PROGRESS UNDER THE NEXT GENERATION FIRE SUPPRESSION TECHNOLOGY PROGRAM IN FY2000

by

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INTRODUCTION

This is a year of transition for the Next Generation Fire Suppression Technology Program (NGP). The future funding level has been reduced, and the goal has been modified to "develop and demonstrate, by 2005, 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 NGP strategy has been updated and can be found at the NGP web site: www.dtic.mil/ngp/. The demands on the new fire suppression technologies have not lessened, but expectations from the NGP were reduced. By FY2001, the NGP would deliver an understanding of how chemicals must interact with flames to be as effective as Halon 1301, appraisal of the world of useful chemicals, identification of the best places to look for alternative suppressants and a first set of "best looks," a suite of screening tests, and a method for comparing the life-cycle costs of new fire suppression technologies. At the end of FY2000, the NGP has completed its fourth year of research, having produced nearly all of these deliverables. The following sections highlight the new knowledge gained from recent NGP research and where the research will proceed from this time forward.

TECHNICAL PROGRESS

SUPPRESSANT SCREENING TESTS

The NGP development of a set of efficient, accurate screening tests for new suppressant chemicals has been completed. Already published are protocols for progressive evaluation of compounds for environmental impact, toxicity, materials compatibility, inhalation toxicity, and fire suppression efficiency of gases and liquid aerosols.

The last screening tool, the Transient Application, Recirculating Pool Fire **(TARPF)** facility, can simulate situations not possible in cup or Tsuji burners: impulsively discharged gases (such **as** from a pressurized storage bottle or solid propellant gas generator, SPGG), the impact of a hot surface on continuous suppression, the impact of a recirculating flow, and the effectiveness of a liquid spray. With the added capability to test SPGGs, for the first time both compressed and solid-propellant-generated gases can be compared side by side, and the effect on performance of different formulations, particle loadings, and burning rates for various SPGG designs can be unambiguously discriminated. The fact that, in Figure I, the agents (chemically or physically active, discharged from an SPGG or a compressed gas bottle) all lie close to the theoretical equation shows the value of this new apparatus.

From computer simulations and related experiments, it was determined that the most difficult fire to extinguish results when the flame is anchored to the trailing edge of an obstacle in the flow and is established in the mixing layer between the re-circulation zone immediately behind the step and the main flow. The worst case for re-ignition (minimum re-ignition time) occurs when the time required to mix the air and fuel is short compared to the time necessary for the fuel surface to cool.

NGP research has now used a variety of tools to **look** for candidate agents and understand how they function to quench flames. The latter is especially important, both for considering the potential of agents that have not yet been synthesized and for gaining confidence that the chemicals **will** be effective on the practical fires of concern. We have found that the effectiveness of some types of chemicals varies significantly in different laboratory tests.

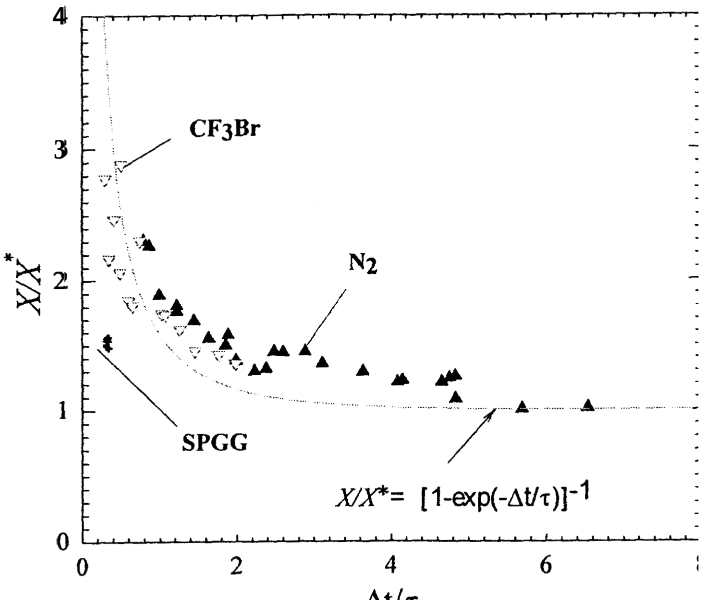

Figure 1. Comparison of N_2, CF_3Br, and SPGG effectiveness in the TARPF.

