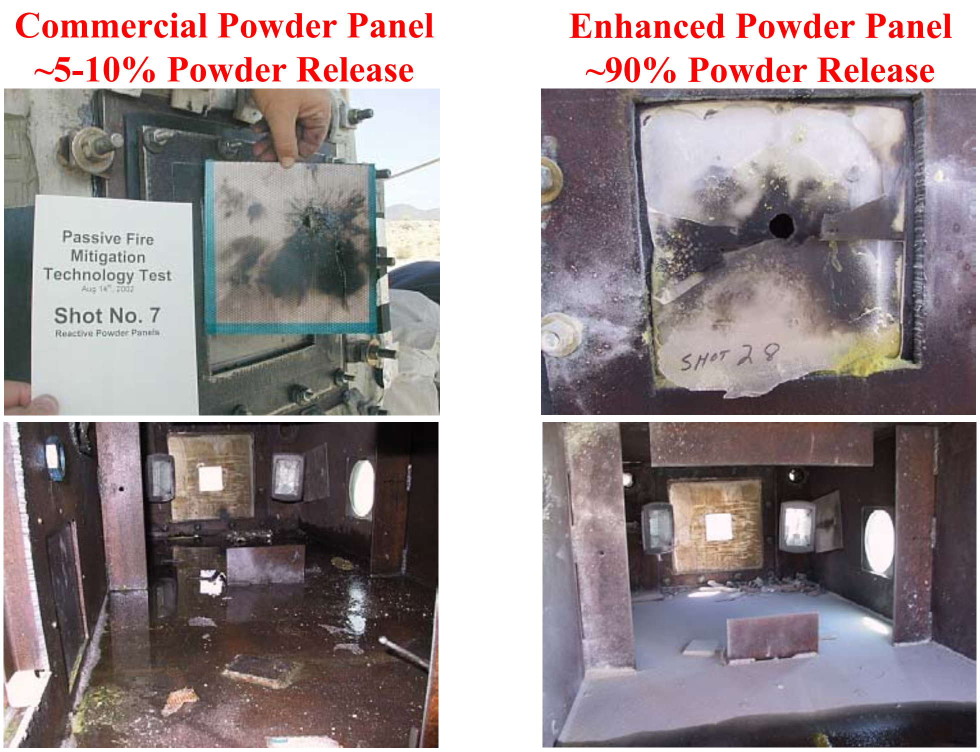
4. Enhanced Powder Panels for Dry Bay Fire Protection

Powder panels have been applied to the lining of aircraft dry bays to provide passive, lightweight, effective fire protection against ballistic impact. Projectile penetration of the dry bay and adjacent fuel tank releases agent from the powder panel into the fire zone to inert the space before the adjoining fuel spills into the space and is ignited by incendiaries. An NGP survey indicates that U.S. fixed wing aircraft do not employ powder panels, but there is growing interest. Their use in rotary wing aircraft is established. Currently, the Navy UH-1Y Huey and AH-1W Super Cobra aircraft operate with powder panels. AH-1W and UH-1N legacy aircraft are being upgraded to the AH-1Z Super Cobras, which uses powder panels for dry bay protection. The V-22 Osprey tiltrotor aircraft uses powder panels extensively. Evaluations have also been conducted recently for integrating powder panels into the AH-64 Apache and the RAH-66 Comanche helicopters.

NGP success with enhanced powder panel designs has sparked interest by several aircraft programs. As a result, NGP researchers have entered into proprietary rights agreements with Bell Helicopter Textron, Inc./The Boeing Company and Sikorsky Aircraft Corporation/The Boeing Company to discuss the possibility of integrating enhanced powder panels into aircraft such as the V-22 and RAH-66. These agreements allow for the free exchange of design details and production or qualification requirements that may be levied on newly developed panels. In addition, discussions have been held recently with F-35 Joint Strike Fighter engineers to apprise them of recent enhanced powder panel developments for dry bay fire protection.

In addition, under sponsorship of the DoD Joint Technical Coordinating Group on Aircraft Survivability (JTCG/AS), NGP researchers participated in live fire proof-of-concept testing in early FY2002. The tests examined the concept of reactive powder panels that add an energetic backing to any powder panel design to enhance powder delivery effectiveness. Four tests of enhanced powder panels without reactive backing were conducted, demonstrating their capability to prevent dry bay fires in tests involving JP-8 fuel and 12.7mm Armor Piercing Incendiary Projectiles. Figure 18 compares the amount of fire extinguishing powder released from an enhanced powder panel with a commercially available powder panel. Figure 19 shows some images captured from high-speed video demonstrating the fire mitigation capability of enhanced powder panel designs.

Figure 18. Comparison Of Commercial And Enhanced Powder Panel Agent Release In JTCG/AS Dry Bay Fire Extinguishing Testing



Additional examination of NGP enhanced powder panel designs was conducted by the Federal Aviation Administration (FAA). They were interested in the feasibility of using powder panels to prevent commercial aircraft fuselage fires caused by the impact of an uncontained engine rotor blade with flammable fluid lines. Figure 20 shows that impact of the enhanced powder panel by a rotor blade resulted in release of all the fire extinguishing agent, as it prevented a fire ignition. Baseline testing showed that unprotected fuselage areas did indeed result in sustained fires.

Figure 19. Enhanced Powder Panel Fire Mitigation Capability Demonstrated

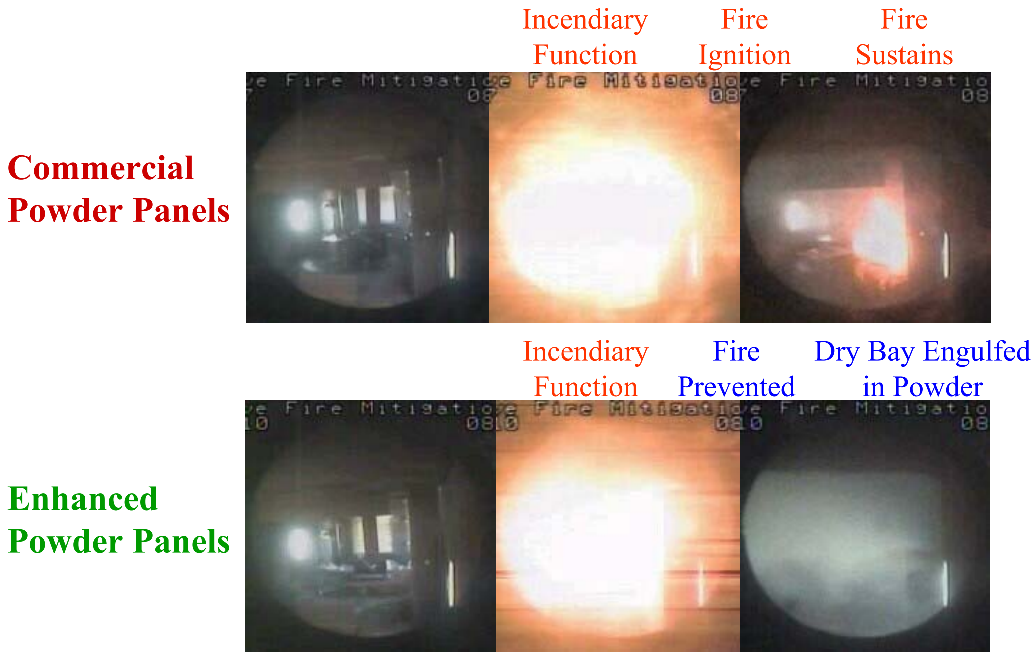


Figure 20. Post-test Remains of Enhanced Powder Panel Showing All Powder Released (Fire Prevented)

In both the JTCG/AS and FAA test programs, the NGP enhanced powder panels showed a vast improvement over current powder panel designs. Fire ignition was prevented in all five tests involving enhanced powder panels. These tests will be documented in the NGP Enhanced Powder Panel Final Report.

