# Chapter 11: VERIFICATION OF FIRE SUPPRESSION PRINCIPLES

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## 11.1 CONTEXT

As can be learned from the prior chapters of this book, the participants in the Next Generation Fire Suppression Technology Program accumulated and developed abundant knowledge of the subject. This new knowledge falls into five categories:

- Sources of difficulties of suppression of in-flight fires
- Fire suppressants and the fire suppression process
- Tools for evaluating fire suppressants and fire suppressant systems
- Potential for new fire suppressant chemicals
- Precepts for optimizing a fire suppression system, capitalizing on even a mediocre agent

Much of the understanding of fire suppressants and the fire suppression process was obtained from computations and reduced-scale experiments. This chapter summarizes those findings, including verified prior knowledge, and documents a series of real-scale experiments to verify the most important of the principles developed from those findings.

As stated in its goal, the NGP focused on processes, techniques, and fluids that meet the operational requirements currently satisfied by halon 1301 systems in aircraft. Nonetheless, both the knowledge gained and the principles developed have application to a range of military and civilian installations.

## 11.2 COMPLEXITY OF IN-FLIGHT FIRES AND THEIR SUPPRESSION

Analyses under the TDP (Chapter 2) had revealed the geometric intricacy of engine nacelles and dry bays and the difficulty of suppressing fires in those spaces. The NGP studies confirmed and clarified the implications of the complexity to new suppressant technologies.

Aircraft engine nacelle fires have resulted in the loss of aircraft both in combat and non-combat operations (Chapter 2). 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 ºC. The interior of the annulus, the exterior of the engine housing, is somewhat warmer (Chapter 2).

A fire can arise in numerous locations within the nacelle. In a typical peacetime fire scenario, one of the fluid lines leaks and sprays or streams the flammable fluid onto the 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 or spray.

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, 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 dry bays (Chapter 2). In fuselage dry bays, the majority of peacetime fires are due to an equipment failure or failure of the engine or starter. Equipment failures also have caused a large number of fires in wing dry bays. 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 critically on the location and extent of breach of the outer wall.

The rapid pressure buildup 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.

From examination of fires in both venues, there were findings that guided the search for alternatives to the current halon 1301 systems:

- Efficient and rapid distribution of the suppressant is essential. Halon 1301 accomplishes this with little assistance, because its boiling point ($T_b$) is below even the lowest ambient temperatures, which leads to flashing (Chapter 8). Other suppressants must have similarly low boiling points or be dispersed by other means. Effective dispersion can be affected by improved powder panels (for dry bays) and solid propellant fire extinguishers (Chapter 9). Misting of a high boiling chemical will not necessarily be sufficient, due to the potential for condensation of the droplets on the inside of the cold exterior surface of the aircraft.
- There are significant weight and storage volume penalties for an inefficient or inefficiently distributed agent that affects the relative cost of alternative fire suppressant technologies (Chapter 10).
- Despite the complexity of the flames in actual in-flight fires, there are existing laboratory burners that manifest sufficiently similar properties that they can be used to extract the properties of chemicals that effect fire suppression.

Fuel tank fires during combat are also a major cause of aircraft losses (Chapter 2). However, only two U.S. aircraft, the F-16 and the F-117, use halon 1301 to inert the fuel tanks against ballistically caused explosions. At the time of the NGP, the decision had been taken to vintage the existing halon 1301 systems. Thus, no detailed examination of the dynamics of inerting against this type of fire was performed.

The suppression requirements for fires in military ground vehicle crew compartments are similar to those for in-flight dry bay fires. Most commonly, these vehicle fires are mist explosions or hydraulic spray fires, initiated by hot fragments from ballistic impact. The flames must be quenched within 250 ms to prevent incapacitation of the crew (Chapter 5).

For most other common fires that have historically been controlled using halon 1301, the requirement for rapid suppression is not as stringent. However, the physics and chemistry of the fires is similar.

## 11.3 NEW UNDERSTANDING OF THE FIRE SUPPRESSION PROCESS

### 11.3.1 Overview of Fire Suppression

The quenching of flames can be accomplished by:

- Removing the fuel or separating the fuel from an air supply,
- Reducing the available oxygen supply,
- Reducing the time in which the fuel and oxygen are mixed and available to react,
- Cooling the fuel/air mixture below a temperature that supports sufficiently rapid chemical reaction for flame propagation, or
- Adding a combustion inhibiting chemical at a concentration sufficient to reduce the rate of fuel oxidation below that needed for flame propagation.