(1) Experiments with gaseous thermal agents indicate that extinguishing concentrations for diffusion flames vary by up to 20% depending on the flow configuration and the fuel, but the relative effectiveness of the agents remainsfixed. Kinetic modeling of these flames indicates that differences in the maximum flame temperature account for the observations. The Dispersed Liquid Agent Fire Suppression Screen (DLAFSS) produces the most conservative results.

(2) Gaseous halogenated agents have shown consistency in the concentrations needed to suppress flames in diverse laboratory burners and real-scale tests (notwithstanding the poor performance in the SPGG experiments reported below). Thus, any of the laboratory diffusion flames are useful to verify that a halogenated chemical is not unusual. The DLAFSS allows examination of the added contribution of the heat of vaporization.

(3) There is disparity in the measured suppression efficiency of "super-effective" chemicals such as those containing metal atoms. For instance, modeling and experiments suggested that ferrocene in **a** thermal bath should be a powerful suppressant of practical flames. However, when hot product gases from an SPGG passed through a bed of ferrocene and then to a spray flame, the combination did not have the intended high efficiency and failed to extinguish the flame. While this may be attributed to inefficient delivery of the ferrocene to the flame, further examination at laboratory scale seemed warranted.

(a) $Fe(CO)_5$ was ineffective at reducing the amount of CO_2 needed to quench a heptane cup-burner flame, while far less $Fe(CO)_5$ reduced premixed methane-air flame velocity **by** a factor of eight. Similar experiments with the quantity of a CF_3Br-CO_2, which would halve the premixed flame burning velocity, reduced the CO_2 required for extinction of the diffusion flame **by a** factor of two to three.

(b) Aqueous solutions of iron, sodium, and manganese salts suppressed flames in the **DLAFSS** at concentrations far below the suppression concentration of pure water. The iron result **is** consistent with the finding from opposed flow diffusion flames, OFDF (which had a higher flame strain rate) but at odds with the lower strained cup-burner flames.

(c) Phosphorous-containing compounds (PCC) show the same disparate behavior between the low strain, co-flow diffusion flame and the higher strain, counterflow diffusion flames. In the OFDF and **DLAFSS,** dimethylmethylphosphonate extinguished the flames at about 1% by volume. However, extinction of a cup-burner flame by this compound required the addition to the air stream of about 5% by volume, about the same extinguishing mass fraction as CO_2. There are no quantitative data on the effectiveness of PCCs on practical fires.

(d) Kinetic modeling of inhibited premixed flames provides some circumstantial indication of a delicate balance between the thermal and catalytic components of flame quenching. The thermal effect lowers the temperature, which leaves the flame radicals further away from equilibrium, making catalytic processes more efficient. However, if the temperature gets too low to permit adequate generation of the catalytic species from the parent compound in the available amount of time, the suppression efficiency will be diminished, not enhanced. Thus, for flame geometries in which suppressants will have short residence times in the flame zone, the rate and temperature at which the catalytic species is released is a critical property of a prospective agent. This will be especially important for suppressants added as droplets or solid particles.

Resolving the issue of the proper laboratory burner(s) for screening candidate suppressants is a priority for FY2001 research.

NEW FLAME SUPPRESSION CHEMISTRY

There are a large number of families of chemicals, and the NGP is working systematically to ensure examination of all pertinent compounds. The principal desirable properties guiding the search are the following:

- Fire suppression efficiency at least comparable to Halon 1301 and certainly higher than 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. **A** tentative upper limit is **80** °C, but slow evaporation or poor dispersion may reduce this significantly.

