

FY2001 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

FY2001 Annual Report Next Generation Fire Suppression Technology Program (NGP)

Richard G. Gann
Building and Fire Research Laboratory

National Institute of Standards and Technology
Gaithersburg, MD 20899-8664

March 2002



U.S. Department of Commerce
Donald L. Evans, Secretary

Technology Administration
Phillip J. Bond, Under Secretary for Technology

National Institute of Standards and Technology
Dr. Arden L. Bement, Jr., Director

National Institute of Standards
and Technology
Technical Note 1445
Natl. Inst. Stand. Technol.
Tech. Note 1445
40 pages (March 2002)
CODEN: NTNOEF

U.S. Government Printing Office
Washington: 2002

For sale by the
Superintendent of Documents
U.S. Government Printing Office
Washington, DC 20402-9325



FY2001 ANNUAL REPORT

Next Generation Fire Suppression Technology Program (NGP)

[PP-1059]

Richard G. Gann, Ph.D.
Technical Program Manager
March 11, 2002

This page intentionally left blank.

ABSTRACT

The Department of Defense's Next Generation Fire Suppression Technology Program (NGP) has completed its fifth 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

This page intentionally left blank.

TABLE OF CONTENTS

I. INTRODUCTION	1
II. TECHNICAL PROGRESS	2
A. NEW FLAME SUPPRESSION CHEMISTRY	2
B. NEW AND IMPROVED AEROSOL SUPPRESSANTS	10
C. IMPROVED SUPPRESSANT DELIVERY	11
D. VIABILITY OF NEW SUPPRESSANT TECHNOLOGIES	23
III. INDEPENDENT PERFORMANCE ASSESSMENT	26
IV. WHAT'S COMING NEXT?	27
APPENDIX: NGP PROJECTS	29

This page intentionally left blank.

INTRODUCTION

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

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

The principal support for the NGP is from the DoD Strategic Environmental Research and Development Program (SERDP), with cost sharing from some of the participating laboratories.

Fires and explosions continue to be among the greatest threats to the safety of personnel and the survivability of military aircraft, ships, and land vehicles in peacetime and during combat operations. 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 replacements for halon 1301, but each had unresolved operational features that compromised its implementation.¹ The new Program was to identify fire suppression technologies with reduced compromises.

Over the past five years, research to identify replacement fire suppressants has declined considerably, within the NGP, domestically and internationally, despite the continuing need. To date no commercial or military aircraft have had their halon 1301 systems replaced, while new systems are being installed in the cargo bays of commercial jetliners. Since new halon 1301 is unavailable, these systems are being filled with recovered chemical or existing reserves.

Meanwhile the concentration of bromine in the stratosphere is predicted to peak within the next few years, signaling the beginning of a rise in the earth's protective ozone layer. The international community is continuing to cast an eye on the necessity of maintaining the larger halon 1301 reserves and even considering the requirement of a total phaseout.

Thus, the demands on research to identify new approaches to aircraft fire suppression are unabated, nor have the demands on the new technologies lessened. 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.

As the NGP enters its sixth year of research, the participants have generated unparalleled contributions to the published literature, all of which can be obtained via the NGP web site, which has moved to www.bfrl.nist.gov/866/NGP. The systematic search for new suppressant chemicals and technologies for assured, efficient delivery is continuing to produce new results. The following pages highlight the new knowledge gained from the NGP research and the progress made towards the NGP Goal. 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.

I. TECHNICAL PROGRESS

A. NEW FLAME SUPPRESSION CHEMISTRY

From the time when it was realized that environmentally friendly alternatives to halon 1301 would be needed until the initiation of the NGP, nearly all research on alternative fire suppressants was focused on saturated halocarbons, a subset of the possible halons (halogenated hydrocarbons). In large part, this was because the other ozone depleting chemicals (*e.g.*, refrigerants, degreasers) constituted far larger markets, and it was assumed that the search for alternatives to those chemicals would lead to usable fire suppressants. In the research documented in the 1998 final report of the Department of Defense's *Technology Development Plan for Alternatives to Ozone Depleting Substances for Weapons Systems Use*¹, all the fluids investigated as fire suppressants were halons.

There had been more far-reaching work in the search for a replacement for halon 1211, a streaming agent, as well as a survey of non-conventional alternatives to halon 1301. As a result, in the earlier years of the NGP, investigators were in a position to look at some families of chemically diverse compounds. We sought to identify chemicals that met a list of criteria that has evolved to the following:

- Fire suppression efficiency at least comparable to halon 1301 (about 3 % by volume) and certainly higher than the hydrofluorocarbons (HFCs).
- Short atmospheric lifetime (current preference of the order of a month), to keep ozone depletion, global warming and any future unidentified environmental contamination issues to a minimum.
- Low toxicity relative to the concentration needed for suppression.
- 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 80 °C, but slow evaporation or poor dispersion will reduce this significantly for some chemicals.

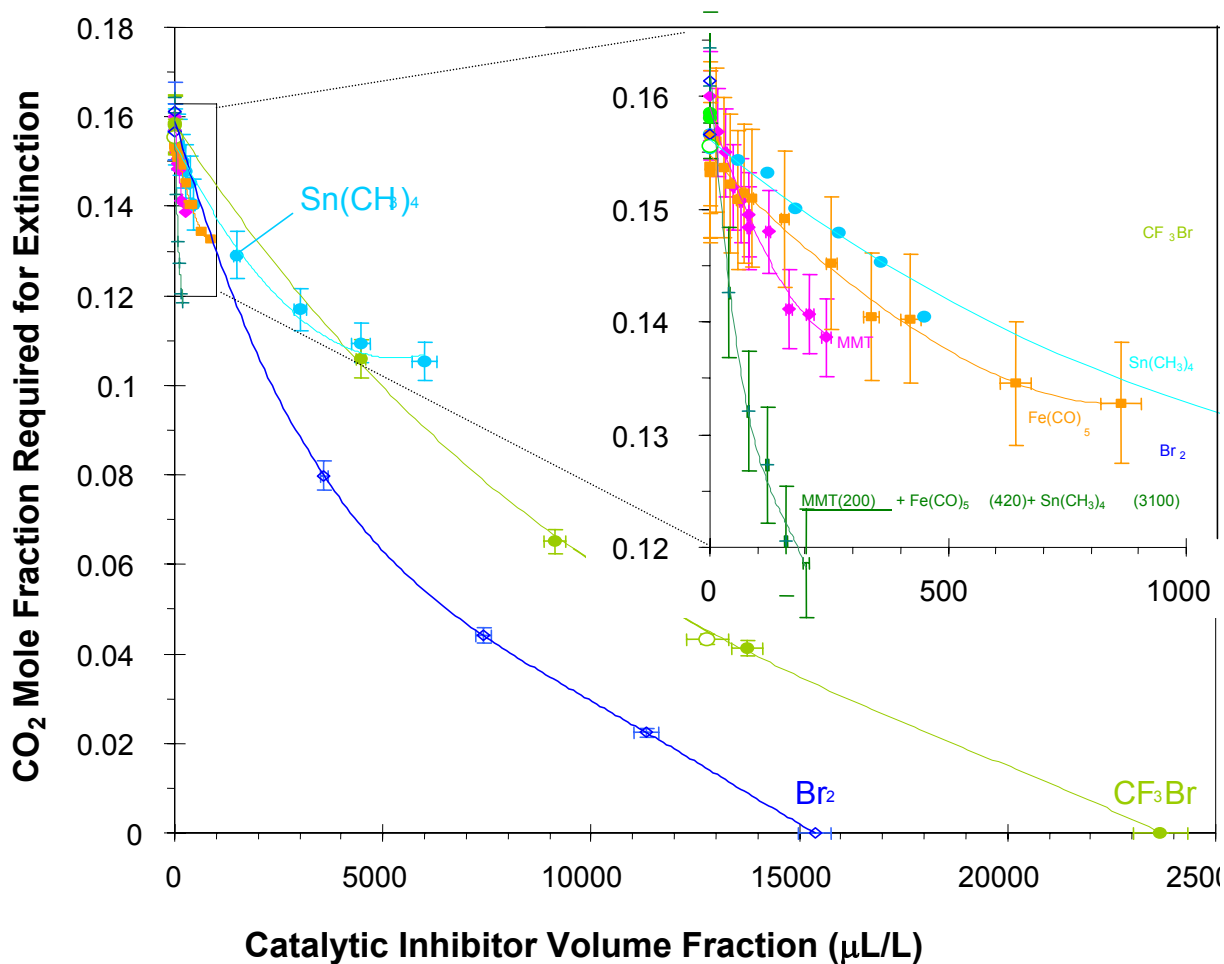
The families examined each produced additional knowledge of what makes a good suppressant, a list of most suitable members of that family, and criteria for future searches.

- Physically-active suppressants. The most effective compounds identified were already known: lactic acid and $\text{CH}_3\text{OC}_4\text{F}_9$. The latter has a cup burner suppression molar concentration of 5.5 % when introduced as a gas. This compound is four times more effective when introduced as a liquid aerosol, emphasizing the contribution of the heat of vaporization of the suppressant when the aerosol reaches the flame zone.
- Main group compounds (*e.g.*, based on Si, S, B chemistry). There were no compounds identified within these families that were especially attractive relative to HFC-125 (C_2HF_5) or HFC-227ea (CF_3CHCF_3), both of which are in current production.
- Tropodegradable bromocarbons. The initial look was at brominated alkenes, and was performed in conjunction with the Advanced Agent Working Group. Four compounds were shown to have fire suppression efficiency comparable to halon 1301, boiling points of 34 °C to 56 °C, atmospheric lifetimes of the order of days, and low acute inhalation

toxicity. However, the one compound tested for cardiotoxicity produced effects on the test animals at a molar concentration of about 1 %. This showed that our ability to anticipate this use-limiting effect needed refinement.