Conversely, flame extinguishment will not occur, or be less efficient, if:

- Too little of the flame suppressant reaches the fire zone in a timely manner,
- The flame suppressant passes through the flames too quickly to effect its role,
- The flame suppressant is released so slowly, or disperses so broadly, that the fire is not exposed to an extinguishing concentration.

### 11.3.2 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 (Chapter 8). The material would be applied to the downstream end of the housing so that 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:

- Decreasing the flow of air through the nacelle, which would increase the residence time of the chemical in the flame zone; giving it longer to work, and
- Allowing the flames to deplete the local oxygen concentration, reducing the flame reaction rate, and allowing a smaller mass of fire suppressant to complete the extinguishment.

A second effect of air supply to the fire results from the inflow of the fire suppressant. The turbulence created can enhance the mixing of air with the vaporizing fuel, enhancing the rate of combustion (Chapter 8). This increased reaction rate and heat release, combined with a marginal or insufficient concentration of fire suppressant, can create an overpressure that could damage the aircraft.

### 11.3.3 Delivery of the Fire Suppressant to the Fire

#### Dispensing from a Storage Bottle

In the absence of extensive distribution piping, the discharge rate of a suppressant fluid from its storage bottle depends on the prevailing internal pressure within the bottle ullage. To ensure the high pressure needed for rapid discharge of the fluid at low ambient temperatures, a compressed gas is added to the bottle.

The pressure in the ullage of the storage bottle 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 (Chapter 8).

### 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 (choked) flow can occur at various locations. This can severely reduce the discharge rate of the fluid into the engine nacelle or dry bay.

The mass flow of a two-phase fluid through a complex pipe run (with bends, tees, and elbows) depends on the nature of the piping and several thermodynamic and transport properties of both phases: specific heat, thermal expansion coefficient, isothermal compressibility, specific volume, specific entropy, dynamic viscosity, and thermal conductivity. The surface tension of the liquid phase and the saturation temperature are also needed.

The computer code FSP estimates the pressure history and discharge flow from a pipe run of arbitrary design (Chapter 8). The code is also able to replicate the qualitative behavior associated with the release of dissolved gas as the delivery system undergoes rapid depressurization during the discharge of the suppressant agent. The shapes of the calculated pressure histories are similar to experimental curves. The predicted discharge times are accurate to within 15 %. Because of these characteristics, the code appears to be a viable tool for the analysis or design of suppressant delivery systems.

### Effective Fluid Dispersion

Coordinated experiments and fluid dynamics modeling added the following knowledge enhancements to the general expectations that (a) clutter retards the flow of suppressant and can reduce the mass available to reach the site of a fire and (b) fires stabilized behind obstructions are the most difficult to extinguish (Chapter 8):

- 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. For chemically active suppressants, the reaction rates are a few orders of magnitude faster than the residence time inside the nacelle. Consequently, if a "wave" of sufficiently high agent concentration reaches all the potential zones of fire for even a fraction of a second, the fire will be extinguished.
- A fire suppression system design based on room temperature test data may well fail to provide adequate fire protection when activated at low temperatures.

  - Low temperatures of the agent storage bottle, airflow, and nacelle surfaces can adversely affect agent dispersion performance, especially when the prevailing temperature is below the normal boiling point of the agent. These increase the probability that a gaseous or aerosol suppressant will condense, resulting in liquid pooling at low points in the space. The subsequent evaporation from the pool is likely to be too slow to generate an extinguishing concentration.
  - Similarly, high clutter density and low air velocity significantly and synergistically act to reduce the mass of agent convected downstream by increasing the likelihood of agent contact with cold surfaces.
- The transport of liquid droplets downstream is dependent on the droplet size. Droplets larger than 30 µm to 50 µm 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. It is unlikely that droplets will shatter (and produce smaller droplets) upon impact with clutter.
- Electrically charged droplets of agents offer no advantage over neutral droplets, despite the presence of ions in flames.
- Clutter at an elevated temperature, e.g., heated by the engine, can affect the agent effectiveness.
  - A vapor stream can form downstream of the object due to liquid vaporizing off the hot surface.
  - Coating of the obstacle surface with droplets can result in significant surface cooling, which can be advantageous in preventing re-ignition.
- 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 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.
- Three fire simulation programs (VULCAN, FDS, and FPM) used in the NGP research capture much of the physical knowledge summarized above.
  - Any of the three can help design a fire suppression system in practically any space inside an aircraft. (While their application to spaces in ground vehicle, shipboard or

buildings was not investigated in this effort, there seems to be no conceptual impediment to such an application.)