Previous NGP research had established the value of compounds that contain both a bromine atom for fire suppression efficiency and an additional feature that leads to rapid degradation of the compound in the troposphere. From a list of over **80** promising chemicals, four have emerged as particularly encouraging: **1-bromo-3,3,3-trifluoropropene, 2-bromo-3,3,3-trifluoropropene, 4-bromo-3,3,4,4-tetrafluorobutene,** and **2-bromo-3,3,4,4,4-pentafluorobutene**. New computational techniques indicate that the atmospheric life-times of these compounds are 4 to **8** days; their measured flame suppression efficiencies are comparable to other brominated chemicals. Evaluation of various toxicity properties for these compounds, pursued by the Advanced Agent Working Group, has been positive.

The main caution with these chemicals for aircraft **use is** their high boiling points. Prior research had indicated problems dispersing chemicals with boiling points of about -20 "C when the storage container and the environment are as low as -40 "C, a design specification for fire suppressants in aircraft. NGP research is underway to determine whether CF_3I (with a boiling point of -22 "C) will disperse well. **If** CF_3I floods the volume efficiently, the developed test procedures will be used to examine higher boiling chemicals. Meanwhile, a rigorous search is underway to identify and procure for testing additional bromofluoroalkenes, bromofluoroamines, and bromofluoroethers with significantly lower boiling points.

Prior NGP research had demonstrated the high flame quenching efficiency of PCCs in an opposed flow diffusion flame. New results show that the suppression efficiencies of PCCs are determined by the number of phosphorus atoms delivered to the flame with little sensitivity to the bonding environment. Detailed chemical modeling of the flame with added DMMP shows that the concentrations of the key P-containing radicals reach a plateau *before* an extinguishing concentration is reached. This further supports the concept that while small amounts of agent may reduce flame radicals to equilibrium levels, additional added heat capacity is needed to effect extinction.

To date, NGP research has investigated several chemical families as sources of alternative fire suppressants. With this enhanced knowledge, a comprehensive review of the world of chemicals has now been performed to identify those chemical families most ripe for examination in the NGP. 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 the main screening criteria. The following families were identified as the most promising: amines and nitriles; phosphorus-containing acids, esters, nitriles and halides; sulfides, mercaptans and sulfoxides; manganese and tin compounds; iodinated alkenes; and brominated or iodinated ethers. It is expected that substantial fluorination would be needed to obtain the desired low boiling points.

NEW AND IMPROVED AEROSOL SUPPRESSANTS

Nearly all suppressants of interest emerge from pressurized storage containers as liquids or powders, along with a gaseous component. NGP research has already shown that the properties of the dispensed aerosol can have a profound effect on the mass of suppressant needed to quench flames. The work this year has proceeded in two directions.

(1) The first involves improving the effectiveness of water-based aerosols. Since water dispersion and vaporization are problematic at the lower temperatures experienced by aircraft in flight, the NGP will not pursue this aspect in future years.

   (a) **A** picture has emerged of the suppression of opposed flow diffusion flames by water droplets. On a mass basis, water droplets can be at least as efficient as gaseous Halon 1301. The transition from very effective, smaller droplets to larger, less effective ones depends on the aerosol boiling or decomposition temperature, the density of the liquid or solid, the local temperature, and the residence time of the aerosol at that temperature.

   (b) NGP research has pursued the use of additives to water to increase its effectiveness and lower the freezing point. While calculations indicated that lactic acid, a compound with a high heat of vaporization, might reduce the mass of water required for extinguishment, measurements in the **DLAFSS** revealed it had the opposite effect. The enhanced heat extraction is outweighed by the lactic acid's contribution as a fuel.

