

# ADVANCED FIRE SUPPRESSION TECHNOLOGY FOR AIRCRAFT: FINDINGS OF THE NEXT GENERATION FIRE SUPPRESSION TECHNOLOGY PROGRAM

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## INTRODUCTION

In 1974, it was discovered that certain fully halogenated chemicals (chlorofluorocarbons, CFCs) could result in major changes in life on this planet.<sup>1</sup> These long-lived compounds would rise to the stratosphere, where they were photodissociated by ultraviolet (UV) light. The chlorine atoms catalyzed the conversion of ozone, which absorbs solar UV light and protects the earth's flora and fauna from excessive UV radiation, to ordinary oxygen, which provides no such protection.

The nations of the world reached agreement to protect the environment.<sup>2</sup> In the process, it was realized that some brominated compounds were potentially more dangerous than the CFCs, and the firefighting halons were named explicitly. Their production was curtailed sharply in amendments to the U.S. Clean Air Act of 1990. As of January 1, 1994, halon 1301 (CF<sub>3</sub>Br), a broadly used fire suppressant, was out of production, except in developing countries and countries whose economies were in transition.

The U.S. Department of Defense (DoD) had come to rely heavily on halon 1301 systems for many critical applications. One of these applications was for aircraft, which were vulnerable to fire during combat and needed in-flight fire protection during routine missions, a need shared by the commercial fleet. Initial research found that HFC-125 (C<sub>2</sub>HF<sub>5</sub>) was the best commercially available alternative fire suppressant for this use. However, this less efficient agent carried weight and storage volume penalties of up to a factor of three. Further research was needed on efficient and effective alternate technologies.

In 1997, the DoD Next Generation Fire Suppression Technology Program (NGP) began, with an objective that evolved 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." In its decade of research, the NGP revitalized the field of fire suppression science. The NGP final report documents how the NGP came about, what research was performed, how it modernized the thinking in the field, and the technical findings for fire suppression in aircraft. **Information regarding copies of the report can be found at [www.bfrl.nist.gov/866/NGP](http://www.bfrl.nist.gov/866/NGP).** While the research focused on the extreme conditions operative in in-flight fires in aircraft engine nacelles and dry bays, much of the science and understanding (summarized below) is applicable to a broad range of fire scenarios.

## THE NATURE OF IN-FLIGHT AIRCRAFT FIRES

Aircraft engine nacelle fires have resulted in the loss of aircraft both in combat and non-combat operations. The roughly annular interior of an aircraft engine nacelle is bounded by the engine core on the inside and the aerodynamic skin on the outside. To cool the engine and to mitigate the buildup

of flammable fuel/air mixtures, air flows through this space, with a typical residence time of the order of tenths of a second. Because of the fluid lines (for fuel, oil, and hydraulic/brake fluids) and other hardware in the annular space, the surfaces are irregular, and the air flow is highly turbulent. The exterior shell of the nacelle is nominally at ambient temperature, which can be as low as -40 °C. The interior of the annulus, the exterior of the engine housing, is somewhat warmer.

A fire can arise in numerous locations within the nacelle. In a typical peacetime fire scenario, one of the fluid lines leaks and sprays the flammable fluid onto hot machinery components, which results in a fire. The flaming fluid can also settle in the lower cavities of the engine nacelle, burning as a pool fire. During combat, there is the additional risk of an incoming round rupturing a line and causing the leak. Upon detection of a fire and the shutdown of the engine, the fire suppressant agent must get from the storage bottle to the nacelle quickly, and then fill the entire space with a sufficient concentration of agent for sufficient time duration to quench the flames. This must be accomplished before the air flow flushes the agent out the nacelle exhaust. Because mass and storage volume are at a premium on any aircraft, the mass of the agent and its hardware must be kept to the minimum to do the job.