  - Any of the three can be used to guide the optimization of the design of qualification tests which may be required for acceptance of a fire-suppression system for an aircraft or ground vehicle. Such utility allows the planner of tests to focus on those cases for which these simulations show that flame extinction is marginal, thus reducing the number of tests required to “prove” the system.
  - Each of these software programs incorporates a slightly different set of assumptions, so that using more than one of them may ameliorate unforeseen effects of the peculiar, embedded assumptions in any particular model. Thus, if two or more fire simulation programs agree in the outcome, the tests likely will confirm. If there be disagreement in the predicted outcome from different fire-simulation programs for the same case, then the conditions are approaching the edge of the extinguishment envelope.
  - In NGP full-scale nacelle testing, almost all the predictions of borderline extinguishment outcomes were, in fact, extinguished.

- Improved powder panels, as weight efficient as halon 1301 systems, can provide excellent quenching of ballistically initiated explosions in aircraft dry bays (Chapter 9).
  - 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.
  - Front face crack growth, which promotes more and better powder dispersion, can be optimized through the use of particular front face materials, thicknesses, rib designs, attachment methods to the ribs, and even surface scoring.
  - Additional benefit can be obtained by back face improvement and taking advantage of the strong synergism between the rib structure and the front face design.
  - Accidental leakage can be prevented by proper choice of plastics or composites, combined with modern adhesives.
  - While these improvements were demonstrated using $Al_2O_3$, 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 vehicles.
- A new generation of solid propellant fire extinguishers offers effective fire suppression for both engine nacelles and dry bays (Chapter 9).
  - Effluent temperature reduction of 30 %, thus reducing the potential for thermal damage, was obtained by incorporating the new high nitrogen propellant BTATZ ($C_4H_4N_{14}$) and by the introduction of a coolant to the propellant formulation.
  - Enhanced fire suppression efficiency can be obtained by the introduction of chemically active compounds to the formulation. The incorporation of $K_2CO_3$ 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.
  - This technology has been demonstrated effective in the quenching of automotive gasoline tank fires.
- Significant masses of some suppressants can be adsorbed onto inorganic particles, at mass fractions of 0.2 or higher. This might be a delivery option for compounds whose fire suppression efficiency is about a factor of five or more higher that of halon 1301 and which pose environmental or toxicological threats.

### 11.3.4 Effectiveness of a Fire Suppressant at Quenching Flames

#### 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. (See below.) For occluded flames, there are two distinct flame stabilization conditions: rim-attached and wake-stabilized. In the former, the flame detaches and goes out as soon as the agent arrives. In the latter, the shear layer first becomes unstable, followed by flame extinguishment in the recirculation zone. Time is required for an extinguishing concentration of agent to exist in this recirculation zone. 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 minimum volume fraction of $CF_3Br$ for suppression at different injection time intervals, normalized by its value for continuous application, correlates with $[1 - \exp(-\Delta t/\tau)]^{-1}$, where $\Delta t$ is the injection time interval and $\tau$ characterizes the mixing time behind the obstacle in the flow (Chapter 8). 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 wake stabilized flames investigated is similar to the value determined in cup burner tests.

To the extent that 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 (Chapter 4). For a given mass of suppressant, small droplet diameters are to be preferred. 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. Droplets with diameters below about 30 μm were entrained into laboratory flames and evaporated fully.

Combined with the boiling point requirement for non-loss at cold services, this small droplet requirement for effective evaporation has significant implications for the dispensing of an agent. To make use of the full mass of suppressant stored and released in the bottle, a chemical must be:

- Released as a gas, a condition virtually impossible for a volume-efficient fluid;

- Prone to flashing upon release, requiring a boiling point below the ambient temperature, a condition satisfied for very few fluids; or
- Dispensed as fine droplets, a condition requiring fine nozzles on the distribution piping and a high backing pressure. This will be difficult to achieve a sufficiently high discharge rate.

## Chemistry of Fire Suppression

Building on more than 50 years of flame inhibition research, intensive NGP efforts have generated more detailed understanding of the interaction of inhibiting chemicals with flames and culminated in a unified model of fire suppression. This included effectiveness by both physical and chemical processes. In different ways, each of these affects the rates of the chemical reactions that must proceed at rates sufficient to sustain fuel combustion.