Meanwhile, the NGP continues experiments to examine means for effecting:

- Greater powder release into dry bay
- Better dispersion of powder to prevent ignition off-shotline
- Longer powder suspension to prevent fire ignition for longer period of time
- Design flexibility of enhanced powder panels which can be utilized to target weight, durability, and application-specific design goals

Optimization test variables include panel materials and thicknesses, fire extinguishing powder loading (density of powder inserted into a given panel size), rib designs, and the assembly process. The project will conclude with live fire demonstration tests of the optimized powder panels at the Air Force 46th Test Wing Aerospace Vehicle Survivability Facility, Wright-Patterson Air Force Base.

5. Mechanisms of Unwanted Accelerated Burning

In real-scale fire suppression tests, the operators have observed flare-ups of the fire and pressure surges as the agent is applied. If experienced during flight, this could have a negative effect on aircraft survivability.

The cause of this phenomenon appears to be enhanced combustion of vaporizing liquid fuel that mixes with air more efficiently in the turbulence accompanying suppressant delivery. To understand this process, NGP staff analyzed three sets of fire suppression tests, one in an aircraft dry bay and two in large compartments. The three cases varied in the timescale of the suppression events and the geometric configuration of the experiments, yet in all cases a volatile liquid was the fuel. When wood was substituted for the liquid fuel in one of these series, the large pressure fluctuations were not observed.

In the first series of enclosure fires[2] significant fire flare-up and pressure increases were observed for HFC agents, water mist, and hybrid agents involving HFC/powder mixtures. All the deflagrations observed were in the presence of a hot (~550 ^{o}C) ignition source. The investigators suggested that these unwanted burning effects occurred when there was insufficient suppressant to assure quenching and prevention of re-ignition. In this sense, unwanted accelerated burning effects are already embedded in the resulting design equations.

The second case study examined suppression of moderate-sized (~400 kW) heptane pool fires in an enclosure.[3] Figure 21 shows that calculations using the NIST Fire Dynamics Simulator (FDS) show pressure fluctuations similar to the experimental observations. Figure 22 is a snapshot of the simulation showing the fire and temperature-colored velocity field just as an inert suppressant was released from the ceiling of the room.

Figure 21. Comparison of the Room Pressure Measured Experimentally (Left) and That Calculated Using FDS (Right)

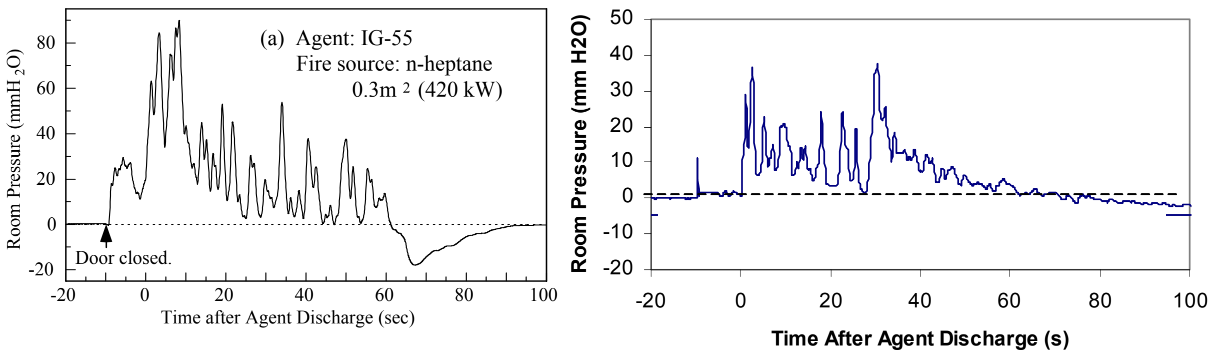
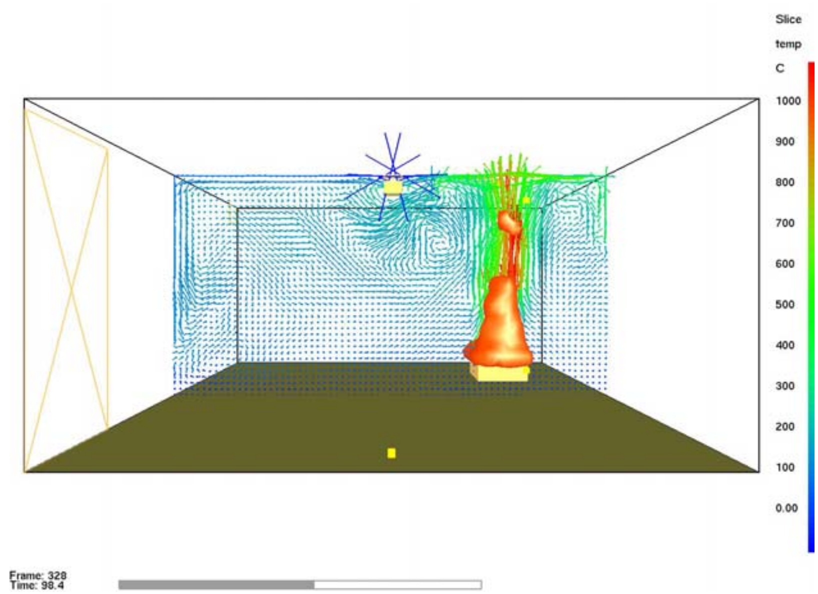


Figure 22. FDS Calculation Showing the Fire and Temperature-Colored Velocity Field of the Suppression of a Heptane Pool-Fire in an Enclosure



The third case was the unanticipated over-pressurization that destroyed a C-130 Wing Leading Edge Dry Bay Test Facility during real-scale fire suppression testing. Six tests previous to the catastrophic event using N_2-pressurized HFC-125 had led to routine suppression results. The seventh test was designed to test the impact of the N_2 used for pressurization on the fire. The N_2 concentration was 0.4% of the cup burner value, an amount that would have little impact on the stability of the fire and certainly would not extinguish the fire. The fire scenario was extremely complex due to the presence of a ballistic round, accompanying shock waves, fuel splashing (two-phase flow), multiple ignition sources (hot shrapnel), etc. To better understand the conditions in the dry bay during fire suppression, an analytic approach was taken to simulate the pressure in the enclosure. Two salient results emerged:

- Only a small difference in the sensible enthalpy release could have caused failure of the fixture and
- The pressure rise is larger for smaller vent sizes (small diameter projectiles).

The most important overall finding from analysis of these three cases is that the over-pressure risk is low unless insufficient amounts of suppressant are applied to a fire. The viability of design equations derived from full-scale tests hinges on the assumption that the tests are representative of the range of actual fire conditions. The fire conditions in full-scale suppression tests should be carefully designed to be worst-case, or else extreme or unanticipated unwanted burning effects may occur in actual applications.

6. Enhancing Engine Nacelle Extinguishment with Intumescent Coatings

Quenching a fire in an engine nacelle requires maintaining a sufficient concentration of agent in the flame zone for a sufficient time interval. This must be accomplished while a forced air flow through the nacelle (to prevent the accumulation of any flammable vapors, and possibly also provide some machinery cooling) serves to sweep the suppressant out the exhaust.

The NGP had pioneered the novel approach of using strategic placement of an intumescent material to reduce the cross sectional area of the nacelle in the event of a fire. This “instant firewall” allows achieving the needed residence time with a smaller amount of suppressant.

Now, a project funded by the Joint Technical Coordinating Group on Aircraft Survivability (JTCG/AS) will demonstrate and optimize the use of these intumescent materials, and identify and evaluate the potential for use on unmanned aerial vehicles, rotorcraft, and other customers needing low-cost protection.

The first phase of the project is already underway, evaluating the expansion ratios and response times of candidate intumescent materials and designs in a mini-nacelle fire test fixture. Successful candidates will then be tested in a full-size mock-up of an X-45 UCAV engine nacelle supplied by Boeing Aerospace, the manufacturer of the X-45 UCAV.

Recent Publications: Improved Suppressant Delivery

(* indicates archival publications)

Yang, J.C., Manzello, S.L., Nyden, M.R., and Connaghan, M.D., “Discharge of CF3I in a Cold Simulated Aircraft Engine Nacelle,” *Proceedings of the 2002 Halon Options Technical Working Conference*, NIST Special Publication 984 (CD), National Institute of Standards and Technology, Gaithersburg, MD, 2002.