- Metal-containing compounds (Fe, Mn, Sn). Some iron, manganese, and tin compounds showed very high flame inhibition effectiveness on premixed flames and highly strained diffusion flames (Figure 1), but were unimpressive on cup burner flames. We are in the process of identifying why this difference occurs and which set of laboratory test conditions are appropriate for capturing the suppression efficiency of these compounds under aircraft fire conditions. These compounds are all very high boiling liquids or solids, and thus would most likely be used in conjunction with solid propellant gas generators (SPGGs).

Figure 1. Mole fraction of CO₂ required for methane-air cup burner flame extinction as a function of catalytic inhibitor mole fraction, CF₃Br, Br₂, Fe(CO)₅, (Sn(CH₃)₄, MMT [(CH₃C₅H₄Mn(CO)₃], or a blend of the last three (insert shows data with expanded x- and y-axes). The termination of the curves at high CO₂ mole fraction indicates the limit of suppression effectiveness.



- Phosphorus-containing compounds. NGP research established that the phosphorus atom imparts good flame suppression efficiency to a compound and that the binding state of the phosphorus is unimportant. There are very few low boiling phosphorus-containing compounds, so these would need to be dispersed as aerosols or be used with SPGGs.

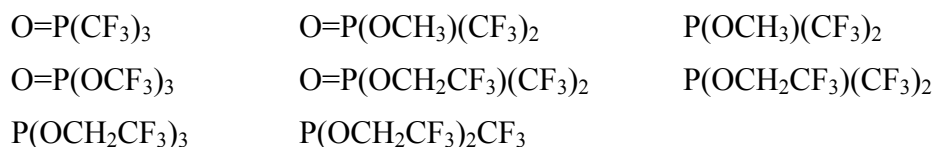
During FY2000 and FY2001, the NGP used this updated knowledge to conduct a comprehensive review of the world of chemicals to identify those chemical families still ripe for examination in the NGP. For each type of chemical functionality, assessments were made of the extent of prior fire suppression studies and the potential for success in any (further) study. Expected flame suppression efficiency, atmospheric persistence, boiling point, and toxicity were again the main screening criteria.

The following families were identified as the most promising:

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

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

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



These represent some of the lowest boiling points for phosphorus-containing compounds, with the first having the highest volatility of any non-flammable chemical in the family, 32 °C. The cup burner extinguishment concentration for $\text{P}(\text{OCH}_2\text{CF}_3)_3$ was found to be 1.9 % by volume.

We are also continuing our examination of the tropodegradable halocarbons, now concentrating on the brominated ethers. Some of these are used as surgical anesthetics, but thus have high boiling points for ease of handling and administration. Therefore, the candidate ethers will need to be synthesized. Cup burner extinguishment values for two ethers, $\text{CH}_2\text{BrO}(\text{CF}_3)_3$ and $\text{CH}_2\text{BrOCF}_2\text{H}$, are close to that for halon 1301 and the atmospheric lifetimes should be very short. The boiling points are 40 °C and 70 °C, respectively.

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

Another factor affecting the use of brominated compounds is their atmospheric lifetimes. Since bromine atoms are potent depleters of stratospheric ozone, brominated species must not rise to those altitudes. A sure way to prevent this transport is for the compound to be degraded in the lower atmosphere. The NGP has completed a methodology for estimating the reactivity of halocarbons with atmospheric OH, the major tropospheric elimination pathway. Beginning with compounds for which the reaction rates are known, the method developed relationships for extending to related compounds, such as those with increased fluorination. The tropospheric lifetime together with the stratospheric lifetime lead to the impact of the particular compound on the ozone layer. We have developed a method to estimate the latter using the integrated molecular absorption over the 200 nm to 210 nm band in the ultraviolet. With this new array of techniques, we have now estimated ozone depletion potentials for a variety of halogenated alkanes, alkenes, and ethers (Tables 1 and 2).

Table 1. Arrhenius Parameters for Reactions with OH, Estimated Atmospheric Lifetimes, and Ozone Depletion Potential (ODP) values.

Molecule	$k(298) \times 10^{12}$ cm ³ molecule ⁻¹ s ⁻¹	$A \times 10^{12}$ cm ³ molecule ⁻¹ s ⁻¹	E/R K	$Lifetime^*$ days	ODP [*]
CF ₃ Br	-	-	-	65. (years)	13.
CF ₂ =CFBr	7.62	2.02	-396	1.4	0.0015
CF ₂ =CHBr	4.53	1.30	-370	2.4	0.0028
CH ₂ =CBr-CF ₃	3.94	1.36	-317	2.8	0.0049
CH ₂ =CBr-CF ₂ -CF ₃	3.39	0.98	-369	3.2	0.0049
CH ₂ =CH-CF ₂ -CF ₂ Br	1.68	0.85	-201	7.0	0.0045
CH ₂ Br-CH ₂ -CH ₃	1.01	3.04	329	14.	0.015
CH ₃ -CHBr-CH ₃	0.76	1.90	275	19.	0.018
CHF ₂ -O-CHF ₂	0.0025	0.63	1646	24. (years)	
CF ₃ -CH ₂ -O-CH ₂ -CF ₃	0.16	2.32	790	0.28 (years)	
CH ₃ -O-CF ₂ -CH ₂ Br	0.065	1.5	930	0.76 (years)	0.21
CF ₂ =CF ₂	9.98	3.39	-323	1.1	
CF ₂ =CF-CF ₃	2.20	0.54	-413	5.3	
CF ₃ -CF=CF-CF ₃	0.51	0.33	-126	25.	
(CF ₃) ₂ -CF=CF-C ₂ F ₅	0.073	0.085	46	182.	

* Lifetimes are due to reactions with tropospheric OH only. Atmospheric lifetimes and ODP values were estimated in the manner typically used for long-lived compounds. Such estimation assumes a uniform tropospheric distribution that is not necessarily correct for short-lived compounds.

Table 2. Calculated Arrhenius Parameters for Reactions with OH, Estimated Atmospheric Lifetimes, and ODP values.*

Molecule	$k(298) \times 10^{14}$ $\text{cm}^3 \text{molecule}^{-1} \text{s}^{-1}$	$A \times 10^{12}$ $\text{cm}^3 \text{molecule}^{-1} \text{s}^{-1}$	E/R K	$Lifetime^{**}$ years	ODP^{**}
CF ₃ Br	-	-	-	65.	13.
CH ₃ Br	2.4 <i>2.9</i>	5.4 <i>4.0</i>	1610 <i>1470</i>	2.5 <i>2.0</i>	1.2 <i>0.99</i>
CHF ₂ Br	1.0 <i>1.0</i>	1.5 <i>1.1</i>	1505 <i>1400</i>	6.0 <i>5.6</i>	1.6 <i>1.5</i>
CH ₂ FBr	3.0	3.8	1440	1.9	0.59
CH ₂ ClBr	9.2 <i>11.4</i>	2.2 <i>3.04</i>	945 <i>978</i>	0.52 <i>0.43</i>	0.23 <i>0.19</i>
CHFCIBr	6.8	1.5	920	0.70	0.27
CH ₂ Br ₂	8.9 <i>12.0</i>	2.5 <i>2.4</i>	995 <i>900</i>	0.55 <i>0.41</i>	0.43 <i>0.32</i>
CHBrBr ₂	10.0	1.6	825	0.46	0.30
CHCl ₂ Br	26.4 <i>12.0</i>	0.8	330	0.15	0.047
CHClBr ₂	34.6	0.8	250	0.11	0.08

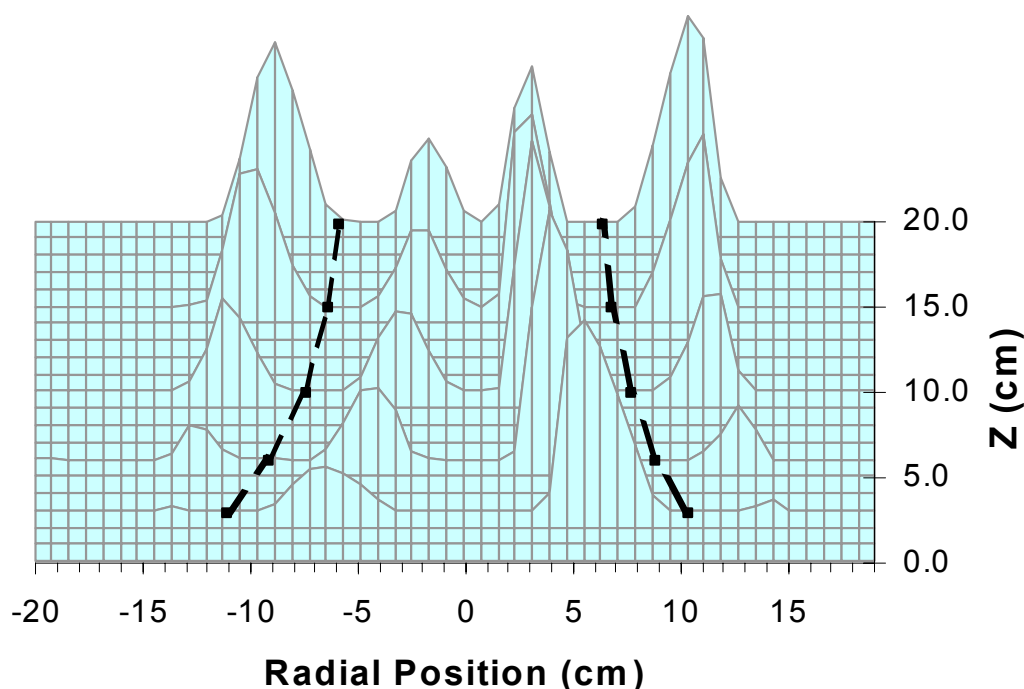
* Parameters obtained from the available experimental measurements are shown in italics.