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 (Chapter 7). For a gaseous agent, this enthalpy is determined by its heat capacity. A high heat capacity typically results from a molecule having a large number of atoms, with the associated large number of excitable vibronic modes. It is also possible that one or more weak chemical bonds can be thermally dissociated. 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.
- Fire suppressants also dilute the fuel/air mixture, slowing the reaction rates. This is small effect in any case, since the magnitude is linear in additive concentration, while the thermal cooling has an exponential effect on reaction rate. For compounds near halon 1301 in flame suppression effectiveness, the effect is negligible.
- For a constant mass of an aerosol, there is a monotonic increase in the flame extinction efficiency with decreasing droplet size. Water aerosols below about 30 μm in diameter were found to be more effective on a mass basis than halon 1301 at extinguishing counterflow diffusion flames. These droplets are small enough to evaporate fully in the flame zone. Modeling studies confirm that this effectiveness is largely due to the high heat of vaporization and the complete evaporation of such small droplets.
- Aerosols delivered to the hot surfaces in the vicinity of a fire can assist in quenching the flames and preventing relight by cooling surfaces. Effectiveness is enhanced by high values of the mass delivered, the droplet diameter, and the droplet velocity.

Efficient chemical extinguishment of flames results from depletion of the H, OH, and O radicals that drive flame propagation (Chapter 3). The process can be simple removal or catalysis of radical combination to less reactive compounds. In either case, the vibronic modes of the suppressant also absorb enthalpy and function, in part, as a thermal suppressant. Typically, for agents that are comparable in flame suppression efficiency (mass basis) to halon 1301, this thermal component is smaller than the chemical component.

Many of the pre-NGP (and some NGP) studies of the effects of additives on flames addressed flame *inhibition*. The additives were added to the flames in small quantities, and decreases in burning velocity, free radical concentrations, etc. were measured. The additive concentrations were generally not increased to near the point of flame extinguishment, since these flames become unstable, and measurements become difficult. From these studies emerged insights into the chemical and physical processes that degraded the flames. It is recognized that additional processes contribute to the extinguishment of actual fires.

In the simplest chemical process, radical trapping, a suppressant's breakdown products react with the radicals to form stable product species which are relatively inert in the flame. The most prevalent example is that of fluorine atoms. These are generated by pyrolysis or reaction of fluorine-containing suppressants and combine with hydrogen atoms to form HF. The H-F chemical bond is sufficiently strong (570 kJ/mol) that the H atom no longer participates in the flame propagation chemistry.

By contrast, catalytic radical recombination is a chain reaction process. Species formed from the thermal or chemical breakdown of the suppressant molecule initiate a cyclical process. (The typical bond energy between a catalytic scavenger and a flame radical is in the range of 300 kJ/mol to 400 kJ/mol, notably weaker than the H-F bond energy.) The net result is that pairs of reactive radicals combine to form more stable molecules, while the catalytic species is regenerated. In flames, the H, OH, and O radical concentrations in the reaction zone are well above those that correspond to thermal equilibrium. The rapid catalytic process drives the system toward thermal equilibrium (Chapter 3).

Among compounds containing non-metallic elements, catalytic activity has only been determined for the halogen atoms, Br, I, and Cl, and for phosphorus.

- The addition of bromine- (and by analogy, iodine- and chlorine-) containing compounds to flames does decrease the H atom and OH radical populations. This decrease occurs at a slightly lower temperature location in the flame zone than at the location of the peak H atom concentration.
- 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 $Cl < Br = I$. This reflects the ratio of the forward to reverse rates of the $HCl + H = H_2 + Cl$ reaction, which causes Cl to be less effective at flame temperatures.

Extensive research on phosphorus-containing compounds (Chapter 3) showed that:

- Compounds containing a single phosphorus atom are at least as effective as halon 1301 on a molar basis.
- These compounds catalytically decrease the H and O atom and OH radical populations, as do the halogens.
- The effectiveness is independent of the structure of the non-phosphorus moiety, as long as the phosphorus is fully in the gas phase in the flame zone. This requires vaporization or decomposition with sufficient residence time.
- Chemical kinetic modeling of an organophosphonate (DMMP) showed that the active phosphorus-containing species concentrations reached plateaus at levels below those required for flame extinguishment. This indicated that thermal effects also contributed to flame extinguishment.

From a detailed examination of the published literature, compounds containing 21 transition metallic elements demonstrated inhibitory effects in flame systems and/or on engine knock. Of these, five (P, Cr, Pb, Fe, and Mn) have a high potential for flame inhibition and three (Ni, W, and Mo) a medium potential, in the absence of condensation of the active species to form inactive particles.