*Yang, J.C., Manzello, S.L., Nyden, M.R., Connaghan, M.D., “Cold Discharge of CF_3I in a Simulated Aircraft Engine Nacelle,” *Proc. Seventh International Symposium on Fire Safety Science,* Worcester, MA, June 16-21, 2002.

Dolinar, J., Hudgins, D., and Keyser, D.R.,” F/A-18 E/F Nacelle Simulator Input/Output Boundary Condition Flows,” Report NAWCADPAX/SUM-2002/171, 2002.

Black, A.R. *et al*, "Numerical Predictions and Experimental Results of Air Flow in A Smooth Quarter-Scale Nacelle," Sandia National Lab Report SAND2002-1319, 2002.

DesJardin, P.E., et al., “On the Development of a Subgrid Model for Clutter,” AIAA2002-0984, 40th AIAA Aerospace Sciences Meeting and Exhibit, Reno, NV, 2002.

Black, A.R. et alia: "Numerical Predictions and Experimental Results of Air Flow in A Smooth Quarter-Scale Nacelle", AIAA2002-0856, 40th AIAA Aerospace Sciences Meeting and Exhibit, Reno, NV, 2002

Presser, C., Widmann, J.F., DesJardin, P.E., and Gritzo, L.A., “Homogeneous Turbulent Flow over a Cylinder: Measurement and Numerical Prediction,” AIAA 2002-0905, Am. Inst. Aero. Astro., Washington, DC, 2002.

Presser, C., Widmann, J.F., and Papadopoulos, G., "Liquid Agent Transport Around Solid Obstacles," *Proceedings of the 2002 Halon Options Technical Working Conference*, NIST Special Publication 984 (CD), National Institute of Standards and Technology, Gaithersburg, MD, 2002.

DesJardin, P.E., Presser, C., Disimile, P.J., and Tucker, J.R.., "A Droplet Impact Model for Agent Transport in Engine Nacelles," *Proceedings of the 2002 Halon Options Technical Working Conference*, NIST Special Publication 984 (CD), National Institute of Standards and Technology, Gaithersburg, MD, 2002.

Presser, C., Widmann, J.F., and Papadopoulos, G., "PIV Measurements of Droplet Transport in a Homogeneous Turbulent Flow over a Cylinder," 41st AIAA Aerospace Sciences Meeting & Exhibit, Reno, NV, accepted, 2003.

Presser, C., Papadopoulos, G., and Widmann, J.F., "Droplet_laden Homogeneous Turbulent Flow past Heated and Unheated Cylinders," 4th ASME/JSME Joint Fluids Engineering Conf., Honolulu, Hawaii, accepted, 2003.

Cyphers, D. C., Frederick, S. A., and Haas, J. P., "Enhanced Powder Panels," *Proceedings of the 2002 Halon Options Technical Working Conference*, NIST Special Publication 984 (CD), National Institute of Standards and Technology, Gaithersburg, MD, 2002.

C. VIABILITY OF NEW SUPPRESSANT TECHNOLOGIES

1. Benefit Assessment of Fire Protection System Changes

Both objective cost factors and subjective value factors must be considered when making a decision on whether and how to retrofit a fire suppression system. Accordingly, the NGP has developed a methodology (Figure 23) to quantify a fire suppression technology by its total, life cycle cost and to enable superimposing on this a subjective value system. The purpose is to provide a means of identifying a halon alternative agent/system option that provides the best cost-of-ownership value to specific aircraft customers over the operating lifetime of their platform.

The methodology determines the net cost of the fire suppression system: the cost of the system (which is a function of system size/weight) minus the cost savings provided by the system (which are a function of extinguishant effectiveness and result in aircraft saved). The developed examples:

- compare an existing halon 1301 system and a system of equivalent and altered performance using an off-the-shelf-alternative, HFC-125;
- include both legacy platforms (for decision makers who must consider retrofit costs for existing platforms) and future platforms (for decision makers currently designing new platforms); and
- apply to engine nacelle applications for representative and rotary wing aircraft in addition to the cargo and fighter aircraft present in last year's Annual Report.

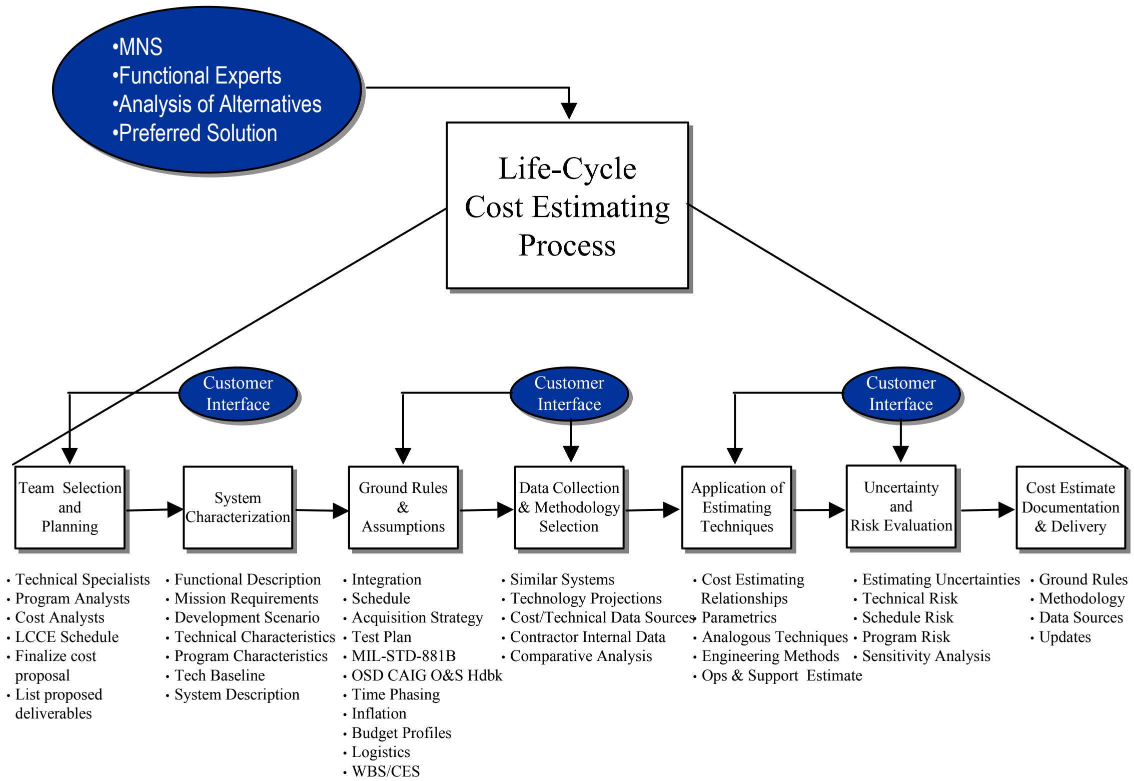
In all cases, the benefit of having either fire protection system substantially outweighs its cost, and the difference in total cost of the two systems is modest compared to the total cost of owning and operating the aircraft.

Using the rotary wing aircraft fire suppression system cost and cost savings information, the following conclusions were reached:

- Even if the rotary-wing aircraft fire suppression system only saved eight percent of the aircraft assets it was designed to protect, the benefit (assets saved) would still be greater than the cost of the fire suppression system.
- Using a conservative value of 60 percent fire suppression system effectiveness, a system cost of up to $307K per aircraft could be justified. Note that the current as well as forecast fire suppression system costs per aircraft are an order of magnitude less than this value. This value is a breakpoint between system cost and benefit.

The U.S. Army is now using this methodology, in concert with the baseline cases for halon 1301 and HFC-125, as part of their evaluation of three additional fire suppression alternatives (CF_3I, Novec 1230, and gas generators) for the Comanche rotorcraft. This same model will be used by the Army Chinook, Apache and Blackhawk rotorcraft Programs for their retrofit selection criteria.