   (c) The strain rate (defined in terms of the velocities of the air and fuel streams, their densities, and a characteristic length) is a flame property that enables relating laboratory burners to actual fires. Velocities are difficult to measure for aerosol-laden air streams in which the particles or drops in the air stream carry a substantial amount of momentum, but the individual particles or drops may be too large to follow the gas flow. NGP research has developed a technique for measuring the true air stream velocity by saturating (io minimize evaporation) the air with fine (<1 μm diameter) droplets and following their movement using Phase Doppler Particle Anemometry. However, at water suppressant loadings over 5% by mass, the local strain rate is strongly affected; work continues to develop a suitable metric.

(2) The NGP is exploring the concept of storing effective but otherwise harmful chemicals stably in a safe medium, which would then release the chemical when the medium was discharged and reached the high-temperature neighborhood of the flame.

(a) Last year, NGP research had shown that it is possible for an inert host to transport a practical mass of a suppressant to the fire. The remaining question was the speed of release in the flame. We have now designed and tested a system for introducing the host particles into premixed and counterflow diffusion flames. We established a good correlation between the inhibition effects of $NaHCO_3$ in premixed and diffusion flames despite the significantly different structures of these flames. Hence, we expect that tests with two flames should be comparable in demonstrating the release of chemically acting agents.

(b) The original intent to try $Fe(CO)_5$ as the adsorbed suppressant will not be fulfilled. While several hosts absorbed significant $Fe(CO)_5$, they also all showed reaction of the absorbed agent when exposed to air, making it unavailable to provide the gas phase Fe required for efficient flame inhibition. Consideration of other metal-containing compounds may also be unwarranted if, as noted earlier, they prove ineffective on practical flames. Fortunately, the zeolites can absorb about 25% by mass of either Br_2 or I,. Their release from these particles will be tested soon.

IMPROVED SUPPRESSANT DELIVERY

Improving the efficiency of getting the suppressant to the site of the fire is as important as finding new agents. Last year, the NGP completed and validated a new computer code for prediction of two-phase fire suppressant flows during discharge, enabling appraisal of a new suppressant's compatibility with existing distribution plumbing. The focus of the research has now progressed to storage and discharge technology and transport once the agent has been dispensed from the system hardware.

NGP research is developing new SPGGs that have both reduced combustion temperatures and increased flame suppression efficiency, which in turn will enable suppressant stream momentum reduction. **A** first set of propellant compositions designed to produce cooler effluent was based upon novel high-energy, high-nitrogen fuels: 5-aminotetrazole and $C_4H_4N_{14}$. They were formulated with potassium perchlorate or strontium nitrate oxidizer and an elastomeric binder. Gas temperatures were reduced in some cases by 10 to 20% relative to a state-of-the-art chemically inert formulation. Lower levels of oxidizer or the use of different oxidizers will likely reduce the temperature further while maintaining high nitrogen generation. Compositions incorporating combustion inhibitors (decabromodiphenyl oxide [DBDPO], KNO_3, K_2CO_3, Fe_2O_3) were burned efficiently and were effective in fire suppression.

Exploratory tests were also conducted to bound the **mass** of an ***entrained*** fire suppressant needed to suppress a 1 MW **JP-8/air** spray flame. The agents were loaded inside the discharge section of a neutral-burning SPGG (Figure 2), whose exhaust consisted mainly of CO_2, N,, and H_2O. During SPGG discharge, the agents were to be vaporized and delivered into the fire zone by the high pressure, high temperature exhaust gases. About 40 g of either KI or K_2CO_3 was sufficient to suppress the flames. Flames were not suppressed by the addition of 40 g of iron oxalate, by **60** g of KBr or DBDPO, or by **80** g of Fe_2O_3 or ferrocene. Based on the distinctive colors imparted to the flames by several of the impinging agents, the powders seemed to be ejected out of the SPGG throughout the test duration of about **8** seconds. In the ferrocene tests, needle-shaped ferrocene crystals were deposited on the exit port of the delivery tube.

The similarity in performance between KI and K_2CO_3 reflects that observed in turbulent spray burner tests. This likely reflects the lead role of the potassium ion in suppression effectiveness rather than the anion. The cause of the reduced effectiveness of KBr relative to KI is unknown. It is also difficult to understand why the bromine-laden DBDPO and the iron compounds appear ineffective, although the ferrocene crystals at the SPGG exit implies that not all of the agent is reaching the flame. Additional work is planned to quantify the mass of agent reaching the flame and improve the agent delivery.