** Lifetimes are due to reactions with tropospheric OH only. Atmospheric lifetimes and ODP values were estimated in the manner typically used for long-lived compounds. Such estimation assumes a uniform tropospheric distribution that is not necessarily correct for short-lived compounds.

As noted in the FY2000 NGP Annual Report², we had discovered that while metal-containing compounds could be effective flame inhibitors, they might not be effective *in any form* in quenching practical flames. This made it imperative to determine the reasons for the unexpected low effectiveness in cup burner flames. Now, a clear picture has emerged concerning the potential and limitations of metallic agents as fire suppressants in unoccupied areas.

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

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



Recent Publications: New Flame Suppression Chemistry

(* indicates archival publications.)

*Rumminger, M.D. and Linteris, G. T., "Particle Formation in Counterflow Diffusion Flames Inhibited by Iron Pentacarbonyl," *Combustion and Flame*, **128**, 145-164 (2002).

*Linteris, G. T., Knyazev, V., and Babushok, V., "Inhibition of Premixed Methane Flames by Manganese and Tin Compounds," *Combustion and Flame*, accepted for publication (2001).

Linteris, G.T. "Suppression of Cup-Burner Diffusion Flames by Super-Effective Chemical Inhibitors and Inert Compounds," *Proceedings of the 2001 Halon Options Technical Working Conference*, Albuquerque, pp.187-196, Albuquerque, 2001.

Linteris, G. T., Knyazev, V., and Babushok, V., "Premixed Flame Inhibition by Manganese and Tin Compounds," *Proceedings of the 2001 Halon Options Technical Working Conference*, Albuquerque, pp. 72-82, Albuquerque, 2001.

Chelliah, H.K., Lazzarini, A.K., Wanigarathne, P.A., and Linteris, G. T., "A Comparison of Fire Suppression Effectiveness of Sodium Bicarbonate Particles and Fine-Water Droplets in Non-Premixed and Premixed Flames," *Proceedings of the 2001 Halon Options Technical Working Conference*, Albuquerque, pp. 389-394, Albuquerque, 2001.

*Linteris, G.T., Rumminger, M.D., Babushok, V.I., and Tsang, W., "Flame Inhibition by Ferrocene, and by Blends of Inert and Catalytic Agents," *Proceedings of the Combustion Institute* **28**, 2965-2972 (2000).

*Lazzarini, A.M., Krauss, R.H., Chelliah, H.K., and Linteris, G.T., "Extinction Conditions of Non-premixed Flames with Fine Droplets of Water and Water-NaOH Solutions, *Proceedings of the Combustion Institute* **28**, 2939-2945 (2000).

Pitts, W.M., Bryant, R.A., and Yang, J.C., "Thermal Agent Extinguishment of Two Types of Diffusion Flames," *Proceedings of the Second Joint Meeting of the United States Sections: The Combustion Institute*, March 26-28, 2001.

Pitts, W.M., "Detailed Chemical-Kinetic Modeling of Thermal-Agent Diluted Methane and Propane Flames Near Extinguishment," *Proceedings of the 2001 Technical Meeting of the Eastern Section of the Combustion Institute*, Hilton Head, SC, 2001.

Pitts, W.M., Yang, J.C., and Bryant, R.A., "Fuel Effects on the Extinguishment of Laminar Diffusion Flames by Thermal Agents," *Proceedings of the 2001 Halon Options Technical Working Conference*, Albuquerque, pp. 241-252, Albuquerque, 2001.

Mather, J.D., and Tapscott, R.E., "Tropodegradable Bromocarbon Extinguishants – II. Research Update," *Proceedings of the 2001 Halon Options Technical Working Conference*, Albuquerque, pp.197-203, Albuquerque, 2001.

*Louis, F., Gonzalez, C., Huie, R. E., and Kurylo, M. J., "An Ab Initio Study of the Kinetics of the Reactions of Halomethanes with the Hydroxyl Radical. Part 3. Reactivity Trends and Kinetics Parameter Predictions for the Potential Halon Replacements CH₂FBr, CHFBr₂, CHFClBr, CHCl₂Br, and CHClBr₂," *J. Phys. Chem. A*, **105**, 1599-1604 (2001).

B. NEW AND IMPROVED AEROSOL SUPPRESSANTS

FY2001 brought to a close the NGP investigation of the properties of droplets that enhance their flame suppression efficiency. Collaborative research with NASA-funded collaborators led to a validated model for the inhibitory effects of small drops ($< 5 \mu\text{m}$) and water vapor on premixed flames (Figures 3 and 4). The multi-phase flame model includes elementary combustion chemistry and multicomponent molecular transport. The model also predicts a small-drop limiting behavior for premixed flames similar to that previously observed for non-premixed counterflow flames consistent with other NGP modeling predictions.

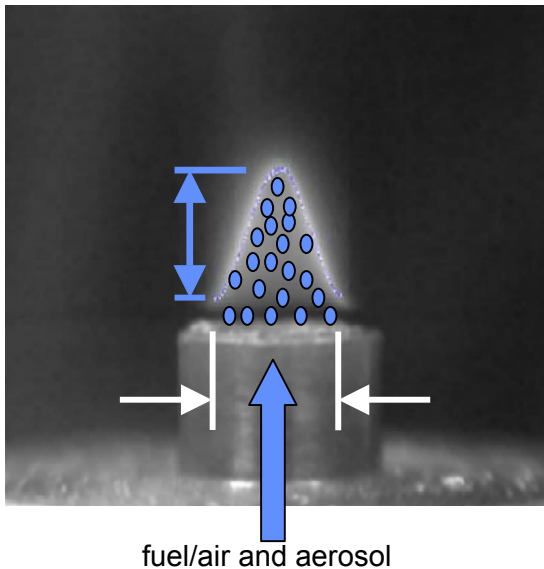


Figure 3. Schematic for the experimental determination of the effect of aerosols on the burning velocity of atmospheric pressure premixed methane/air flames. Flame cone heights are typically 0.3 to 1.5 times the diameter of the burner exit. Burning velocities are determined by the total area method [1].

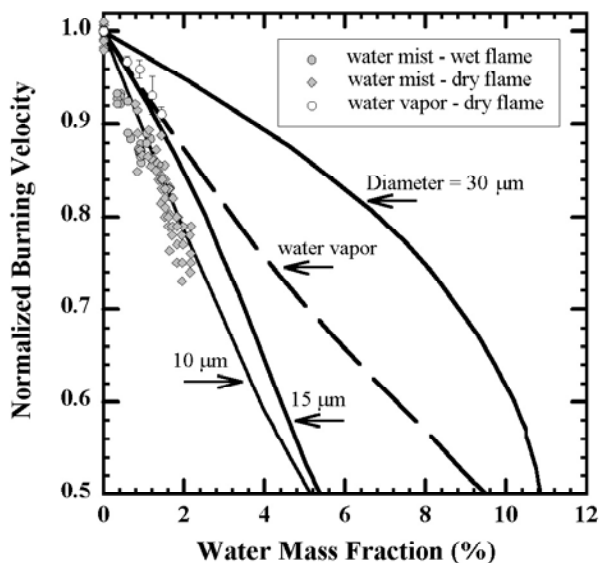


Figure 4. Premixed methane-air burning velocity as a function of agent mass fraction, normalized by the uninhibited burning velocity. $0.35 \mu\text{m}$ water mist in dry flame (gray diamond), $0.35 \mu\text{m}$ water mist in humidified (1.5 % mass fraction water vapor) flame (gray circle), water vapor (open circle). Modeling results for humidified flames inhibited with mists (solid lines), and modeling results for humidified flames (dashed line).

Recent Publications: New and Improved Aerosol Suppressants

(* indicates archival publications)

*Zegers, E.J.P., Williams, B.A., Sheinson, R.S., and Fleming, J.W., “Dynamics and Suppression Effectiveness of Monodisperse Water Droplets in Non-Premixed Counterflow Flames,” *Proceedings of the Combustion Institute* **28**, 2931-2938 (2000).

Zegers, E.J.P., Fuss, P., Fleming, J.W., Williams, B.A., Maranghides, A., and Sheinson, R.S., “Better Use of Water for Fire Suppression,” *NRL Review*, Naval Research Laboratory, Washington DC, pp.102-104, 2001.