Figure 23. Life-Cycle Cost Estimating Process



2. Suppressant Concentration Measurement for Real-scale Fire Tests

A user's guide to the Differential Infrared Rapid Agent Concentration Sensor (DIRRACS-2) is in final preparation. It contains a description of the device, its potential for use in both fire tests and system certification, detailed operating procedures, components list, etc. Before release the Guide will be evaluated by an inexperienced user to promote its utility by the engineering community.

Recent Publications: Viability of New Suppressant Technologies

Bennett, J.M. and M.L. Kolleck, "Cost Analysis of Fire Suppression Systems," *Proceedings of the 2002 Halon Options Technical Working Conference*, NIST Special Publication 984 (CD), National Institute of Standards and Technology, Gaithersburg, MD, 2002.

III. INDEPENDENT PROGRAM ASSESSMENT

At the suggestion of SERDP management, the NGP Technical Program Manager commissioned an Independent Review Panel (IRP) to assess progress to date and to recommend actions that could enhance the prospects for the NGP program to result in viable and practical alternative fire suppression technologies with NGP resources remaining at or near currently projected levels.

The IRP conclusions are that:

- The NGP program as presently structured and as modified to date is technically strong and targeted realistically.
- The NGP program as presently structured is resulting in research output in quality and quantity far above what is considered typical by the review panel for the resources available and applied.
- Much of the research output has high potential for near term use in design of fire protection systems for aircraft.
- With relatively modest adjustments, the utility of the NGP research findings can be further enhanced.

They then offered 19 specific recommendations, all of which have been incorporated into the NGP.

The final report of the IRP is attached as Appendix B and the implementation response by the NGP is attached as Appendix C.

IV. 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. Thus, for other applications or should suppressant requirements change for fire suppression in aircraft, future investigators will have the benefit of the current program findings.
- 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 efforts 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.

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 number of concurrent projects, which peaked at 23, has decreased to 12 in FY2001 and to 5 in FY2002. Maintaining an active presence in broader meetings is thus an essential factor in NGP success. The NGP has recently enabled the continuation of the annual Halon Options Technical Working Conference and will work to keep this as a principal forum for communication and collaboration. The NGP will seek to enhance the participation in its autumn Annual Research Meeting, inviting past investigators and other experts. It is hoped that these two meetings will continue to broaden the perspective and stimulate the innovation of the NGP investigators.

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.

References

[1] *Technology Development Plan for Alternatives to Ozone-depleting Substances for Weapons Systems Use; Final Report (TDP)*, Office of the Deputy Undersecretary of Defense (Science and Technology)/Weapons Systems, 1998.

[2] Maranghides, A., and Sheinson, R.S., "Deflagration Induced During Total Flooding Halon Replacement Suppression," *Fire Safety Science-Proceedings of the Sixth International Symposium*, IAFSS, p.1199, 2000.

[3] Kashiwagi, H., Oshikawa, S., Yui, J., Fujii, M., Kitano, J., Shiga, A., and Saso, Y., "Effect of Fire Size on Suppression Characteristics of Halon Replacement Total-Flooding Systems," *Proceedings of the 2001 Halon Options Technical Working Conference*, Albuquerque, NM, pp. 272-281, 2001, and companion report, "Report of the Research Committee for Establishment of Safety Standards on Halon Replacement Agents," Fire and Disaster Management Agency and the Japanese Fire Equipment Inspection Institute, 2000.

APPENDIX A. NGP PROJECTS

The system for the identifier codes for the projects was developed at the beginning of the NGP and follows the now outdated program structure in the original NGP Strategy Document, which is available at the NGP web site. For current use, the important information is located following the second slash (*e.g.*, 3A/1/**789**). In this example, the project was funded in fiscal years 1997, 1998, and 1999.

A. SUPPRESSANT SCREENING TESTS

3A/1/789. DISPERSED LIQUID AGENT FIRE SUPPRESSION SCREEN
Principal Investigator: Jiann C. Yang, NIST

3A/2/890. TRANSIENT-APPLICATION-RECIRCULATING-POOL-FIRE AGENT EFFECTIVENESS SCREEN
Principal Investigator: William Grosshandler, NIST

3B/1/89. TOXICOLOGICAL ASSESSMENT OF HUMAN HEALTH CONSEQUENCES ASSOCIATED WITH INHALATION OF HALON REPLACEMENT CHEMICALS
Principal Investigator: Darol Dodd, AFRL

3B/2/8. AGENT COMPATIBILITY WITH PEOPLE, MATERIALS AND THE ENVIRONMENT
Principal Investigators: Marc Nyden, NIST; Stephanie Skaggs, Universal Technical Services

B. NEW FLAME SUPPRESSION CHEMISTRY

2A/1/7890, /2/890. MECHANISMS OF ULTRA-HIGH EFFICIENCY CHEMICAL SUPPRESSANTS
Principal Investigators: James Fleming, NRL; Kevin McNesby, ARL

4D/2/7. IDENTIFICATION AND PROOF TESTING OF NEW TOTAL FLOODING AGENTS
Principal Investigator: Robert E. Tapscott, NMERI
COR: Andrzej Miziolek, ARL

4B/1/8,4D/15/01. TROPODEGRADABLE BROMOCARBON EXTINGUISHANTS
Principal Investigator: J. Douglas Mather, NMERI
COR: Ronald Sheinson, NRL

4B/2/8,4D/3/7. FLAME INHIBITION BY PHOSPHORUS-CONTAINING COMPOUNDS
Principal Investigator: Elizabeth M. Fisher, Cornell University
COR: Andrzej Miziolek, ARL

4D/14/1. FLUOROALKYL PHOSPHOROUS COMPOUNDS
Principal Investigator: Douglas Mather, NMERI

4C/1/890. SUPER-EFFECTIVE THERMAL SUPPRESSANTS
Principal Investigator: William Pitts, NIST

4D/13/1. EFFECTIVE, NON-TOXIC METALLIC FIRE SUPPRESSANTS
Principal Investigator: Gregory Linteris, NIST

4B/3/8901. ENVIRONMENTAL IMPACT OF NEW CHEMICAL AGENTS FOR FIRE SUPPRESSION
Principal Investigators: Robert Huie and Marc Nyden, NIST; Andrzej Miziolek, ARL

4B/4/01. PERFORMANCE DATA ON COLD TEMPERATURE DISPERSION OF CF_3I AND ON MATERIALS COMPATIBILITY WITH CF_3I
Principal Investigator: Jiann Yang, NIST

4B/5/012. ALTERNATIVE SUPPRESSANT CHEMICALS
Principal Investigator: Richard Gann, NIST

4B/6/2 ENVIRONMENTALLY ACCEPTABLE SUPPRESSANTS
Principal Investigator: Douglas Mather, NMERI
Scientific Officer: Richard Gann, NIST

C. NEW AND IMPROVED AEROSOL SUPPRESSANTS

2B/1/78901. SUPPRESSION EFFECTIVENESS OF AEROSOLS AND PARTICLES
Principal Investigator: Ronald Sheinson, NRL

2B/2/89. DROPLET INTERACTIONS WITH HOT SURFACES
Principal Investigator: Yudaya Sivathanu, En'Urga, Inc.
COR: William Grosshandler

2B/3/89. TECHNICAL SUPPORT FOR THE STUDY OF DROPLET INTERACTIONS WITH HOT SURFACES
Principal Investigator: Jiann Yang, NIST

4A/1/890. POWDER-MATRIX SYSTEMS
Principal Investigators: Gregory Linteris, NIST

4D/1/7.	ELECTRICALLY CHARGED WATER MISTS FOR EXTINGUISHING FIRES	
	Principal Investigator:	Charles H. Berman, Titan Corp.
	COR:	Ronald Sheinson, NRL
4D/4/7.	DEVELOPMENT OF A SELF ATOMIZING FORM OF WATER	
	Principal Investigator:	Richard K. Lyon, EER, Inc.
	COR:	William Grosshandler, NIST
4D/7/8.	DENDRITIC POLYMERS AS FIRE SUPPRESSANTS	
	Principal Investigator:	Nora Beck Tan, ARL