The second principal location of aircraft fires is in the fuselage and wing dry bays. The majority of peacetime fires there are due to an equipment failure or failure of the engine or starter. By contrast, combat dry bay fires are usually initiated by a ballistic projectile penetrating the dry bay wall and an adjacent fuel cell. The interiors of dry bays are irregular in shape and highly cluttered. The nature and magnitude of air flow within the dry bay depends on the location and extent of breach of the outer wall. The pressure spike following an ignition can rupture the dry bay wall. This can result in an explosion as air mixes with the released fuel. Thus, dry bay fires must be suppressed before the pressure reaches levels that threaten the survival of the aircraft, typically within a few tenths of a second.

## NGP FINDINGS

### New Understanding of the Fire Suppression Process

- Required Agent Residence Time. For an open flame, the criterion for flame extinguishment is that the concentration of suppressant exceeds some minimal value long enough for the chemical kinetics to quench the flame chemistry. For occluded flames, time is required for an extinguishing concentration of agent to exist in the recirculation zone behind the obstruction(s). This time depends on the concentration of the agent in the free stream and the time interval over which the agent has been injected into the free stream, i.e., the duration of the suppressant wave. The agent mass needed for suppression can be minimized by injecting the agent for a period near the characteristic mixing time, which scales with the obstacle height divided by the velocity of the flow. The minimum volume fraction of agent required to suppress the flames is similar to the value determined in cup burner tests.
- If a significant fraction of the suppressant mass is in the form of a volatile aerosol, there are additional dwell time and droplet size considerations that determine whether that fraction will take part in the flame extinguishment process. Droplets that are too large will not be entrained into the recirculation zone. Smaller droplets may be entrained, but may require extended time within the recirculation zone to evaporate fully.

### Chemistry of Fire Suppression

- Many of the pre-NGP (and some NGP) studies of the effects of additives on flames addressed flame *inhibition*. The additive concentrations were generally not increased to near the point of flame extinguishment. It was recognized that additional processes contribute to the extinguishment of actual fires.
- Flame propagation results from the fast reactions of key species (H and O atoms, OH radicals) with vaporized fuel molecules. These species exist at concentrations far above those expected from thermal equilibrium at flame temperatures. Chemically active agents decompose in the

flame to generate the entities that catalytically reduce the radical concentrations toward equilibrium levels. While this catalytic process slows the flame, it does not necessarily extinguish it. Both chemically active and physically active suppressants increase the heat capacity of the fuel/air mixture, reducing the flame temperature and thus, along with the decreased concentrations of radical reactants, decrease the flame reaction rates below the level needed to sustain combustion. These two effects are synergistic.

- The addition of bromine-, iodine- and chlorine- containing compounds to flames does decrease the H atom and OH radical populations. These families of compounds are more effective at inhibiting laboratory flames when added to the air than when added to the fuel. The effectiveness of these compounds is not sensitive to the form of the non-catalytic moiety. However, any included hydrogen acts as fuel, which offsets the apparent flame suppression effectiveness. The relative efficiency of these atoms in inhibiting flames is  $\text{Cl} < \text{Br} = \text{I}$ , reflecting the lower ratio of the forward to reverse rates of the  $\text{HCl} + \text{H} = \text{H}_2 + \text{Cl}$  reaction, which causes Cl to be less effective.
- Compounds containing a phosphorus atom are at least as effective as halon 1301 on a molar basis. The effectiveness is independent of the structure of the non-phosphorus moiety, as long as the phosphorus is fully vaporized, with sufficient residence time in the flame zone. The active phosphorus-containing species concentrations reached plateaus at levels below those calculated to cause flame extinguishment, indicating that thermal effects also contributed to flame extinguishment.
- Metal-containing compounds, especially those with Cr, Pb, Fe, and Mn, have a high potential for flame inhibition, and Ni, W, and Mo have a medium potential. However, condensation of the active species to form inactive particles has been observed for most of these. Were this condensation to occur in practical fires, as was observed for ferrocene, compounds of these metals would likely not demonstrate fire suppression capabilities commensurate with their observed high flame velocity inhibition efficiency. Prediction of the potential loss of effectiveness due to condensation is presently difficult.
- For effective catalytic flame inhibition, the active species need to be present at the right part of the flame. The active species are usually one or more decomposition products of the agent. Hence, the agent must decompose near the flame (due to high reactivity or a sufficiently low activation energy), so that the proper intermediates for the catalytic cycle are present for a sufficient time to deplete the radical pool. An active species will be most effective if it is in high concentration where the peak chain branching reactions (and hence, peak radical volume fractions) are located.
- Flame extinguishment without any direct chemical or catalytic activity entails making it harder for the flame-generated enthalpy to maintain the fuel/air “bath” at a temperature high enough for these reactions to continue. The sink for this enthalpy is the heat needed to raise the suppressant from the ambient temperature to flame temperature. For a gaseous agent, this high heat capacity results from excitable vibronic modes of a number of chemical bonds and perhaps dissociation of one or more weak chemical bonds. For compounds that reach the flame zone as an aerosol, additional endothermic contributions come from the liquid phase heat capacity and the heat of vaporization. For a constant mass of an aerosol, there is a monotonic increase in the flame extinction efficiency with decreasing droplet size.
- If weight limitations allow, the effectiveness of a chemical agent can be enhanced by combination with a high heat capacity chemical.