C. 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.

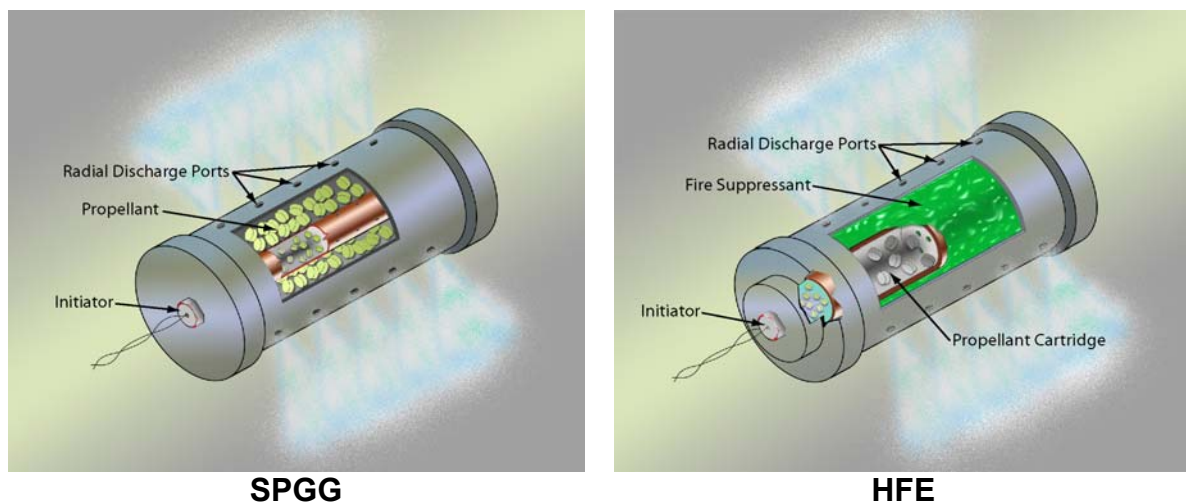
NGP research had co-developed a new high nitrogen propellant compound, BTATZ ($C_4H_4N_{14}$), and prototype formulations incorporating it have reduced discharge temperatures by 20 %. This year, process improvements in the preparation of BTATZ have progressed to the 0.5 kg scale, enabling more extensive use in testing, including re-formulation with additional coolants.

There are two approaches to cooler, more efficient solid propellant fire extinguishers (Figure 5):

- 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.

Following last year’s demonstration that some chemical additives enhanced the efficiency of an otherwise inert gas generator, additional experiments were performed to quantify the benefit. Additives were added to either the propellant (SPGG) or the fluid (HFE). Several solid propellant and hybrid configurations were evaluated for fire suppression effectiveness using a mid-scale Fire Test Fixture (FTF), developed to simulate typical military aircraft fire scenarios. The structure was approximately 0.7 m^3 (24 ft^3) in volume, with a JP-8 flame in a forced air stream yielding a fire intensity of about 1 MW. SPGG and HFE fire suppression devices were used to deliver both inert and active agents into the fire. The gas generator device was mounted upstream of the fire, on an arm in the middle of the airflow, but shielded from the fire zone by a baffle. All SPGG and HFE discharge times were maintained at $\approx 200 \text{ ms}$ for ease of comparison.

Figure 5. Solid Propellant Fire Extinguishers

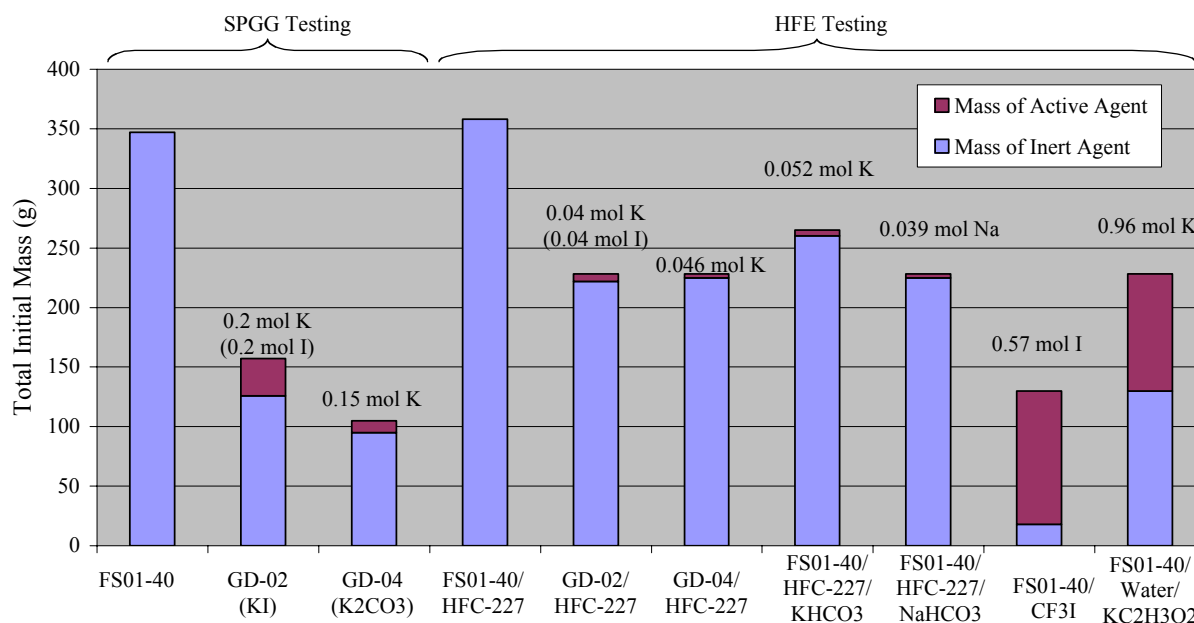


The test results are summarized in Figure 6. The values are based on multiple tests and represent the threshold amount of agent needed to extinguish the fire. The threshold is defined as the amount of agent needed to extinguish the fire at least two out of three times. Typically three tests were conducted at the threshold amount and three additional tests were conducted at an agent load greater than the threshold amount.

There is clearly an efficiency improvement with any of the blends of inert gases with chemically active additives in both systems. On an equimolar basis, potassium carbonate appears to be a more effective chemical additive than potassium iodide. This may be related to more facile vaporization of the carbonate-based species after melting or to an antagonistic interaction between the halogen and alkali metal species in the flame region. On a mass basis, the inert HFE and SPGG systems appear to provide similar suppression protection. Testing conducted with additives incorporated into the hybrid fluid of the HFE system produced results similar to results with active agents added into the propellant.

Testing conducted with the HF scavengers KHCO_3 and NaHCO_3 added into the hybrid fluid of the HFE system produced results similar (based on moles of K/Na) to results with active agents (KI , K_2CO_3) added into the propellant. Active hybrid systems were also tested using potassium acetate (KOAc)/water blends, and using trifluoromethyl iodide (CF_3I). The water-based system delivers performance comparable to HFC-227/active-agent blends, and avoids the formation of toxic and corrosive HF. The CF_3I system was the most effective HFE system tested, but was observed to produce significant quantities of I_2 vapor during suppression testing.

Figure 6. Summary of SPGG and HFE Fire Effectiveness Testing



2. Dispersion of Suppressants at Low Temperature

In a space where the fire could be anywhere, efficient dispersal of a suppressant throughout the volume is essential. Halon 1301, with a boiling point of $-58\text{ }^{\circ}\text{C}$, flash vaporizes and distributes well, even at the lowest temperatures (*ca.* $-40\text{ }^{\circ}\text{C}$) it experiences in in-flight aircraft. Earlier research had indicated that fluids with higher boiling points might not disperse well. For instance, while CF_3I has a flame suppression efficiency and heat of vaporization similar to halon 1301, it has a higher boiling point of $-22\text{ }^{\circ}\text{C}$. Similar concerns arose over many of the novel compounds being examined under the NGP. This could lead to a reduction in the upper boiling point limit for screening chemicals for further consideration.

The initial experiments involved examination of CF_3I discharges in a simulated engine nacelle (Figure 7) under different thermal conditions (Table 3). Two outer circular ribs and one horizontal rib in the cylindrical flow space induce turbulence, mimicking the flow a real engine nacelle.