D. IMPROVED SUPPRESSANT DELIVERY

2C/1/789.	STABILIZATION OF FLAMES	
	Principal Investigator:	Vincent Belovich, AFRL
4D/6/8.	DUAL AGENT APPROACH TO CREW COMPARTMENT EXPLOSION SUPPRESSION	
	Principal Investigator:	Douglas Dierdorf, ARA Corp.
	COR:	Andrzej Miziolek, ARL
4D/17/0.	A METHOD FOR EXTINGUISHING ENGINE NACELLE FIRES BY USE OF INTUMESCENT COATINGS	
	Principal Investigator:	Leonard Truett, Eglin AFB
5A/1/012.	PARAMETRIC INVESTIGATION OF DROPLET ATOMIZATION AND DISPERSION OF LIQUID FIRE SUPPRESSANTS	
	Principal Investigator:	Cary Presser, NIST
5D/1/901.	ADVANCED PROPELLANT/ADDITIVE DEVELOPMENT FOR GAS GENERATORS	
	Principal Investigators:	Gary Holland, General Dynamics; Russell Reed, NAWC-WPNS
	COR:	Richard Gann, NIST
5E/1/12.	ENHANCED POWDER PANELS	
	Principal Investigator:	Dan Cypher, Skyward, Inc.
	COR:	Martin Lentz, Eglin AFB
6A/1/012.	FIRE SUPPRESSANT DYNAMICS IN CLUTTERED WEAPONS SYSTEM COMPARTMENTS	
	Principal Investigator:	David Keyser, NAVAIR

6B/1/89. SUPPRESSANT FLOW THROUGH PIPING
Principal Investigator: John Chen, Lehigh University
COR: William Grosshandler, NIST

6C/1/1. MECHANISM OF UNWANTED ACCELERATED BURNING
Principal Investigator: Anthony Hamins, NIST

E. VIABILITY OF NEW SUPPRESSANT TECHNOLOGIES

1A/1/78. DEVELOPMENT OF MODEL FIRES FOR FIRE SUPPRESSION RESEARCH
Principal Investigator: Anthony Finnerty, ARL
Associate Investigators: James Tucker, AFRL and Juan Vitali, ARA; Ronald Sheinson, NRL

1C/1/8901. RELATIVE BENEFIT ASSESSMENT OF FIRE PROTECTION SYSTEM CHANGES
Principal Investigator: Michael Bennett, Eglin AFB

3C/1/789. LASER-BASED INSTRUMENTATION FOR REAL-TIME, IN-SITU MEASUREMENTS OF COMBUSTIBLE GASES, COMBUSTION BY-PRODUCTS, AND SUPPRESSANT CONCENTRATIONS
Principal investigator: Kevin McNesby, ARL

3C/2/890. FAST RESPONSE SPECIES CHARACTERIZATION DURING FLAME SUPPRESSION
Principal Investigator: George Mulholland, NIST

F. FUEL TANK INERTION

5C/1/9. ACTIVE SUPPRESSION FOR FUEL TANK EXPLOSIONS
Principal Investigator: Leonard Truett, Eglin AFB

REPORT OF THE 2001 INDEPENDENT REVIEW PANEL

ON THE

NEXT GENERATION FIRE SUPPRESSION TECHNOLOGY PROGRAM (NGP)

February, 2002

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REPORT OF THE 2001 INDEPENDENT REVIEW PANEL (IRP) ON THE NEXT GENERATION FIRE SUPPRESSION TECHNOLOGY PROGRAM (NGP)

This report summarizes the general comments and recommendations of the IRP. For comments and recommendations for individual NGP projects, see the attached Appendix A.

INTRODUCTION

The Department of Defense (DoD) Strategic Environmental Research and Development Program (SERDP) has been supporting a multi-year interagency effort to develop new fire-suppression chemicals, techniques, and systems to replace halon fire extinguishing agents in DoD weapon systems. The SERDP initiative, the Next Generation Fire Suppression Technology Program (NGP), targets the halons because of their recognized high ozone depletion potential and the resultant adverse influence on stratospheric ozone.

An Independent Review Panel (IRP) was commissioned by the NGP Technical Program Manager at the suggestion of SERDP to assess progress to date in the NGP program and to recommend changes to the program or actions that could enhance the prospects for the NGP program to result in viable and practical alternative fire-suppression technologies with NGP resources remaining at or near currently projected levels. The IRP convened coincident with the NGP annual review meeting on December 18-19, 2001. The IRP encompassed an array of expertise and experience from university, government, and industry environments.

This report summarizes the findings of the IRP. This NGP program evaluation was based on the present research status as seen as a snapshot through the annual review meeting in the context of the history of the research, the SERDP goals, and the collective expertise imbedded in the IRP.

BACKGROUND

Research to find alternative technologies to replace halon fire extinguishing agents has been but one of many efforts over the past 15 years to reduce or eliminate emissions of substances with high ozone depletion potential. However, the specific requirements associated with fire-extinguishing agents for military weapons systems have proven refractory in many applications. These applications are characterized by the unusual convergence of three issues:

1) Threat of immediate loss of life due to proximity of fire to personnel and flight critical systems;
2) High-energy environment associated with substantive quantities of fuel and flammable fluids, weapon explosives and propellants, and kinetic energy levels of the weapons platform along with threats and targets; and
3) Severe retrofit constraints due to weight and space limitations on legacy systems (especially true of airborne systems).

In addition to these major considerations, there are issues of replacement agent toxicity and corrosivity, material compatibility, cost, and agent effectiveness throughout the operating environment. With alternate technologies such as solid gas generators and powder panels, the same or similar issues need to be considered.

The original NGP goal was to "develop and demonstrate, by 2004, retrofitable, economically feasible, environmentally acceptable and user-friendly process, techniques, and technologies that meet the operational requirements currently satisfied by halon 1301 systems in aircraft, ships, land combat vehicles, and critical mission support facilities." This program was originally expected to be an 8-year program with funding peaking at about $7 million per annum. In actuality, the funding is presently running at about $1 million per year with a slightly protracted time duration. This reduction has forced considerable contraction in the goals that would be realistically attainable. The present program focus is now almost exclusively on solutions for aircraft fire protection, especially for engine nacelles.

In both U.S. military and commercial aircraft, the dominant type of engine nacelle fire protection system involves the high rate discharge of halon 1301. While there have been a limited number of system designs with other agents like CB, halon 1211, halon 1011, and halon 2402 in certain aircraft, halon 1301 by far comprises the dominant portion of the airborne inventory for nacelle applications. "High rate discharge" is aerospace terminology referring to the design requirements, which specify that upon discharge, the extinguishing gas sensors throughout the nacelle must simultaneously indicate a 6 % halon 1301 concentration for a one-half second interval. Historically, the high rate systems replaced less efficient systems involving longer duration but lower rate agent discharge into an engine compartment. For the last half century, halon 1301 has filled the aircraft engine nacelle niche because of its properties of low toxicity, high effectiveness, cleanliness, and high volatility for low temperature operations. To date, no "drop-in" replacements have been deployed on an equivalent weight or volume basis. While there has been successful testing and deployment of the F/A-18E/F, V-22 and F-22 with HFC-125, modest weight penalties and changes to the distribution systems, compared to halon 1301, have been accepted. Some helicopters are also considering HFC-125; however, some of these replacements involve substituting a two-shot halon 1301 system with a single shot HFC-125 system to accommodate the larger quantities of HFC-125 needed to reliably extinguish an engine nacelle fire.

Because aviation has been exempted from the environmental ban on usage of halon 1301 so long as the agent obtained from the bank of existing stockpiles, there has been a tendency in some quarters to dismiss the earlier urgency attendant on halon replacement research. The present quasi-equilibrium with regard to use of the halon bank is susceptible to rapid upset from any number of circumstances. An example is the present controversy on whether CF_3I should be immediately substituted for halon 1301 in F-16 wing tank inerting applications. (The F-16 now discharges halon 1301 on each combat sortie to protect the fuel tanks from fire or explosions produced by ballistic damage.) In starts and stops, the justifications for continued use of halon 1301 in aerospace applications appear to be becoming more arguable, and the U.S. Environmental Protection Agency support of the exemption is contingent on credible efforts to find alternative technologies or chemicals.