### **Delivery of the Fire Suppressant to the Fire**

This is technology for obtaining the best fire suppression system performance for a given suppressant, including how best to deliver a flame extinguishing chemical to a fire.

- Dispensing from a Storage Bottle. The discharge rate of a suppressant fluid from its storage bottle depends on the prevailing internal pressure within the bottle ullage. This pressure is a

function of the fluid vapor pressure (which is exponentially dependent on the bottle temperature), the partial pressure of pressurizing gas in the ullage, and the solubility of the pressurizing gas in the fluid. The computer code PROFISSY predicts the pressure to within 10% using only the agent mass, the bottle volume, the fill temperature, and either the nitrogen mass needed to pressurize the vessel or the fill pressure of the vessel.

- Fluid Flow through Distribution Plumbing. Upon the opening of the storage bottle, the fluid enters the distribution piping as a two-phase mixture of superheated liquid and vapor. There is significant thermodynamic and thermal non-equilibrium between the phases. Furthermore, due to the large pressure drop in the piping, continuous flashing is anticipated as the fluid travels through the piping, and two-phase critical flow can occur at various locations. This can severely reduce the discharge rate of the fluid into the engine nacelle or dry bay. The computer code FSP estimates the pressure history and discharge flow from a pipe run of arbitrary design. The shapes of the calculated pressure histories are similar to experimental curves. The predicted discharge times are accurate to within 15 %. The code is thus a viable tool for the analysis or design of suppressant delivery systems.

### Effective Agent Dispersion

- To make use of the full mass of suppressant stored in the bottle, a chemical must be prone to flashing upon release, requiring a boiling point below the ambient temperature, a condition satisfied for very few fluids.
- The mass fraction of suppressant in the air stream is a key determinant of the success of flame extinguishment. Thus, the speed of suppressant injection is more important than the total mass of agent deployed.
- To deliver an extinguishing concentration of suppressant to a fire, a significantly higher mass of an agent with a boiling point higher than the engine nacelle temperature must be discharged compared to an agent with a boiling point below the prevailing temperature. Thus, a fire suppression system design based on room temperature test data may well fail to provide adequate fire protection when activated at low temperatures.
- The transport of liquid droplets downstream is dependent on the droplet size. Droplets larger than 30  $\mu\text{m}$  to 50  $\mu\text{m}$  tend to impinge on clutter surfaces. Smaller droplets entrain into the gas stream and transport around the clutter into the recirculation region behind an obstacle. Droplets with lower boiling points tend to vaporize more readily, resulting in decreased droplet size or even complete evaporation.
- Rapid lateral distribution of the suppressant in an engine nacelle is enhanced by multiple injection ports, as contrasted with the single port that is sufficient for halon 1301. Three well-located ports is a reasonable starting point for suppression system design.
- The extinguishant concentration established in the recirculation zone is a function of the free stream concentration, the nature of the obstacle (“clutter”) that stabilizes the flame, and the mixing time behind that obstacle. The time to mix agent into the flame-stabilizing recirculation zone behind *isolated* clutter is proportional to the size of the clutter divided by the velocity past the clutter. Interaction between *multiple* clutter objects can reduce or extend the time to mix agents into recirculation zones behind obstructions. A nearby (second) piece of clutter that is the same distance from the agent injection port as a flame-stabilizing piece of clutter *reduces* the mixing rate of agent into the flame stabilization region. The second object pulls the streamlines away from the recirculation zone. A nearby (second) piece of clutter that is behind (downstream of) a flame-stabilizing piece of clutter *increases* the mixing rate of agent into the flame stabilization region. The downstream object pushes the streamlines into the recirculation zone. The magnitude of these effects is related to the drag of the adjacent clutter object. Larger drag coefficients tend to influence the mixing process more strongly.
- Agent concentrations in the recirculation zone near a fire can be estimated from concentration measurements made under the same nacelle operating conditions, but without the fire.