Figure 7. Schematic of the modified test facility

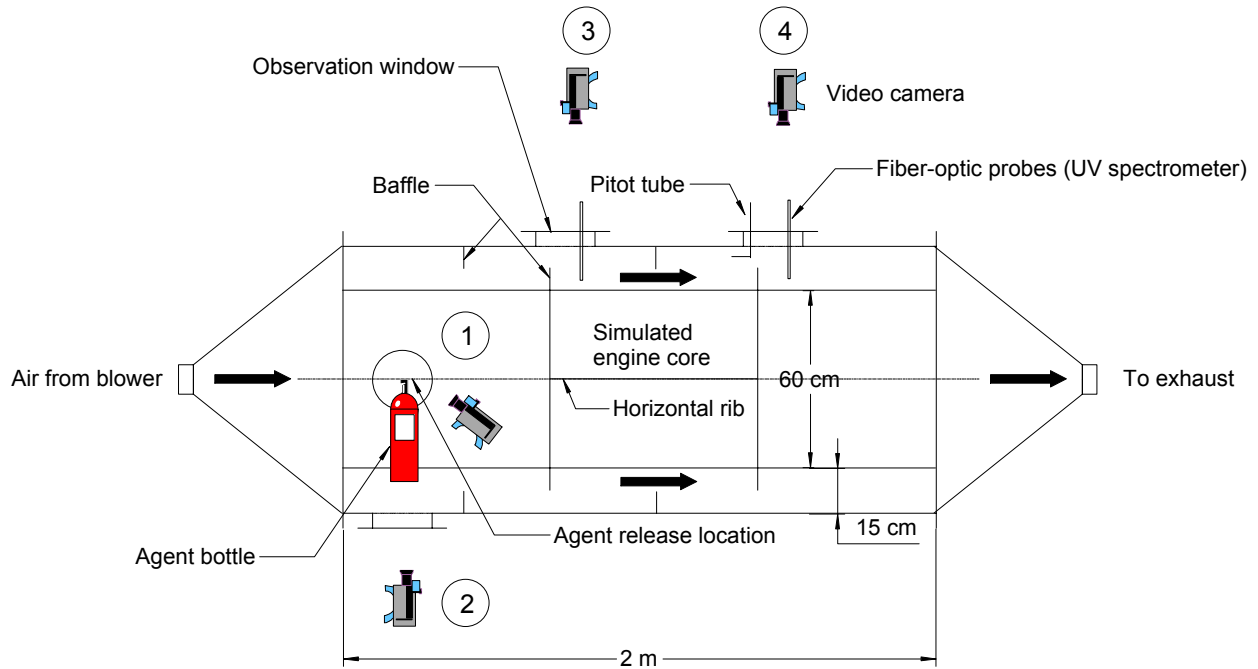


Table 3. Experimental matrix for cold temperature agent dispersion

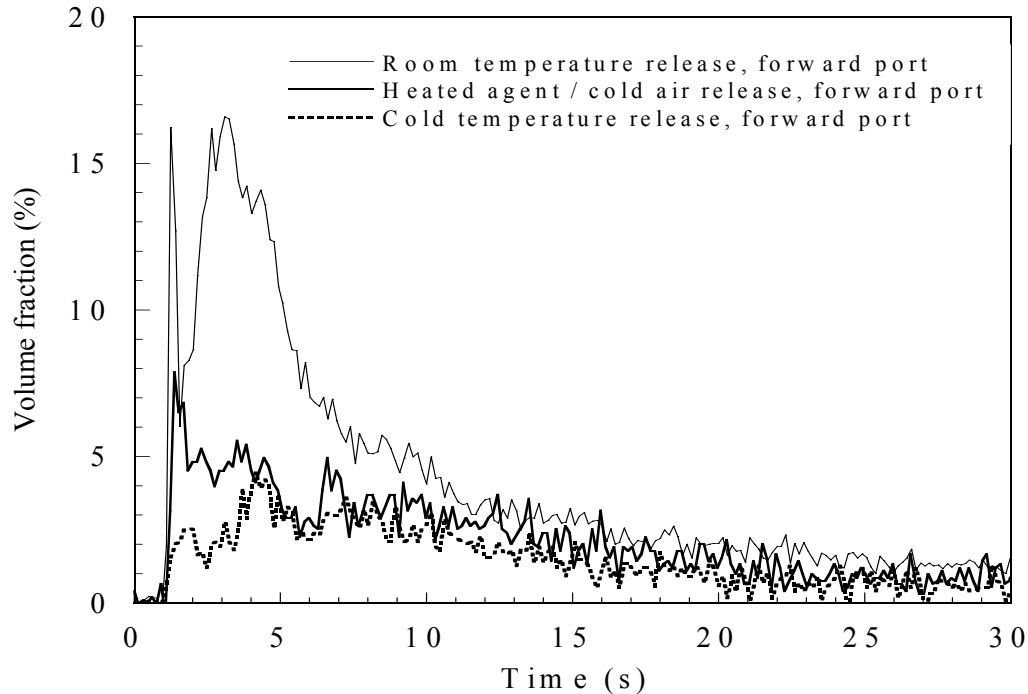
Nominal initial conditions of vessel	Nominal conditions of vessel before discharge	Nominal conditions in the simulator
22 °C and 4.12 MPa	−40 °C at prevailing P^{\S}	−40 °C §
22 °C and 4.12 MPa	22 °C and 4.12 MPa	22 °C (baseline)
22 °C and 4.12 MPa	22 °C and 4.12 MPa	−40 °C §

§ Tests were performed in an environmental test chamber.

The agent bottle was charged with ≈ 1 kg of CF_3I and then pressurized with nitrogen to the desired pressure (4.21 MPa) at room temperature. The airflow through the simulator was maintained at $1.5 \text{ kg/s} \pm 0.1 \text{ kg/s}$ (mean \pm standard deviation).

As shown in Figure 8, during the crucial initial 10 s, for this temperature differential of about -20 °C (ambient temperature minus fluid boiling point), the concentration of suppressant is well below the concentration when the temperature differential is 44 °C. Liquid CF_3I droplets were present for only a short period of time (< 2 s) immediately following the discharge. Rather, a significant amount of the fluid pooled at the bottom of the chamber upon release, then evaporated slowly over many seconds. Heating the storage container to room temperature shows improvement but does not correct the problem.

Figure 8. Concentration profiles of CF_3I at the forward measurement location under three test conditions



3. Suppressant Dynamics in Engine Nacelles

Understanding of the dispersion of a suppressant to random fire locations in the variety of engine nacelle geometries under diverse flight conditions can best be developed by either an extensive set of full-scale fire suppression tests or from validated computer modeling of the process. The NGP is following the latter approach in order to provide guidance on preferred location(s) and styling of suppressant discharge. The computational fluid dynamic (CFD) model will include gaseous and aerosol suppressant flow, a fire, and fire extinguishment in cluttered environments. Several flow facilities are being used concurrently to provide both input and validation data in a timely manner.

The model for air flow through a smooth nacelle was completed last year. Sensitivity studies have now been performed to assess the effect of grid resolution, turbulence models, and wall functions on the predictions. The results were not sensitive to mesh size except near the walls from lack of resolution. Examination of two turbulence approaches showed that an assumption of zero cross-stream turbulent velocities produced results in better agreement than did an assumption of isotropic turbulent flow. This conclusion also agrees with experimental observations. Finally, calculations with two different wall functions showed no impact on the solution for this application.

The next step is to add the effects of nacelle clutter to the calculations. This requires data (drag and turbulence intensity) on the change in flow behavior as the droplet-laden stream moves around obstacles. For these experiments, three obstacle tubes (diameters of 3 mm, 13 mm, and 32 mm) were chosen to span the ranges of clutter sizes: smaller, on the same order, and larger than the integral length scales of turbulence. Each, in turn, was placed in a straightened air flow in an existing spray facility (described in the FY2000 NGP Annual Report²). The flow field upstream and downstream of the obstruction was characterized using three-dimensional particle image velocimetry (PIV) with a spatial resolution of approximately 600 μm . The 3-D stereo PIV system differed from traditional PIV systems in that two CCD cameras were used and three velocity components were measured. The flow mean velocity of 4.5 m/s, corresponding to a Reynolds number of 3700, was representative of air speeds through aircraft engine nacelles. The downstream flow field was relatively uniform as shown in Figure 9 except for some local jetting within 25 mm downstream of the flow straightener. The cylindrical obstacles were placed 100 mm downstream where these jets had dissipated.

A preliminary version of this case of a single cylinder in a cross flow was integrated into the VULCAN fire physics code, along with a more sophisticated turbulence model. Comparison of the CFD predictions to the PIV measurements indicate that qualitatively the location and size of the recirculation zone for the largest cylinder case was well captured. The numerical results overpredicted the streamwise mean velocity by 20 % and underpredicted the RMS fluctuations in the streamwise velocity by 15 %. These differences indicate that the numerical predictions underestimate the extent of turbulent mixing behind the cylinder, and may be attributed to the use of the $k-\epsilon$ model that is known to perform poorly in highly recirculating flows.

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

The third component is the evolution of a fire suppression capability for VULCAN. Prototype simulations of the 2-D nacelle fixture have been run for two agents (N_2 and HFC-125) with and without a typical rib located downstream of the inlet. The flow and size of the rib and nacelle were chosen to be representative of the flow and geometry in an actual nacelle. Fire extinguishment occurs between 40 % and 60 % N_2 by volume without a rib. Cold flow cases with the rib geometry reveal a sharp increase in turbulent kinetic energy over the top of the step resulting in high values of turbulence intensity (75 % or greater) as indicated in Figure 10.

Figure 9. Variation of mean streamwise and cross-stream velocities with downstream distance. (The black circles are the ends of the obstruction cylinders.)