DISCUSSION

The present revised NGP goal is to "develop and demonstrate technology for economically feasible, environmentally acceptable and user-safe processes, techniques, and technologies that meet the operational requirements currently satisfied by halon 1301 in aircraft." This goal is considerably scaled back from the initial NGP goal quoted in the background section of this report.

The IRP observed that not only are the applications reduced from ships, aircraft, ground vehicles, and ground installations to halon 1301 systems in aircraft but also the comprehensiveness of the approach to nacelle installations has been affected by the budget constraints. The IRP observed that toxicity testing has been all but eliminated, that large-scale demonstrations have been minimized, and that the synthesis and screening of new chemicals is at a barely sustainable level.

The IRP believes that the remaining core of research, if brought to conclusion, can provide a product that will enable successful substitutions for halon 1301 in aircraft nacelle applications. This belief assumes the research findings will be translated into useable heuristics for design and test personnel in government installations and in the aerospace industry. The IRP cautions that the research efforts omitted or dropped comprise an "IOU" that is likely to become due in the future. Halon 1301 substitutes that are effective in firefighting but less desirable from standpoints of toxicity and material compatibility may result in future costs associated with special handling requirements, revised maintenance procedures, and modified engine system component specifications. Reduction of full-scale demonstration testing will lead to more costly weapon system platform development and test programs to obtain the actual fire extinguisher system performance that the research program demonstrates as attainable.

During the annual research meeting, the IRP was briefed by the principal investigator of each active NGP project and had adequate time and opportunity to ask any pertinent questions. The IRP's specific comments and recommendations on each project are documented in the Appendix to this report.

The NGP projects included those seeking and evaluating new agents including tropodegradable bromocarbons and phosphorus-containing compounds. Also presented were experimental and modeling research on metallic fire suppressants (both transition metal and alkali metals) in aerosol and powder form, research on powder panels and on solid propellant gas generators, and life-cycle system cost comparisons between various alternate agents and halon 1301 in given aircraft model fleets. Finally, a series of projects were briefed that dealt with modeling and experimental investigations of atomization and dispersion of aerosols in nacelle type, clutter-filled, ventilated enclosures. These projects were especially relevant to the behavior of higher boiling point replacement agents in cold environments.

It is hard to imagine any viable halon 1301 replacement with lower molecular weight or equivalent volatility. Consequently, the issues of dispersion and evaporation of higher boiling point liquids gets elevated in importance. Major associated issues are: vapor pressure as a function of temperature, droplet evaporation times, droplet penetration and residence in fire zones, droplet impingement on surfaces, and localized liquid accumulation. These factors all come into play in development of heuristics for system design.

CONCLUSIONS

The NGP is an excellent example of a government-managed research program. Information developed here is likely to be used for decades. This type of research should be managed by the government with a large government laboratory role and should not be left to private industry alone, although private industry can play an important role. Some of the projects under this program may appear to be interesting but not necessarily critical research, but that is not the case. This program needs this fundamental science to solve an important real-world problem, and this scientific work is being done nowhere else. This program is a well balanced blend of basic scientific study and hard headed application. Managers and participants have made excellent progress with limited funds, and should be recognized for their efforts.

The Independent Review Panel unanimously reached the following general conclusions:

1) The NGP program as presently structured and as modified to date is technically strong and targeted realistically.
2) The NGP program as presently structured is resulting in research output in quality and quantity exceeding what is considered typical by the review panel for the resources available and applied.
3) Much of the research output has high potential for near-term use in design of fire protection systems for aircraft.
4) With relatively modest adjustments, the review panel concludes that the utility of the NGP research findings can be further enhanced.

The review panel is optimistic that the NGP research is elucidating important mechanisms and principles involved in fire suppression. The present NGP emphasis can be considered as focused on evaluation of chemical candidates and research on agent delivery. The review panel has used these conclusions as the basis from which to derive recommendations that would facilitate eventual use of the NGP research findings in practical aerospace applications.

GENERAL RECOMMENDATIONS

The Independent Review Panel presents three major recommendations:

1) Establish a separate project on re-ignition or elevate this issue within existing projects. In engine nacelle fire extinguishing systems, relight of fire after agent delivery has been a continuing design, test, and evaluation problem. Experience has shown that even the delivery of air through an agent distribution system can sometimes blow out the fire but rapid re-ignition is likely to follow.

2) Expand delivery and dispersion research to include additional high boiling point compounds in the individual research projects. These compounds could include both phosphorus-containing chemicals and tropodegradable bromocarbons.

3) Request summation sheets on "Lessons Learned" from the principal investigators to serve as a starting point for future system design heuristics. These summation sheets should cover the best understanding of the knowledge gained and how it might apply to both future research efforts and design of fire protection systems. Both positive and negative results should be reported.

The review panel presents three secondary recommendations:

1) Prepare a technical information package to expedite hand-off of the portable Differential Infrared Agent Concentration Sensor to government agencies, analyzer vendors, and aerospace manufacturers involved with aircraft extinguishing system certification and testing. There is a dire need for a system to replace the traditional analyzer used for airborne applications. If possible, make this system available to at least one of the large-scale engine nacelle test programs planned for 2002. (FAA engine nacelle testing at the FAA Technical Center {Doug Ingerson}, and the Army engine nacelle testing at AFRL {Jim Tucker}.)

2) Address directly the issue of gas-phase vapor loading from dispersed aerosols of higher boiling point extinguishing agents. At issue are droplet evaporation times, residence times, and saturation vapor pressures. Also at issue is whether fine droplets behave as a vapor in flame suppression. This is particularly important to evaluators because it is frequently cited by advocates of high boiling point fluids in response to expressed concerns about low-temperature performance.

3) Initiate an interim NGP report as early as FY2002 in the form of a compendium of heuristic technical rules capable of being understood and utilized by extinguishing system design and test engineers. It is recommended the NGP final report should be designed to serve as an interface that could convey the research findings to the user community in practical form. Insure that both positive and negative information is included.

REPORT OF THE 2001 INDEPENDENT REVIEW PANEL ON THE NEXT GENERATION FIRE SUPPRESSION TECHNOLOGY PROGRAM (NGP)

APPENDIX

This appendix summarizes the comments and recommendations of the IRP for each individual NPG project. For general comments, see the body of the report

4B/5/01 Assessment of Search for Alternative Chemicals

This work is a central part of the program. Although no cure-all has been identified, some potential candidates have been and the search should continue. For the long term, this may well be the most valuable or one of the most valuable elements of the NPG program. If any true drop-in halon replacement "agent" is ever found it is likely to come from this or related programs. The attributes sought and evaluated make sense. The broadness of the search is well justified. It is not clear how the list is winnowed.

4D/14/1 Fluoroalkyl Phosphorous Compounds

It is essential that this work be completed. Most of the potential candidates appear to have relatively high boiling points. If funding allows, related compounds with lower boiling point materials should be considered.

4D/15/01 Tropodegradable Bromocarbon Extinguishants

It is essential that this work be completed Drawing on the medical database is a valuable innovation. The "tropodegradable" concept is a very attractive method of gaining the benefits of Br and related compounds without the ODS penalties. The expense of some compounds needs to be reconsidered. Although the cost of some of the compounds may stress the R&D budget, researchers should be aware that aircraft programs frequently pay premiums in excess of $1,000 / pound / aircraft to acquire lighter-weight technologies.

4B/3/801 Environmental Impact of New Chemical Agents for Fire Suppression

This project is developing basic information and procedures that support and are essential for many of the other projects. It provides a rational basis for avoiding research on alternate suppressants that in the end would have to be rejected on environmental grounds. The project is exemplary in that the modeling is done in a manner consistent with experimental findings.

4D/13/1 Effective, Non-Toxic Metallic Fire Suppressants

This work appeared extremely thorough, even though the results are discouraging in light of high initial expectations. The IRP recommends enough additional research in this area be done to provide a more complete explanation on why the limiting behaviors exist. The IRP believes further work should be done with light scattering on additional metallic compounds to see if the condensation phenomena observed with iron compounds are generic to other transition metals. The IRP further suggests thermophoretic sampling and chemical analysis of the aerosols.