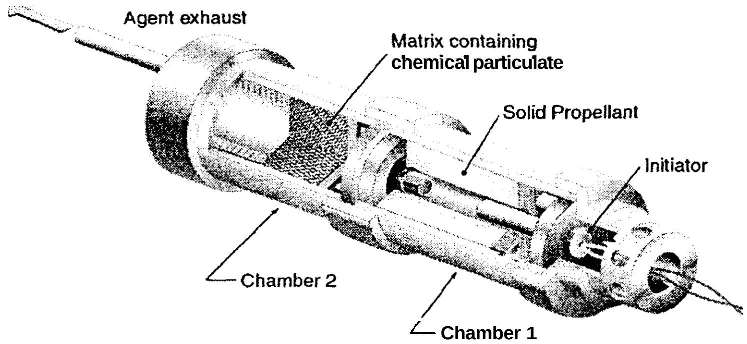

Figure 2. Solid Propellant Gas Generator Test Unit.

The Navy and Air Force aircraft safety and survivability teams have verified the expectation that improved location and styling of discharge sites can significantly reduce the mass **of** agent needed to control a fire in an engine nacelle. The NGP is developing a systematic approach to support such design modifications for all aircraft nacelles using a validated computational fluid dynamic (CFD) model of suppressant flow, a fire, and fire extinguishment in cluttered environments.

To establish a baseline, CFD predictions were compared with detailed measurements in a quarter-scale, smooth nacelle fixture (Figure **3)** under well-controlled conditions. Velocity and turbulent intensity profiles were obtained using hot wire anemometry and Laser Doppler Anemometry (LDA). Two CFD models, VULCAN and CFD-ACE, ably predicted the velocity and turbulence intensity for regions away from the wall. Near-wall discrepancies are likely due to the rectangular mesh in VULCAN and the small velocities near the walls that serve to increase the uncertainty in both the models and the data.

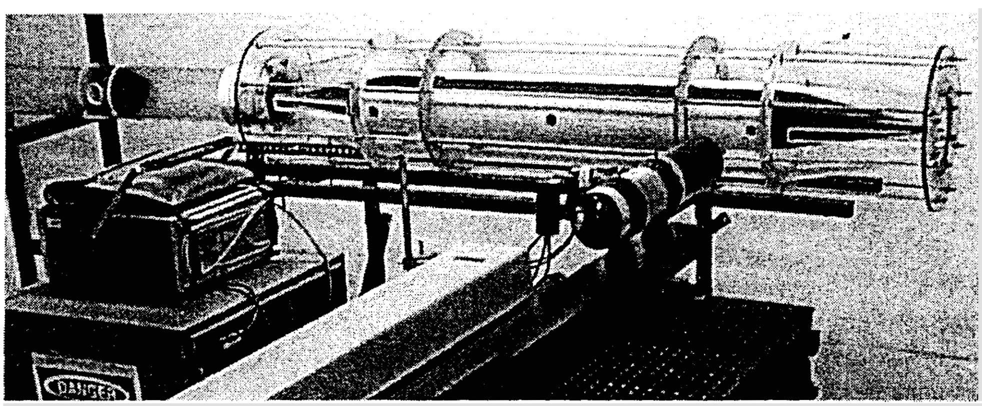

Figure **3.** Quarter-Scale Simulator with LDA test setup.

Representative forms of clutter have been selected for both the models and the test fixture: cylinders to simulate long runs of tubing and body-centered cubes of spheres for the random shaped clutter. The area blockage factor or the volume percent of the spheres will match that of the actual hardware clutter. The subgrid clutter packages have been completed and the experimental plan defined.