Iron-containing compounds were studied as examples of highly efficient flame inhibitors (Chapter 3).

- $Fe(CO)_5$ and ferrocene are 10 times more effective as flame velocity inhibitors as halon 1301.
- The mechanism for the effectiveness of iron-containing compounds primarily results in H atom recombination. A secondary catalytic cycle results in O atom recombination.
- Gas phase transport of the active iron-containing species to the region of high H atom concentration is necessary for efficient inhibition.
- Particle formation near the location of peak H atom concentration can act as a sink for the iron-containing intermediate species and reduce the catalytic effect.
- The volume fraction of inhibitor influences condensation since at low values, it may be below its saturation value.
- The available residence time affects particle growth.
- If the particles are small enough, they can re-evaporate upon passing into the high-temperature region of the flame.
- Thermophoretic forces can be large in the flame and re-distribute particles away from the region of peak H atom concentration.
- Convection and drag forces, combined with the existing flow field in the flame, can prevent particles from reaching the region of peak H atom concentration.
- The flame temperature of the stabilization region of diffusion flames (such as in unwanted fires and the cup burner) is much lower than in premixed or counterflow laboratory diffusion flames, exacerbating the condensation potential.
- Ferrocene was ineffective at suppressing a spray burner flame, presumably due to extensive condensation of the iron-containing species into particles.

This loss of fire suppression potential due to particle formation in some flame systems has been observed for Cr, Pb, Mn, Sn, Co, and Sb, as well (Chapter 3). 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 high flame velocity inhibition efficiency that was observed when added at low concentration to laboratory premixed flames. There are no data to indicate the potential for particle formation for compounds containing Ni, W, and Mo. The vapor pressures of the suggested flame-quenching species (for which data are available) are reasonably high.

Prediction of the potential loss of effectiveness due to condensation is presently difficult. The potential depends upon the local supersaturation ratio in the inhibited flame. Calculation of this ratio depends upon knowing both the detailed kinetic mechanism of inhibition as well as the vapor pressure of all of the intermediate species. Further, the kinetics of the condensation (and potential re-evaporation of particles) will be highly dependent on the flow-field of the particular flame system to be extinguished.

Emerging from these studies is the principle that the effectiveness of a catalytically acting agent can be temperature dependent.

- For a higher temperature (e.g., premixed) flame, the radical pool will be larger, so that a fixed amount of inhibitor will have a smaller relative effect on the radical pool.
- The higher temperature also leads to a smaller difference between the superequilibrium radical concentrations and the equilibrium concentrations, further decreasing the effectiveness of the additive.
- A higher temperature can also lead to a shifting of the equilibrium of the key intermediate species (for example, to the right in the $HBr + HX\cdot \Leftrightarrow H_2 + BrX$ reaction), leading to a lower effectiveness.
- A higher flame temperature can decrease the condensation rate (or increase the vapor pressure) of the particles, increasing their effectiveness.

The spatially resolved experiments and chemical kinetic modeling demonstrated that, 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. The right place in the flame is where the radicals are most prevalent. 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.

In summary, a unified view of the suppression of flames by chemically active agents is as follows:

> Flame propagation results from the fast reactions of key species (H and O atoms, OH radicals) with vaporized fuel molecules. These species exist at concentrations far above those expected from thermal equilibrium at flame temperatures. Chemically active agents 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. Thus, if weight limitations allow, the effectiveness of a chemical agent can be enhanced by combination with a high heat capacity chemical.

## 11.4 EVALUATION OF CANDIDATE FIRE SUPPRESSANT TECHNOLOGIES

### 11.4.1 Screening Measures

The NGP anticipated the need to evaluate thousands of chemicals in its search for alternative fluids to halon 1301. While full-scale testing of chemicals is eventually necessary to demonstrate acceptability, it was impractical to use such tests to narrow that large a list of candidates. Moreover, many of the chemicals would need to be custom synthesized and/or would be of unknown toxicity. 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 the selected screening test.

The screening tests determined to be most critical were for fire suppression effectiveness, volatility, atmospheric impact, and toxicity.

The criterion for fire suppression effectiveness was a cup burner flame extinguishment value below 5 % by volume, comparable to halon 1301 and superior to the HFCs.