2B/1/78901 Suppression Effectiveness of Aerosols and Particles

The IRP viewed this project as having an excellent mix of modeling and experiment. The IRP believes this work should be expanded to include some of the higher boiling point replacement agents from the other projects as well as solutions of alkali metal compounds in some of the higher boiling point liquids. It may be possible to substitute one or more of the high boiling point liquids for water in the water mist work, gain the benefits of water mist and some chemical activity, yet avoid the problems with water. Some simple corrosion screening analysis or simple corrosion screening test for the dry powder aerosols, similar to the environmental screening of 4B/3/8901, should be considered.

1C/1/8901 Relative Benefit Assessment of Fire Protection System Changes

The IRP believes the information developed in this project is essential to implementing alternate compounds and technologies into the military aircraft fleet. The IRP believes that rather than expanding the project into UAV's, it is more important to continue cost comparisons for a targeted model with a view to getting estimates for an optimized halon 1301 system, a CF_3I system, and a gas generator system. Note that at least some of the UAV programs are based on providing no fire protection systems.

5E/1/1 Enhanced Powder Panels

The IRP found the powder panel project an interesting approach to a passive system for dry bay protection. Because of the complexity of dry bay ignition phenomena under live fire conditions and the many variables involved, the IRP does not consider it feasible to demonstrate a developed form of this technology within the time frame remaining for the NGP program. The program would have been stronger if past history of an older version of this technology were better integrated. Although the passive discharge principle on which this project is based is attractive, it is potentially vulnerable to undetected passive failure, hidden corrosion/damage of basic structure, and performance variation based on the impact area, the energy of the ballistic round, etc. The IRP recommends against renewing this program after the current contract phase ends.

6C/1/1 Mechanism of Unwanted Accelerated Burning

The IRP believes the burning acceleration observed during the application of suppressants can be of pertinent interest in relation to the mechanisms by which the suppressants act on combustion. To date, the phenomena seem to be evidenced more in the suppression of pool fires than in nacelle type installations. Nevertheless, this evidence of burning enhancement by physical mixing from the suppressant's addition will be of use in planning future experiments on suppressant effectiveness. This study has the potential for significantly increasing the effectiveness of fire suppression systems.

The feasibility of verifying the current hypotheses using one or more of the scheduled 2002 engine nacelle tests (the FAA engine nacelle testing at the FAA Technical Center {Doug Ingerson} and the Army engine nacelle testing at AFRL {Jim Tucker}) should be considered.

5D/1/901 Advanced Propellant/Additive Development for Gas Generators

The IRP view is that past experience with test and evaluation of gas generators as candidates for engine nacelle applications has been poor due to high temperatures of the generator products, the difficulties in cleaning the residue, and the costs associated with periodic (life-limited) replacement of the pyrotechnics. Relight has also been a dominant issue in all past nacelle tests. The IRP believes the new propellant formulations show clear performance benefits over the older formulations, and that the hybrid devices involved in this project demonstrate clear possibilities to overcome the past problems with gas generators.

The IRP recommends:

a) Further work on the hybrid devices with effort devoted to flame suppression mechanisms and relight susceptibility.

b) Emphasis on design concepts to minimize the periodic replacement costs of the pyrotechnic elements.

c) Verification testing to show that “Cooled Soaked” CF_3I hybrids (or other high-boiling "agents") will perform well at low temperatures.

d) Generation of chamber pressure and burning time variation with temperature for the all the propellants being considered. In older propellants, peak chamber pressure variations of 4 to 1 over a 135 °F temperature range were reported.

4B/4/01 Performance Data on Cold Temperature Dispersion of CF_3I and on Materials Compatibility with CF_3I

The IRP considers this work invaluable and recommends that the work be augmented to include additional high boiling point candidates from the other projects. The IRP would like to see useful heuristics from this project relating agent volatility and drop size distribution to vapor phase loading during droplet dispersion. One should consider re-naming this project “Low

Temperature Performance of High Boiling Point Agents" to re-focus the attention of both the researchers and the audience interested in more general results.

The IRP briefing contained no reference to the material compatibility work. The status of the material compatibility tasks needs to be clarified.

6A/1/0 Fire Suppressant Dynamics in the Fire Compartment

The presented work appears to be a valuable attempt to develop computer sub models that could accurately represent small-scale clutter and spray phenomena for use in a larger grid scale physics-based computer code. However, the IRP believes the project should be restructured and focused to also use the computer capability to develop heuristics that can be applied in practice rather than use the project exclusively as a vehicle for developing the computer code as the end product. Researchers are encouraged to keep in mind the multiple potential applications for the results of this project:

a) Better scientific understanding of the phenomena (Research)

b) Guidance for vent and distribution configurations in future tests. (Test)

c) Potential for future design using a simplified model. (Product Design)

5A/1/01 Parametric Investigation of Droplet Atomization and Dispersion of Liquid Fire Suppressants

The IRP believes the experimental work is valuable for characterizing droplet behavior in flow through a clutter-filled environment.

IRP recommends:

a) The addition of at least one additional liquid test candidate to the project with a lower boiling point than the present two test liquids.

b) Insure that the size of the droplets tested covers the range of sizes expected in normal discharge.

c) If warranted, recommend modifications to the distribution system, based on the results of this study.

Note: Determining realistic droplet size may become a difficult problem considering the variation in "Agent" characteristics, bottle pressure variations as a function of temperature, and discharge nozzle variations. If performance is found to be highly dependent on size, and if size is found to be highly variable, then this program has discovered a valuable truth, but the implications could be serious.

APPENDIX C. RESPONSE TO RECOMMENDATIONS OF THE 2001 NGP INDEPENDENT REVIEW PANEL (IRP)

	#	Recommendation	Response
1	General, 1	Establish a separate project on re-ignition or elevate this issue within existing projects. In engine nacelle fire extinguishing systems, relight of fire after agent delivery has been a continuing design, test, and evaluation problem. Experience has shown that even the delivery of air through an agent distribution system can sometimes blow out the fire but rapid re-ignition is likely to follow.	A project in this area will be funded in FY2003.
2	General, 2	Expand delivery and dispersion research to include additional high boiling point compounds in the individual research projects. These compounds could include both phosphorus-containing chemicals and tropodegradable bromocarbons.	Technically, the issue is whether delivery and dispersion effectiveness fall off as boiling point increases. Generic high boiling compounds have been added to 4B/4 and 5A/1 in FY2002 and will be considered in 6A/1 as a parametric input.
3	General, 3	Request summation sheets on "Lessons Learned" from the principal investigators to serve as a starting point for future system design heuristics. These summation sheets should cover the best understanding of the knowledge gained and how it might apply to both future research efforts and design of fire protection systems. Both positive and negative results should be reported.	Using FY2003 funds, members of the TCC will review the output of prior projects and extract Lessons Learned from them. The Principal Investigators of current projects will be asked to do the same for their ongoing work. The Technical Program Manager will then fashion a living report from the NGP.
4	Secondary 1	Prepare a technical information package to expedite hand-off of the portable Differential Infrared Agent Concentration Sensor to government agencies, analyzer vendors, and aerospace manufacturers involved with aircraft extinguishing system certification and testing to replace the traditional analyzer used for airborne applications. If possible, make this system available to at least one of the large-scale engine nacelle test programs planned for 2002.	Funds were re-programmed in FY2002 to prepare the package. The prototype system will be made available to at least one of the large-scale engine nacelle test programs planned for 2002-2003, if "training" staff is available.
5	Secondary, 2	Address directly the issue of gas-phase vapor loading from dispersed aerosols of higher boiling point extinguishing agents. At issue are droplet evaporation times, residence times, and saturation vapor pressures. Also at issue is whether fine droplets behave as a vapor in flame suppression. This is particularly important to evaluators because it is frequently cited by advocates of high boiling point fluids in response to expressed concerns about low-temperature performance.	This will be done using FY2003 funds.