Including aerosol agents in such a model requires data on the change in flow behavior as the droplet-laden stream moves around obstacles: measurement of gas mean and turbulent velocity data both upstream and downstream of the obstruction. Accordingly, an existing spray facility has been modified to enable measurements of a well-characterized, closely isotropic turbulent flow field around a prescribed obstacle. The flows will be characterized using planar imaging velocimetry and phase Doppler interferometry.

enching a fire in an engine nacelle requires maintaining a sufficient concentration of agent in the flame ıe for a sufficient time interval while a forced air flow through the nacelle is sweeping the suppressant : the exhaust. **A** novel approach to achieving the residence time with a smaller amount of suppressant o reduce the cross sectional area of the nacelle, in the event of a fire, by strategic placement of an intu- :scent material (Figure 4). These materials are coatings that respond to the impingement of heat by elling a factor of **10** or more. Since the width of the (irregular) annular air passage is commonly no ›re than 3 cm - 10 cm, an appreciable reduction in airflow through the nacelle could be achieved. **Such** ocal fire **block** would weaken the fire due to oxygen starvation (by constricting airflow). By reducing e mass of suppressant needed, the constriction could even Iead to extinguishment by itself.

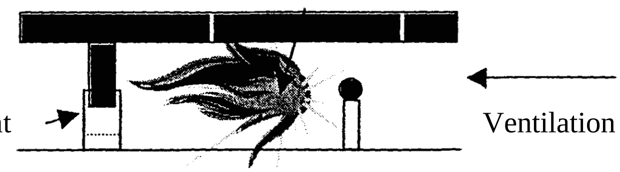

Figure **4.** Use of an intumescent coating to reduce engine nacelle airflow.

Ne have identified over **80** manufacturers of intumescent materials for other flame stop applications and ire reviewing the product data for durability of the coating during normal flight operations; adhesion and ,ibration-resistance of the expanded char following activation of the paint by a fire; effectiveness of the :oatings, including the expected expansion rate and the'fraction of the nacelle flow reduced by the coat- **ing;** and ability to apply the coatings to the nacelle. Data on current aircraft engine nacelles are being obtained to help determine the specific properties of a successful intumescent coating: areas of minimal clearance, potential material compatibility issues), airflow requirements in the engine nacelle, etc. These will enable an estimate of the decreased oxygen and/or increased suppressant residence timg that would result from a given constriction in airflow. This research will in turn lead to an estimate of the reduction in suppressant needed as a result of using this technology.

VIABILITY OF NEW SUPPRESSANT TECHNOLOGIES

Research has been completed on a portable instrument for measuring agent concentration with a 10 ms time response, fast enough for quantification **of** the transient agent concentration during the suppression **of** the fastest fires involving military systems. The Differential Infrared Agent Concentration Sensor **(DIRRACS-2)** was tested in a series of HFC-125 discharges carried out in a Bradley armored personnel carrier. **Ail** of the releases were from a high position just behind the turret. The concentration was monitored either near head height or waist height for an occupant of the vehicle. Figure 5 shows the ability to track the agent concentration; the fluctuations are due to turbulence.

A large number of contributing factors must be considered when making a decision whether or not to retrofit a fire suppression system, including 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 a subjective value system on this. 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). **An** initial case study was developed for the nacelles in C-17 aircraft for the existing Halon **130**I system and a system of equal performance using an off-the-shelf-alternative, HFC-125. Actual data were used to characterize the Halon 1301 system on the C-17.

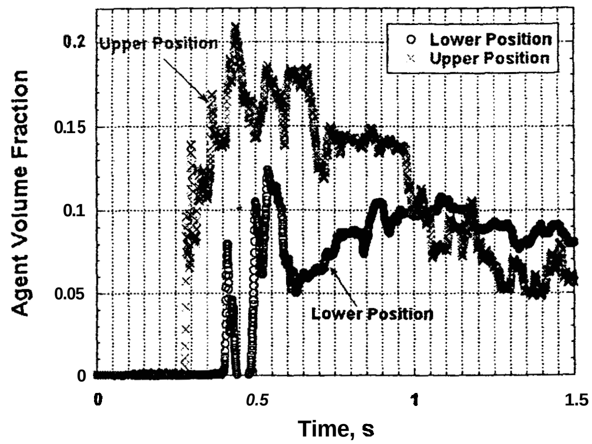

Figure 5. Agent concentrations from two releases of 3.5 kg of HFC-125.