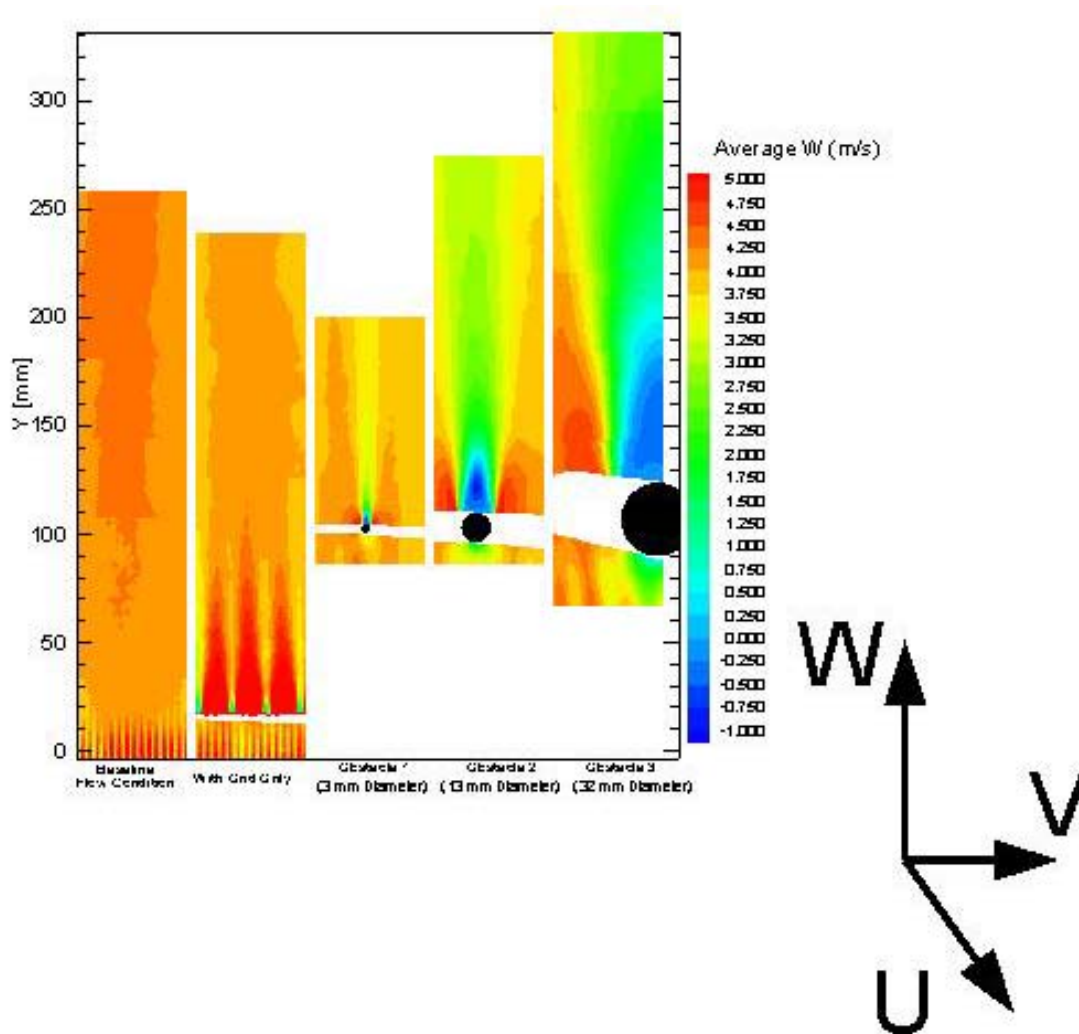
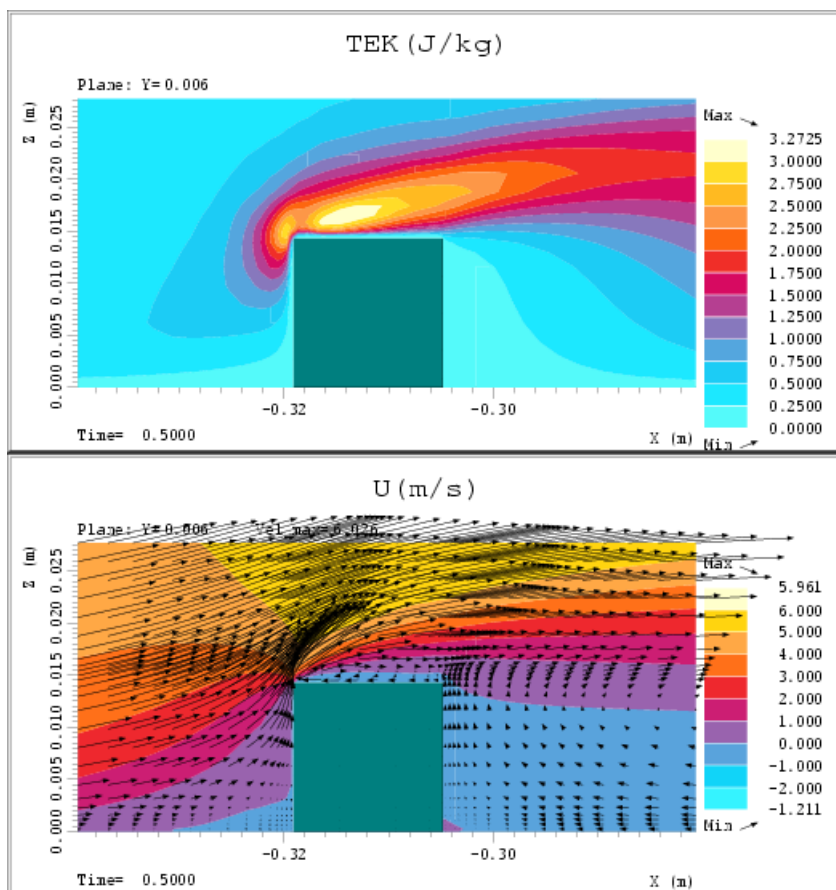


Figure 10. Contour plots of turbulent kinetic energy and velocity field around rib at the centerline of the domain



This detailed information will be used to parameterize the clutter model for regions around the ribs near the nacelle wall. Scenarios using N₂ and HFC-125 agents are being explored to determine the extra suppressant required for a fire stabilized on the downstream side of a rib. The results from these simulations will help provide guidance for the experimental test series of a full-scale nacelle simulator to be conducted in FY2003.

4. Powder Panels for Dry Bay Fire Protection

The NGP is examining new concepts for an old alternative to the discharge of pressurized fluids or dry chemical fire extinguishing agents. Powder panels lining a dry bay can provide passive, lightweight, effective fire protection against ballistic impact by releasing powder into the fire zone to inert the space before the adjoining fuel spills into the space and is ignited by incendiaries. Previous powder panel testing has shown that only about one gram of a typical fire extinguishing powder could prevent a pool fire from igniting for over one minute. In U.S. aircraft, the widest use of powder panels has been in helicopters. Currently, the AH-1W Super

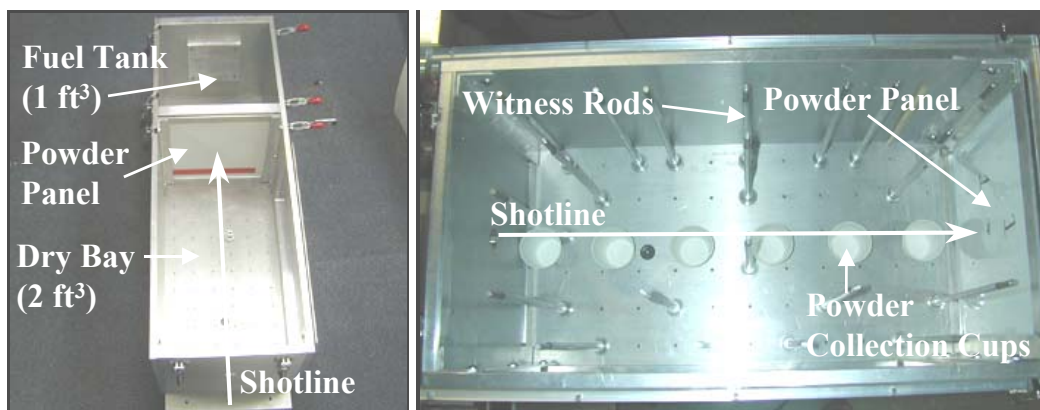
Cobra uses powder panels, as does the V-22 Osprey tiltrotor aircraft, with evaluations underway for the AH-1Z and the RAH-66 Comanche helicopters.

The design and acceptability criteria for these devices are different from conventional fluid suppressant systems. Powder panels add weight based upon the surface area of the fuel wall/fire zone interface, as opposed to the volume of the fire zone, so the relative benefit of the panels is dependent upon the configuration of the particular bay. False discharges do not occur, but cleanup following a fire or inadvertent damage remains a concern.

Today's panels are in essence the same designs that have existed for decades. NGP staff have compiled a list of powder panel materials and designs previously evaluated and those that have been integrated into aircraft designs. The survey also includes powder panel test programs extending back to the 1970s.

An experimental dry bay/fuel tank simulator (Figure 11) was fabricated to enable comparison of powder panel materials and designs. The characteristics examined were panel fracture and material removal, the amount of fire extinguishing powder released into the test article, the dispersion of this powder, and the time the powder remains suspended in the dry bay.

Figure 11. Experimental Test Device and Powder Collection Methods



Witness rods were located throughout the dry bay to capture qualitative powder dispersion characteristics. Powder collection cups were also located in the dry bay along the shotline, where the powder concentration is most important during a ballistic projectile impact. In addition, each panel was weighed before and after each test to determine the amount of powder released. The removed area of the front face (dry bay side) of the powder panels was also determined. Digital video was captured for each test to assist in determining the length of time powder was suspended in the dry bay.

In each test, a light-gas gun was used to launch a 0.50 caliber hard steel ball projectile at a velocity of at least 670 m/s (2,200 ft/s). The initial tests did not involve fluid in the fuel tank nor

air flow to simplify the screening process. The powder was KHCO_3 (Purple K). The tested panel features included the following:

- For the front panel face (dry bay side), materials that exhibit brittle properties upon impact, but durability in handling, were of utmost interest. Thermoplastic materials evaluated included a polycarbonate, a polystyrene, a polypropylene, and an acrylic. Intentional surface scoring of acrylic panels was examined to determine if fracture characteristics could be enhanced. Thermoset polymers evaluated included two polyester resins, a thin epoxy primer, and an epoxy resin.
- Thermoplastic materials were examined for the back panel to determine if the fracture characteristics of the back panel influenced the front panel in any way.
- A number of materials and designs were examined for the powder panel internal rib structure. Panel designs included such diverse features as integral front and back walls and internal channels and honeycomb material. Several rib designs were conceived to enhance powder release and yet prevent the settling of powder. Attempts were made to minimize the number of these ribs, maximize the spacing, and minimize the overall panel thickness.

Table 4 lists some of the more effective (upper section) and ineffective (lower section) designs.