	#	Recommendation	Response
6	Secondary, 3	Initiate an interim NGP report as early as FY2002 in the form of a compendium of heuristic technical rules capable of being understood and utilized by extinguishing system design and test engineers. It is recommended the NGP final report should be designed to serve as an interface that could convey the research findings to the user community in practical form. Insure that both positive and negative information is included.	See response to General Recommendation 3. The NGP Final Report will have a section devoted to this set of Program output.
7	4B/5/012 Assessment of Search for Alternate Chemicals	The search should continue. It is not clear how the list is winnowed.	The project is projected to continue until all the likely chemical families have been considered. The approaches to reducing the list of families and of chemicals within a family are explicit in NIST Technical Note 1443.
8	4D/14/1 Fluoroalkyl Phosphorus Compounds	If funding allows, compounds with lower boiling point materials should be considered.	We are already looking for low boiling compounds using FY2002 funds. If the precepts for identifying these are shown to be valid and if lower boiling compounds are possible, then the project will be extended.
9	4D/15/01 Tropodegradable Bromocarbon Extinguishants	The expense of some compounds needs to be reconsidered. Although the cost of some of the compounds may stress the R&D budget, researchers should be aware that aircraft programs frequently pay premiums in excess of $1,000 / pound / aircraft to acquire lighter-weight technologies.	Cost is not an issue in looking at possible compounds since the eventual price reduction from commercialized synthesis is impossible to predict. At times, however, we have had difficulty finding someone to synthesize some of the "designer" compounds.
10	4B/3/801 Environmental Impact of New Chemical Agents for Fire Suppression	Continue.	At present, this work has produced guidance applicable to volatile halogenated compounds. Rather than pursue chemical families systematically and sequentially, further work will be applied as needed to compounds for which the magnitudes of atmospheric and ground effects are in question.
11	4D/13/1 Effective, Non-Toxic Metallic Fire Suppressants	The IRP recommends enough additional research in this area be done to provide a more complete explanation on why the limiting behaviors exist. The IRP believes further work should be done with light scattering on additional metallic compounds to see if the condensation phenomena observed with iron compounds are generic to other transition metals. The IRP further suggests thermophoretic sampling and chemical analysis of the aerosols.	The recent experimental work supports the particle-formation hypothesis for the confounding behavior. In FY2003, the NGP will consider a thermodynamic search of metallic species for which particle formation is unfavorable at the appropriate temperatures. Positive findings would provide the basis for a limited search for the presence of particles in laboratory flames undergoing suppression.

	#	Recommendation	Response
12	2B/1/78901 Suppression Effectiveness of Aerosols and Particles	This work should be expanded to include some of the higher boiling point replacement agents from the other projects as well as solutions of alkali metal compounds in some of the higher boiling point liquids. It may be possible to substitute one or more of the high boiling point liquids for water in the water mist work, gain the benefits of water mist and some chemical activity, yet avoid the problems with water. Some simple corrosion screening analysis or simple corrosion screening test for the dry powder aerosols, similar to the environmental screening of 4B/3/8901, should be considered.	This project has already indicated that high boiling compounds need long residence times for the heat of vaporization to contribute to the flame suppression efficiency. Experiments in 4B/4 & 5A/1 and modeling in 6A/1 will indicate the value of pursuing higher boiling compounds. [Prior tests have shown that alkali metal compounds and their solutions pose a corrosion threat to aluminum surfaces.]
13	1C/1/8901 Relative Benefit Assessment of Fire Protection System Changes	The IRP believes that rather than expanding the project into UAV's, it is more important to continue cost comparisons for a targeted model with a view to getting estimates for an optimized halon 1301 system, a CF_3I system, and a gas generator system.	The purpose of the project is to establish a methodology for estimating the life cycle costs of both current and future platforms. That has been completed, with examples to facilitate the use of the method. The application to specific platforms is more readily performed by the platform managers, who have better access to the pertinent input data.
14	5E/1/1 Enhanced Powder Panels	Because of the complexity of dry bay ignition phenomena under live fire conditions and the many variables involved, the IRP does not consider it feasible to demonstrate a developed form of this technology within the time frame remaining for the NGP program. The program would have been stronger if past history of an older version of this technology were better integrated. The IRP recommends against renewing this program after the current contract phase ends.	The current two-year project is directed at identifying new approaches to this old concept. When that has been completed, the results will be transferred to platform mangers and commercial product manufacturers, who are already showing interest in the preliminary findings.
15	6C/1/1 Mechanism of Unwanted Accelerated Burning	To date, the phenomena seem to be evidenced more in the suppression of pool fires than in nacelle type installations. The feasibility of verifying the current hypotheses using one or more of the scheduled 2002 engine nacelle tests (FAA, AFRL) should be considered.	The current project is aimed at determining whether the observed phenomenon poses a safety threat. The NGP is prepared to extend this project (probably in FY2004) if the hypotheses indicated that the risk of accelerated burning is high under aircraft suppression conditions.

	#	Recommendation	Response
16	5D/1/901 Advanced Propellant/Additive Development for Gas Generators	1. Further work on the hybrid devices with effort devoted to flame suppression mechanisms and relight susceptibility. 2. Emphasis on design concepts to minimize the periodic replacement costs of the pyrotechnic elements. 3. Verification testing to show that "Cooled Soaked" CF_3I hybrids (or other high-boiling "agents") will perform well at low temperatures. 4. Generation of chamber pressure and burning time variation with temperature for the all the propellants being considered. In older propellants, peak chamber pressure variations of 4 to 1 over a 135 °F temperature range were reported.	1. Additional work on cooler, more efficient effluent with slower burn rates will be supported with FY2003 funds. Alternative engineering concepts may be necessary to control relight and increase assured durability. 2. This is at the perimeter of the scope of the NGP, but should be a market-driven stimulus for manufacturers. The concern will be passed on to the Principal Investigator. 3. Low temperature effects are not expected to be important, but tests of devices with reduced effluent temperature would be appropriate. 4. These measurements are being made.
17	4B/4/01 Performance Data on Cold Temperature Dispersion of CF_3I and on Materials Compatibility with CF_3I	The work should be augmented to include additional high boiling point candidates from the other projects. The IRP would like to see useful heuristics from this project relating agent volatility and drop size distribution to vapor phase loading during droplet dispersion. One should consider re-naming this project "Low Temperature Performance of High Boiling Point Agents." The status of the material compatibility tasks needs to be clarified.	This name change has been made. Higher boiling compounds are in the plan for FY2002. The heuristics are addressed above under General Recommendation 3. The materials compatibility work was just completed and the report is in review.
18	6A/1/0 Fire Suppressant Dynamics in the Fire Compartment	The project should be restructured and focused to use the computer capability to develop heuristics that can be applied in practice rather than use the project exclusively as a vehicle for developing the computer code as the end product. Researchers are encouraged to keep in mind the multiple potential applications for the results of this project: a) Better scientific understanding of the phenomena (Research) b) Guidance for vent and distribution configurations in future tests (Test) c) Potential for future design using a simplified model (Product Design)	The project includes developing practical guidance for agent dispersion hardware. The development of a simplified model will be considered as soon as the capability of the full computer code is assessed.

	#	Recommendation	Response
19	5A/1/01 Parametric Investigation of Droplet Atomization and Dispersion of Liquid Fire Suppressants	1. Add at least one additional liquid test candidate to the project with a lower boiling point than the present two test liquids. 2. Insure that the size of the droplets tested covers the range of sizes expected in normal discharge. 3. If warranted, recommend modifications to the distribution system, based on the results of this study. Note: Determining realistic droplet size may become a difficult problem considering the variation in "Agent" characteristics, bottle pressure variations as a function of temperature, and discharge nozzle variations. If performance is found to be highly dependent on size, and if size is found to be highly variable, then this program has discovered a valuable truth, but the implications could be serious.	1. The intent is to provide data on droplets whose properties indicate they will travel as droplets. 2. Small masses of low boiling fluids that will evaporate before impacting surfaces or reaching the flame zone can be treated as gases. 3. These results feed into 6A, which will generate the guidance for distribution systems.