Design estimates for a HFC-125 system were based on information developed in experiments conducted under the DoD *Technology Development Plan for Alternatives to Ozone-Depleting Substances for Weapon Systems Use.* System costs were derived from data provided by the Defense Logistics Agency, the C-17 Program Office, and engineering estimates. Uncertainties resulted from the lack of historical information over the life of the C-17 aircraft and the non-existence of a fielded HFC-125 system.

The estimated total costs of ownership of the Halon 1301 or HFC-125 systems in the current fleet of C-17 aircraft are close to each other and about one tenth of one percent of the total (life cycle) cost of the aircraft. The benefit of having either fire suppression system far 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. The project will continue with extension of the methodology to nacelles in the F/A-18 E/F and a rotary wing platform and a dry bay application.

IMPROVED FUEL TANK INERTION

Research in this area has been limited. Only two aircraft currently use Halon 1301 to inert fuel tanks when entering combat: F-16 and F-117. The Air Force is considering the use of CF_3I for this application. If this decision is positive, then alternative technologies for fuel tank inerting will not be an NGP task.

As an exploratory measure, the NGP has assessed the current status of alternate systems that had in prior decades shown promise for fuel tank inerting. An extensive literature search identified 25 such systems and characterized them, with regard to, e.g., their latest status, any history of testing or use, and any concerns with their implementation. The most viable of these are the LFE (Linear Fire Extinguisher) and the **PRESS** (Parker Hannifin Reactive Explosion Suppression System). Each has advantages that outweigh the disadvantages, and the LFE and PRESS were deemed capable of being overcome with further development.

WHAT LIES AHEAD?

Because **of** the substantial technical accomplishments in its initial years, the NGP has a solid base from which to develop new fire suppression technology for weapons systems. From this point forward, the NGP will be directed toward two targets.

NEW FLAME SUPPRESSION CHEMICALS

NGP research will complete its review of the world of chemicals in looking for alternatives to CF_3Br. Research into each of these chemical families will identify trends in suppression effectiveness, toxicity, etc., using NGP screening methods and quantitative structure-activity relationships from prior work. The optimal candidates will be flagged for further development. Full toxicological examinations will not be performed. A few real-scale tests will be conducted to demonstrate the reliability of the bench-scale results as a predictor of the success of agents, rather than full characterization of the performance of all candidate agents.

IMPROVED SUPPRESSANT STORAGE AND DELIVERY

NGP research has developed basic principles for the relationship between suppressant flow properties and the enhanced concentrations needed for the quenching of flames in cluttered spaces. The research has also shown the importance of the location (relative to the flame) where a suppressant fluid vaporizes. What remains is completion of the understanding of the interactions between the suppressant flow and the fire in cluttered spaces. This will serve as a guide for the selection of optimal dispensing conditions, nozzle locations, etc., for effective suppression of fires in the various engine nacelle and dry bay configurations. Further work will also develop new ways of positioning the suppressant and controlling its discharge properties, approaches complementary to the traditional pressurized fluid bottles. Combined, these will then constitute a set of source terms for the above models and offer flexibility and efficiency to the platform designer. These models and technologies will be turned over to the platform managers for optimization testing in their particular configurations.

ADDITIONAL EFFORTS

Over the past four 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 NGP thinking. A modest continuation of these solicitations is possible. Much of the innovation in NGP projects has resulted from interactions among a large set of investigators in diverse but related aspects of fire suppression. The NGP will continue to co-sponsor and participate actively in the spring Halon Options Technical Working Conference (29 April-2 May 2002). The NGP will broaden 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.

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