- For thermally active compounds, the first step sufficed (Chapter 7). To be efficient at flame extinguishment without any chemical or catalytic activity, a compound needs to have high values of heat of vaporization, liquid phase heat capacity, total heat absorption due to a phase change, and/or heat needed to raise the liquid or gas to combustion temperatures. Such data were available for thousands of compounds, and thousands more could be eliminated by analogy. The NGP approach involved developing a figure of merit for evaluating each of thousands of compounds based on the total enthalpy absorbed by the compound as it was heated from room temperature to flame temperature, represented by 1400 K.
- For chemically active compounds, the cup burner was the main tool (Chapter 6). Many compounds had already been tested, enabling additional appraisals by analogy. Others were acquired in small quantities and approximate flame extinguishment values determined.
- Two other laboratory flame suppression devices were developed to examine specialized aspects. The Dispersed Liquid Agent Fire Suppression Screen (DLASFSS) was used to appraise the differences between a chemical being applied as a gas or a liquid. The Transient Application Recirculating Pool Fire Agent Effectiveness Screen (TARPF) was used to identify differences in effectiveness that might arise from impulsive (rather than steady state) injection of the suppressant, such as from a solid propellant fire extinguisher. Experiments indicated that reignition of flames could occur at hot surface temperatures as low as 400 ºC. The knowledge gained from each was used in evaluating chemicals in general, but neither was used as a routine screen (Chapter 6).

Volatility was reflected in a compound's boiling point. For reasons noted above, compounds whose boiling points were above 20 ºC were eliminated from further consideration.

- Including compounds with boiling points up to 20 ºC was fairly liberal, in that this allowed consideration of compounds that could only achieve an extinguishing concentration at equilibrium. Reaching this concentration by evaporation from a liquid pool is a slow process. Flushing of the chemical from the engine nacelle or reaching a dangerous overpressure in a dry bay would likely precede flame extinguishment unless a large excess of the chemical were dispensed. This would be the case even if the lowest ambient in-flight temperature were -18 ºC (Chapter 2) rather than the specified -40 ºC.
- If the *surface* temperatures within in-flight engine nacelles were as high as the predicted nacelle interior *air* temperatures (Chapter 2), (about 10 ºC to 30 ºC), then some of the higher boiling point compounds with boiling points near 20 ºC would flash and disperse effectively.
- Meeting the boiling point criterion also discriminated against chemicals indirectly. A chemical that has a high heat capacity and/or a feature that leads to degradation in the troposphere was likely to have a high molecular weight. More massive molecules typically have higher boiling points.

No measurements were made of the molecular properties that determine atmospheric lifetime. A chemical continued under consideration if it had a feature that rendered it tropodegradable, i.e., likely to have a short atmospheric lifetime.

The screening criterion for toxicity was the absence of data indicating that serious effects on people could occur at a concentration lower than that needed to extinguish flames. The focus was on acute toxicity, in particular cardiotoxicity.

- No effective screen was found for the cardiac sensitization of dogs, the standard test. (Dog tests of chemicals, conducted in parallel with the NGP, revealed unexpectedly high toxicity.) In vitro tests are in their infancy, especially for cardiac arrhythmia. The use of octanol/water partition coefficients showed promise as a screen for cardiotoxicity.
- Research was performed to extend and apply a realistic human exposure model (whose input was animal exposure data). This has the potential for more accurate assessment of the hazard from a short exposure to a discharged suppressant.
- Literature values were obtained for some appealing compounds. However, no new compounds survived screening for all four properties. Thus, the NGP performed no animal tests for candidate agents for in-flight fire suppression.

The cost and availability of a compound were not initial screening criteria. However, it was recognized that, for a non-commercial chemical, the difficulty (or non-existence) of a synthetic approach and the cost of the starting materials could prove problematic in obtaining operational quantities of the chemical.

### 11.4.2 Measurements during Fire Tests

Conventional real-scale testing of fire suppression effectiveness involved little instrumentation. This was typically limited to measurement of the time of fire extinguishment and the concentration of suppressant that lead to extinguishment. The latter was measured with a time constant of the order of 0.5 s. 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 suppression event.