Table 4. Comparison of Effective and Ineffective Powder Panel Designs

Test No.	Material Description	Thickness (mm)	Panel Weight (g)	Powder Loss (g)	Powder Loss (%)	Front Face Area Removed (cm^2)
8	0.08" clear acrylic faces, 0.375" acrylic tube ribs	13.5	1402	48	5.6	31.6
9	0.07" cracked Ice acrylic front, 0.06" white styrene back, two white styrene ribs (0.12" thick) at 4" and 8"	6.9	769	23	5.0	17.7
12	0.08" (2" x 2" scored) clear acrylic, 0.08" clear acrylic back, 0.125" polycarbonate honeycomb rib	7.6	579	9	4.6	22.6
21	0.07" acrylic prismatic front, 0.06" white styrene back, two white styrene ribs (0.12" thick) at 4" and 8"	7.8	552	30	12.8	20.3
23	0.07" styrene prismatic front, 0.06" white styrene back, two white styrene ribs (0.12" thick) at 4" and 8"	6.5	517	28.4	12.8	25.6
27	0.098" polyester resin front, 0.06" white styrene back, two white styrene ribs (0.12" thick) at 4" and 8"	7.1	620	8.2	4.0	25.4
28	0.098" polyester resin front, 0.06" white styrene back, two white styrene ribs (0.12" thick) at 4" and 8"	7.4	876	83.3	18.7	80.6
1	0.016" Al front, polyethylene corrugated rib, 0.01" Al foil back	6.0	630	0.6	0.17	1.3
2	0.01" Al foil front, polyethylene corrugated rib, 0.016" Al back	5.9	594	0.04	0.01	1.3
13	0.06" white styrene faces, 0.375" aramid rib	13.5	1128	1.5	0.2	1.3
14	0.07" cracked ice acrylic front, 0.08" clear acrylic back, 0.25" Al honeycomb rib	10.5	832	1	0.23	1.3
15	0.06" white styrene faces, 0.25" Al honeycomb rib	10.2	764	1	0.25	1.3
16	0.08" clear acrylic faces, 0.25" Al honeycomb rib	10.8	942	3	0.65	1.6
18	0.08" (2" x 2" scored) clear acrylic front, 0.08" clear acrylic back, 0.125" Al honeycomb rib	7.2	638	2	0.82	9.5

The outcome of these non-fire screening tests was gratifying.

- The best of the new powder panel designs examined in this project offer the potential to be competitive with halon 1301 in a wider variety of dry bay designs. In one of these cases (epoxy primer front face), nearly 50 % of the front face area was removed, almost 60 % of the powder was released, and the powder remained suspended throughout the dry bay for over four minutes. This compares with testing of other powder panel designs integrated into operational aircraft, where the powder dispersed only along the shotline, dissipated in tenths of a second, and the amount of dispersed powder was limited to the region of projectile penetration. Figures 12 and 13 show major performance benefits achievable with the enhanced design concepts in Table 4.

Figure 12. Effect on Suppressant Delivery of Standard Design Features and Enhanced Designs Showing 5x to 10x Greater Powder Release in the Latter

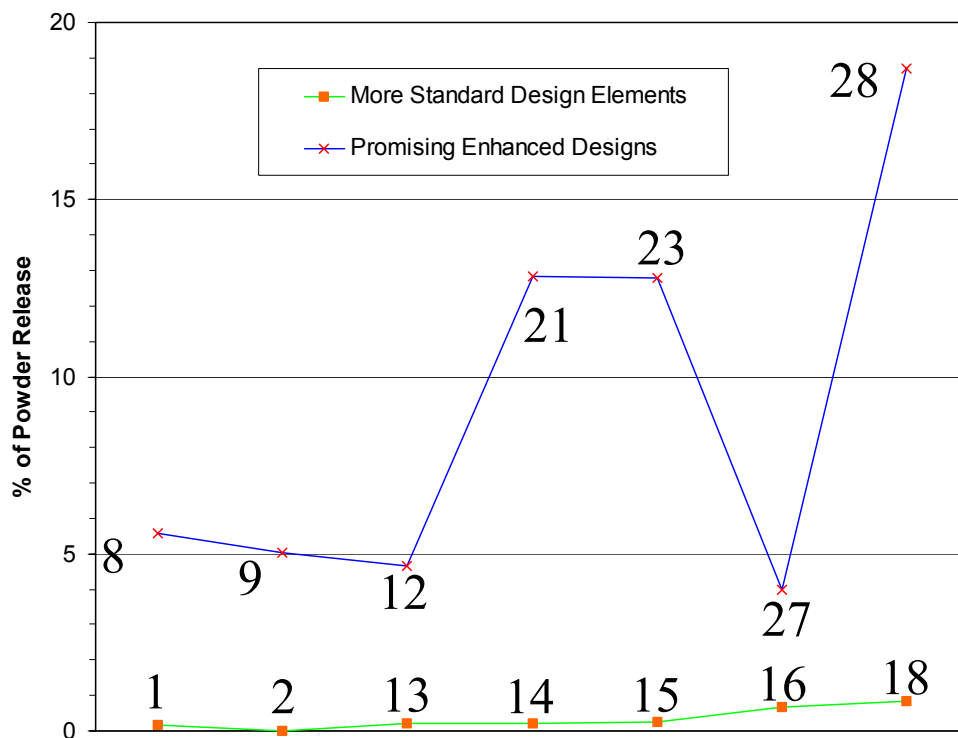
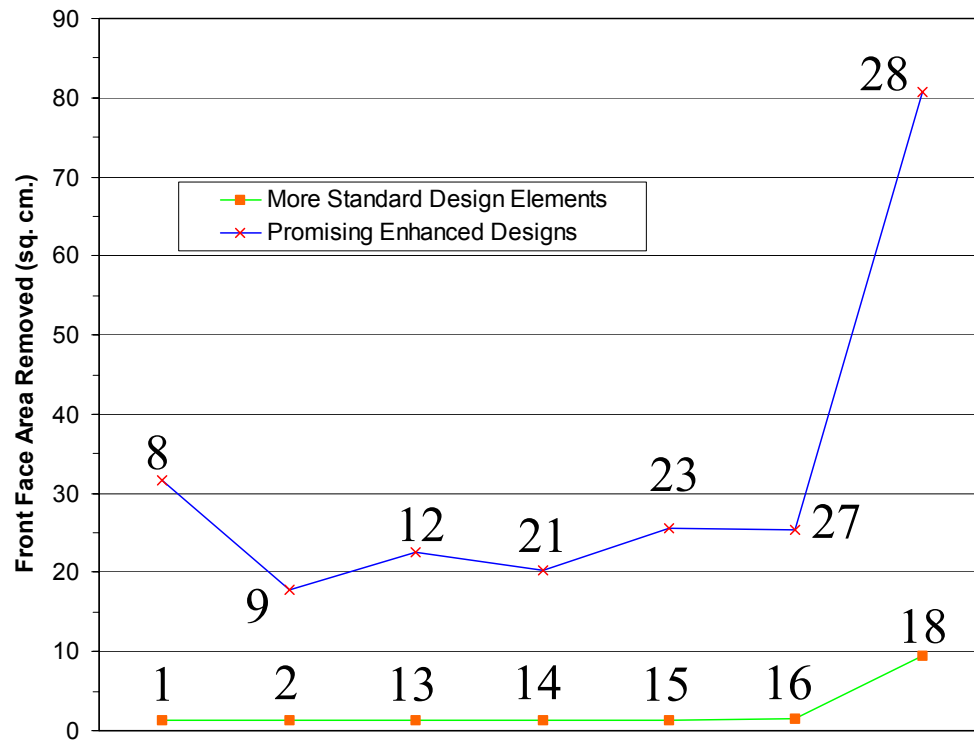


Figure 13. Effect on Powder Panel Fracture Area of Standard Design Features and Enhanced Designs, Showing 15x to 20x More Front Face Area Removed in the Latter



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

Recent Publications: Improved Suppressant Delivery

Presser, C., Widmann, J.F., DesJardin, P.E., and Gritzo, L.A., "Measurement and Numerical Prediction of Homogeneous Turbulent Flow over a Cylinder: A Baseline for Droplet-laden Flow Studies," AIAA 2002-0905, Am. Inst. Aero. Astro., Washington DC, 2002.

Fallis, S., Reed, R., McCormick, J.L., Wilson, K.A., and Holland, G.F., "Advanced Propellant/Additive Development for SPGG Fire Suppression Systems: Hybrid Systems," *Proceedings of the 2001 Halon Options Technical Working Conference*, Albuquerque, pp.364-372, Albuquerque, 2001.

Presser, C., Widmann, J.F., DesJardin, P.E., and Gritzo, L.A., "Measurements and Numerical Predictions of Liquid Agent Dispersal Around Solid Obstacles," *Proceedings of the 2001 Halon Options Technical Working Conference*, Albuquerque, pp.122-130, Albuquerque, 2001.

Yang, J.C., Nyden, M.R., and Manzello, S.L., "Cold Discharge of CF₃I in a Simulated Aircraft Engine Nacelle," *Proceedings of the 2001 Halon Options Technical Working Conference*, Albuquerque, pp.64-71, Albuquerque, 2001.