- Any of three fire simulation programs (VULCAN, FDS, and FPM) can help design a fire suppression system in practically any space inside an aircraft and can guide the design of qualification tests which may be required for acceptance of a fire-suppression system for an aircraft. In NGP full-scale nacelle testing, almost all the predicted borderline extinguishment outcomes were extinguished.
- Improved powder panels, as weight efficient as halon 1301 systems, can provide excellent quenching of ballistically initiated explosions in aircraft dry bays. Compared to conventional designs, these new panel designs provide greater powder release into the dry bay, better dispersion of the powder to prevent ignition off the shotline, longer powder suspension to prevent fire ignition for a longer time, and greater flexibility of design to effect application-specific objectives. The effectiveness of prototype panels was demonstrated in live fire testing. While these improvements were demonstrated using  $\text{Al}_2\text{O}_3$ , an inert powder, additional enhancements can be obtained with chemically active powders that are also lighter. There is logical extension of this technology to fire suppression in ground combat vehicles.
- A new generation of solid propellant fire extinguishers offers effective fire suppression for both engine nacelles and dry bays. An effluent temperature reduction of 30 %, reducing the potential for thermal damage, was obtained by incorporating the new high nitrogen propellant BTATZ and by the introduction of a coolant to the propellant formulation. The incorporation of  $\text{K}_2\text{CO}_3$  into the otherwise inert propellant reduced the mass needed for fire suppression by a factor of 3. Hybrid fire extinguishers (HFES), in which a chemically active suppressant is added to the propellant effluent, offer the potential for even larger gains in fire suppression efficiency. Prototype units have shown *system* weight reductions by over a factor of two, with still greater reductions possible by optimizing the findings.

### **Evaluation of Candidate Fire Suppressant Technologies**

The NGP anticipated the need to evaluate thousands of chemicals in its search for alternative fluids to halon 1301. Thus, a protocol for rapid and inexpensive screening was developed to identify those relatively few agents worthy of further examination. For each property to be screened, the first result from a three-step process was used: literature search for a published value, estimation of the value based on analogous compounds, and performance using one of the technically sound screening tests developed or adapted during the Program;

The screening tests determined to be most critical were for fire suppression effectiveness (< 5 % by volume, superior to HFC-125), volatility (boiling point below 20 °C), atmospheric lifetime (< one month), and toxicity (absence of data indicating a serious effect on people at a concentration lower than that needed to extinguish flames). The cup burner extinguishing concentration was a predictor of the critical flame suppression concentration required within the flame recirculation zone of an engine nacelle fire. No effective screen was found for cardiotoxicity, leaving a reliance on literature values for otherwise appealing compounds.