- Time-resolved measurement of the concentration of a suppressant, $C_2F_5H$, in a single location was performed using a Differential Infrared Rapid Agent Concentration Sensor (DIRRACS, Chapter 5). The portable device used modulated light absorption in the 8.5 μm spectral region. The optical path length is 1 cm. The combined standard uncertainty was about 2 % (0.005 volume fraction). Turbulent fluctuations of about 10 ms were clearly resolved. The technique can be extended to other suppressants with discrete infrared absorption.
- Steady state concentrations of $CF_3I$ were measured using ultraviolet absorption at 270 nm (Chapter 8). The repeatability was ± 15 %. The technique can be extended to other suppressants that absorb in the ultraviolet.
- Concentrations of $O_2$ during live fire testing were measured using a four-location laser absorption apparatus. Data points were obtained every 10 ms, and the optical path was 10 cm. The minimum detection limit was 3000 μL/L.
- Fuel vapor concentrations were obtained using a novel two-laser, infrared absorption probe, with nominal wavelengths of 1.31 μm and 1.71 μm. The limit of detection was about 200 (μL/L)-m. The unit had not yet been tested at real scale.
- Concentrations of HF, a principal combustion product generated during fire suppression by fluorinated agents, were measured using infrared absorption at 1.31 μm. The measurement duration was 10 ms, with a minimum repetition period of 100 ms. The optical path length was approximately 10 cm.

### 11.4.3 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 (Chapter 10). 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. Specifically:

- It is highly cost effective for aircraft to carry fire protection systems, despite their life cycle costs and the infrequency of their use. Based on historical data, the return on investment in halon 1301 fire protection systems (in terms of the cost of aircraft assets saved by their use and their historical extinguishing success rate) was estimated to be over five-fold.
- It would also have been highly cost effective for the larger HFC-125 systems, of fire suppression effectiveness comparable to these halon 1301 systems, to have been installed on military aircraft. The return on investment would have been at least two-thirds that of the halon 1301 systems.
- For comparable fire suppression effectiveness, the net cost of a system using HFC-125 installed in a future aircraft is comparable to the net cost of a conventional halon 1301 system as a ratio of the overall fire protection system cost of ownership to the total aircraft platform cost, although in absolute terms it can differ by many millions of dollars for each aircraft platform of interest, with even higher differences observed for retrofit applications.
- Additional investment in developing systems with superior fire suppression performance (as indicated by higher extinguishing success rates in the field) to systems exhibiting historical levels of performance was observed to be cost effective and beneficial.

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.

## 11.5 POTENTIAL FOR NEW, VIABLE SUPPRESSANTS

Over the course of the NGP, virtually the entire world of chemistry was reviewed, screened, and, if warranted, tested against the criteria described earlier (Chapter 7).

No inorganic compounds were identified that met the screening criteria. The findings for specific families of inorganic compounds are as follows:

- Compounds of radioactive elements were toxicological unsuitable.
- Aqueous solutions of some of the salts mentioned below were highly efficient flame suppressants. However, the freezing points of these solutions are above the lower agent storage temperatures for in-flight aircraft.

- Compounds of Group I elements in the periodic table (lithium, sodium, potassium, rubidium, cesium, and francium) are flammable or are solids at room temperature. Alkali metal compounds applied as dry powders or liquid solutions are well known to be extremely effective fire extinguishants. Since these have not already been accepted for use on in-flight aircraft fires, due to corrosion problems, alternative compounds were not screened. In these powders, potassium salts are more effective than the corresponding sodium salts, consistent with the lower decomposition of the former to generate vapor phase potassium atoms.

- The compounds of Group II elements (beryllium, magnesium, calcium, strontium, and barium) are solids or low volatility liquids and have not shown the needed fire suppression effectiveness.

- The compounds of Group III elements (boron, aluminum, gallium, indium, and thallium) showed no promise. Boron compounds are flammable, toxic, or simply carriers of any bonded halogen or Group I atoms. Aluminum in compounds has not shown any catalytic flame suppressant capability. Thallium and indium compounds are toxic. There are no reported fire suppression data for the rare gallium compounds, but they are not expected to be superior to the other Group III compounds.

- In Group IV (carbon, silicon, germanium, tin, and lead), carbon-based compounds are discussed below as organic chemicals. There are no data to suggest that silicon-based and germanium-based compounds offer flame suppression advantages over the similar carbon-based compounds. Compounds of the heavy metals, tin and lead, are environmentally unacceptable.

- Within Group V (nitrogen, phosphorus, arsenic, antimony, and bismuth), arsenic and antimony compounds are too toxic; antimony and bismuth are environmentally unacceptable heavy metals. As discussed earlier, phosphorus compounds are very efficient at fire suppression; however, they are not sufficiently volatile for total flooding, and some are toxic. Inorganic nitrogen compounds did not show sufficient fire suppression effectiveness.