D. VIABILITY OF NEW SUPPRESSANT TECHNOLOGIES

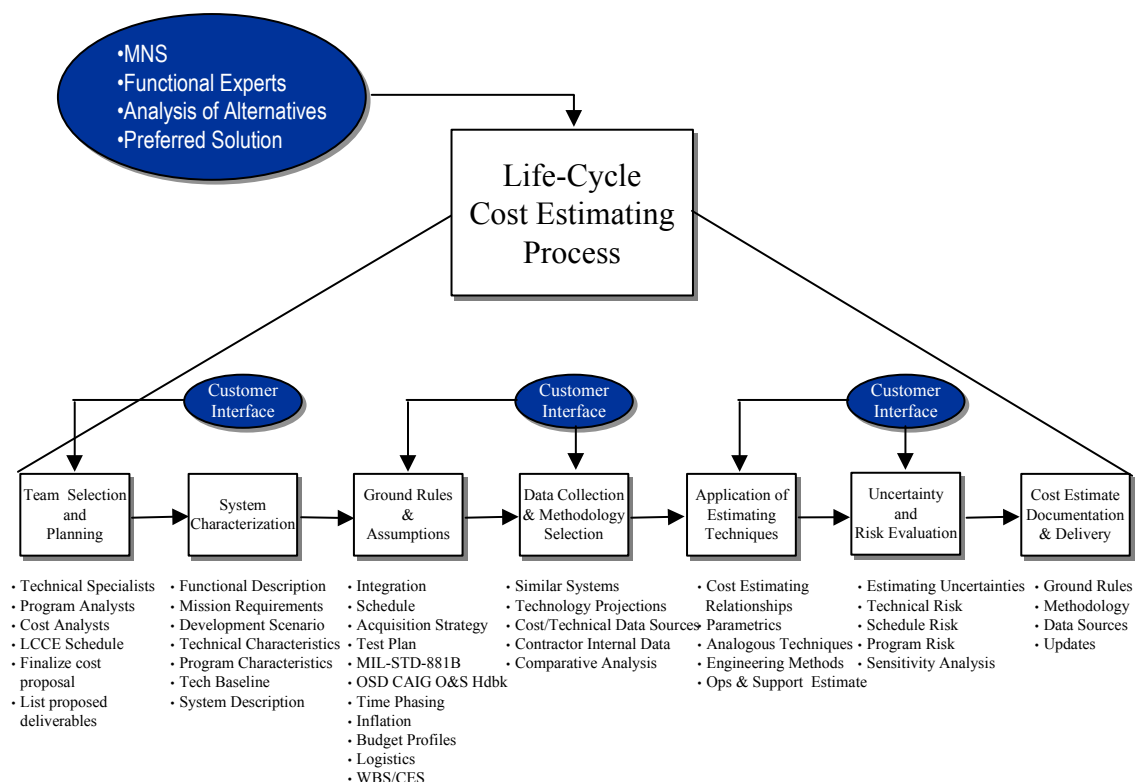
Benefit Assessment of Fire Protection System Changes

There are a large number of contributing factors that must be considered when deciding which fire suppression system to select for a new platform or whether to retrofit the fire suppression system on a legacy platform. These include both objective cost factors and subjective value factors. Accordingly, the NGP has developed a methodology to quantify a fire suppression technology by its total, life cycle cost and to enable superimposing on this a subjective value system. The 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 process shown in Figure 14 was used to determine the fire suppression system costs. The following paragraphs detail this process.

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

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

Figure 14. Life-Cycle Cost Estimating Process



Cost Analysis of Fire Suppression Systems for Cargo Aircraft. The total cost of ownership of the halon 1301 systems in the current fleet of an individual legacy aircraft platform (assuming a life cycle of FY00-22 and a platform total of 121 aircraft) is estimated to be \$25 M and for a legacy HFC-125 system ranges from \$35 M to \$41 M. These are approximately two tenths of one percent of the total (life cycle) cost of the aircraft. Based on an estimated fire cost per flight hour, the total estimated number of flight hours over the life of the legacy cargo aircraft, and a traditional success rate of halon 1301 suppression systems in military aircraft of 60 % to 80 %, it is estimated that the legacy cargo aircraft halon 1301 systems would save the Air Force between \$122 M and \$163 M in avoided fire losses.

The total cost of ownership of the halon 1301 systems (equivalent to that in the current fleet, above) in a fleet of a *future* individual cargo aircraft platform (assuming a life cycle of FY00-31 and a platform total of 121 aircraft) is estimated to be \$36 M. For an HFC-125 system of comparable effectiveness, the cost ranges from \$35 M to \$44 M. These are about 0.2 % of the total (life cycle) cost of the aircraft. Based on an estimated fire cost per flight hour, the total estimated number of flight hours over the life of the future cargo aircraft, and a traditional success rate of halon 1301 suppression systems in military aircraft of 60 % to 80 %, it is estimated that the future cargo aircraft halon 1301 systems would save the Air Force between \$136 M and \$181 M in avoided fire losses.

Therefore, it appears that the benefit of having either fire suppression 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.

Cost Analysis of Fire Suppression Systems for Fighter Aircraft. The total cost of ownership of the halon 1301 systems in the current fleet of an individual legacy aircraft platform (assuming a life cycle of FY00-28 and a platform total of 549 aircraft) is estimated to be \$11.2 M and for a legacy HFC-125 system ranges from \$15.6 M to \$17.8 M. These are approximately 0.05 % of the total (life cycle) cost of the aircraft. Based on an estimated fire cost per flight hour, the total estimated number of flight hours over the life of the legacy fighter aircraft, and a traditional success rate of halon 1301 suppression systems in military aircraft of 60 % to 80 %, it is estimated that the legacy fighter aircraft halon 1301 systems would save the Navy between \$154.7 M and \$206.3 M in avoided fire losses.

The total cost of ownership of the halon 1301 systems in a proposed fleet of a future individual fighter aircraft platform (assuming a life cycle of FY00-32 and a fleet of 549 aircraft) is estimated to be \$14.4 M. For an HFC-125 system of comparable effectiveness, the cost ranges from \$15.8 M to \$18.0 M. These are approximately 0.05 % five of the total (life cycle) cost of the aircraft. Based on an estimated fire cost per flight hour, the total estimated number of flight hours over the life of the future fighter aircraft, and a traditional success rate of halon 1301 suppression systems in military aircraft of 60 % to 80 %, it is estimated that the future fighter aircraft halon 1301 systems would save the Navy between \$156.5 M and \$208.7 M in avoided fire losses.

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

Changes in Cost Analysis for Altered Fire Suppression Performance. The objective of this project included consideration of fire suppression systems with performance different from a halon 1301 system. Using the above methodology, modifications were made to the performance of the cargo and fighter fire suppression systems by utilizing data from the Factor of Safety (FOS) study performed during Phase III of the Halon Replacement Program for Aviation. These suppression system weights and corresponding effectiveness were correlated to the cargo and fighter aircraft platforms. For cargo aircraft, the net cost change per single percent change in extinguishing effectiveness (*i.e.*, 91 % successful vs. 90 % in the field) of the fire system was approximately -\$2.0 M. For fighter aircraft, the net cost change per single percent change in system effectiveness was approximately -\$2.5 M. These estimates showed that additional investment in optimizing fire suppression system performance pays off in assets (costs) saved.

Recent Publication: Viability of New Suppression Technologies

Bennett, J.M. and Kolleck, M.L., "Cost Analysis of Fire Suppression Systems," *Proceedings of the 2001 Halon Options Technical Working Conference*, pp. 160-170, Albuquerque, 2001.

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 examined an array of technical and strategic documents before convening coincident with the 2001 NGP Annual Review Meeting in December 2001. The three-member IRP encompassed an array of expertise and experience from university, government, and industry environments. They have delivered a preliminary report, with the final version expected shortly.

The IRP draft 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.

The Panel also warned that some of the NGP reductions necessitated by reduced resources (e.g., in large scale testing, synthesis and screening of new chemicals, toxicity testing) “comprise an IOU that is certain to become due in the future” and 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.

Along with specific comments on each of the ongoing projects, the Panel made three priority recommendations:

- Establish a separate project on engine nacelle fire reignition or elevate this issue within existing projects. This has been a continuing design problem.
- Expand delivery and dispersion research to include additional high boiling point compounds in the individual research projects.
- Request summation sheets on lessons learned from the principal investigators to serve as a starting point for future system design heuristics.

They also made three further recommendations:

- 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.

- Address directly the issue of gas phase vapor loading from dispersed aerosols of higher boiling point extinguishing agents.
- Initiate the NGP final report preparation 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.

The perceptions inherent in these recommendation validate the value of convening the IRP. The recommendations themselves will be implemented as soon as possible.

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. Ideally such a project would be carried out well before the conclusion of a program, with the outcome of the tests indicating the optimal use of the remaining resources. As warranted and feasible, such follow-on tasks will be proposed.

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

Much of the innovation in NGP projects has resulted from interactions among a large set of investigators in diverse but related aspects of fire suppression. The 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 (available from the NGP web site)

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

² Gann, R.G., *FY2000 Annual Report: Next Generation Fire Suppression Technology Program (NGP)*, Technical Note 1437, National Institute of Standards and Technology, Gaithersburg MD, 48 pages (2001).

APPENDIX I. 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/15/0. 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, NMRI
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 ₃ I AND ON MATERIALS COMPATIBILITY WITH CF ₃ I Principal Investigator: Jiann Yang, NIST
4B/5/01.	ASSESSMENT OF COMPLETENESS OF SEARCH FOR ALTERNATIVE SUPPRESSANT CHEMICALS Principal Investigator: 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/1/01. 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: Lawrence Ash, NAVAIR

5E/1/1. ENHANCED POWDER PANELS
Principal Investigator: Dan Cypher, Skyward, Inc.
COR: Martin Lentz, Eglin AFB

6A/1/01. 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: William Pitts, 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