### **Potential for New, Viable Suppressants**

The NGP screened tens of thousands of compounds, identifying which chemicals work well, which don't, and why;

- No inorganic compounds were identified that met the screening criteria for suppressant fluids.
- There were no organic compounds that did not contain a halogen or phosphorus atom that met all the screening criteria, especially for fire suppression efficiency.
  - There were organophosphorus compounds with fire suppression efficiencies at least comparable to halon 1301. However, even with extensive fluorination, their volatility was too low, and some reacted in air.
  - Nearly all the brominated compounds examined showed cup burner flame extinguishment values comparable to halon 1301. The presence of multiple H atoms tended to offset this

efficiency. The replacement of H atoms with F atoms and fluoroalkyl groups lowered the combustibility and the boiling points of a wide range of organic chemical families.

- To have a negligible ozone depletion potential, a compound containing Br, I, or Cl must have a second feature that leads to rapid decay in the troposphere. The most volatile such compound,  $\text{CF}_2\text{BrCN}$ , has a boiling point of 3 °C and extinguished cup burner flames at under 4 % by volume. This compound may have promise if the low temperature requirement were relaxed. However, a rumor of high toxicity needs to be examined, and the estimation of a modest atmospheric lifetime confirmed.
- $\text{N}(\text{CF}_3)_3$  was reported to have a boiling point of -10 °C and should have fire suppression efficiency superior to HFC-125. However, since the compound is fully fluorinated and since the compound could give rise to nitrogen oxides (potent ozone depleters) in the stratosphere, there was caution about its environmental acceptability. Attempts to synthesize this compound for further testing were unsuccessful.

### **Additional Findings**

Measurements during Fire Tests. Conventional real-scale testing of fire suppression effectiveness involved little instrumentation: measurement of the time of fire extinguishment and the agent concentration that led to extinguishment. To learn more about the fire extinguishment process and to pave the way for improved qualification testing, the NGP developed additional measurement technology for real-time, *in situ* monitoring of the suppressant concentrations of suppressant, fuel vapor, oxygen, and HF, a toxic product generated during fire suppression by fluorinated agents.

Control of the Air Supply to the Fire. An annular band of intumescent material applied to the inside of an engine nacelle can significantly reduce the flow of air through the nacelle. Applied to the downstream end of the housing, the heat from an upstream fire would activate the chemical expansion of the material. This would result in decreasing the mass of fire suppressant chemical needed to effect flame quenching by two processes: increasing the residence time of the chemical in the flame zone, and allowing the flames to deplete the local oxygen concentration, reducing the flame reaction rate.

Life-cycle Cost Assessment. The NGP adapted a life cycle cost model to estimate the cost benefits of carrying fire protection systems for engine nacelles and dry bays on board military aircraft, and developed a methodology for estimating the total cost of either retrofitting existing aircraft or configuring future aircraft with new systems based on a non-ozone-depleting fire suppressant. The calculations were performed for cargo, fighter, and rotary wing aircraft. The currently installed agent baseline was halon 1301; the modeled replacement agent was HFC-125. These estimates showed that additional investment in optimizing fire suppression system performance pays off in assets saved.

The methodologies were fashioned to serve as a stand-alone product, to provide the framework to build modified models for future halon replacements, and to serve as analysis tools to identify key indicators of desirable halon replacement properties to consider in later research on new technologies.

Since their formulation, this approach has already been used on some developmental aircraft. This methodology can be expanded to meet the additional challenges of new aircraft, new fire suppression technologies, and additional applications, such as fuel tank inerting.

### **REFERENCES**

<sup>1</sup> Molina, M.J., and Rowland, F.S., "Stratospheric Sink for Chlorofluoromethanes: Chlorine Atom Catalyzed Destruction of Ozone," *Nature* 249, 810-812, 1974.

<sup>2</sup> "The Montreal Protocol on Substances that Deplete the Ozone Layer as Adjusted and/or Amended in London 1990, Copenhagen 1992, Vienna 1995, Montreal 1997, Beijing 1999," United Nations Environment Programme, <http://hq.unep.org/ozone/Montreal-Protocol/Montreal-Protocol2000.shtml>.