- Of the compounds of Group VI elements (oxygen, sulfur, selenium, tellurium, and polonium), oxygen has no fire suppression function itself, and inorganic oxides are too low in volatility. Sulfur and selenium compounds have not shown good fire suppression efficiency. Selenium compounds are generally toxic, as are the byproducts of sulfur oxidation during suppression. Tellurium and polonium compounds have not been tested, but are unlikely to be more efficient suppressants than sulfur compounds.

- As noted earlier in this chapter and in Chapter 3, compounds of several of the transition metals are far more efficient flame inhibitors than halon 1301. However, these compounds are insufficiently volatile for flooding applications. Ferrocene was not effective at suppressing a spray flame, likely due to condensation of the active iron species into relatively inert particles.

- Compounds containing four of the halogen atoms in Group VII (fluorine, chlorine, bromine, iodine) have been studied extensively. These are discussed further under the organic compounds. Bromine- and iodine-containing compounds are efficient suppressants.

- The noble gases in Group VIII (helium, neon, argon, krypton, and xenon) are inefficient fire suppressants.

Examination of organic compounds was barely more successful (Chapter 7):

- There were no available compounds that did not contain a halogen or phosphorus atom that met all the screening criteria, especially fire suppression efficiency and volatility. $N(CF_3)_3$

was reported to have a boiling point of -10 ºC 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.

- 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.
- The replacement of hydrogen atoms with fluorine atoms and fluoroalkyl groups generally decreased the combustibility and increased the volatility of a wide range of organic chemical families. Nonetheless, only $CF_3CN$ and the small fluorocarbons, fluoroamines, and fluoroethers were sufficiently volatile. The atmospheric lifetimes of the fully fluorinated compounds were too long for consideration. The remaining compounds were not comparable to halon 1301, or significantly superior to HFC-125, in fire suppression efficiency.
- Among the remaining halogenated compounds, most attention focused on those containing bromine. Chlorinated organic compounds are less efficient at flame suppression than the analogous compounds containing bromine or iodine atoms. The iodinated compounds are no more effective fire suppressants than the analogous brominated compounds, and there were concerns regarding stability and toxicity.
- Nearly all the brominated compounds tested, or for which literature data were available, showed cup burner flame extinguishment values comparable to halon 1301. The presence of multiple hydrogen atoms tended to offset this efficiency.
- To have a negligible ozone depletion potential, a compound containing bromine (or iodine or chlorine) must have a second feature that leads to rapid decay in the troposphere.
    - Heavily, but not fully, fluorinated bromoalkenes have sufficiently high fire suppression efficiency and short atmospheric lifetimes. However, even the smallest of these were insufficiently volatile.
    - The bromofluoroethers show good fire suppression efficiency. However, unless somewhat protonated, they are insufficiently reactive in the troposphere. Furthermore, their boiling points are too high for effective dispersion.
    - $CF_2BrCN$ has a boiling point of 3 ºC, the lowest of any tropodegradable brominated compound. It extinguished cup burner flames at under 4 % by volume. This compound may have promise if the low temperature requirement were relaxed, as suggested by the fire suppression incidence data in Chapter 5. However, a rumor of high toxicity needs to be examined, and the estimation of a modest atmospheric lifetime needs to be confirmed.

## 11.6 FIRE SUPPRESSION PRINCIPLES TO BE TESTED

The knowledge summarized above was, for the most part, obtained from laboratory measurements and calculations. These systems were carefully chosen in the context of the actual applications: in-flight engine nacelle and dry bay fires. Nonetheless, laboratory experiments do not fully replicate three-dimensional flows and transient mixing processes, and the computational models must, of necessity, assume some simplifications of geometry and reactivity to be tractable.

Thus, it was important to know the extent to which the research results will be valid for realistic fires occurring in the configuration and environmental conditions of a full-scale, or "real scale" engine nacelle. Accordingly, the NGP Technical Coordinating Committee and Principal Investigators identified a set of principles to be tested in such a test fixture. The following is a list of those principles, a statement of the importance of each, and the real scale experimental approach used to investigate them.

**Principle 1: Extinguishants with boiling points higher than the local engine nacelle airflow and surface temperatures do not disperse sufficiently in time for engine nacelle fire mitigation, whereas those with boiling points below the prevailing temperature can disperse sufficiently if properly applied.**

Importance: The ability of a fire suppressant to fill an engine nacelle quickly and completely is paramount to minimizing the mass needed for flame extinguishment and minimizing the total mass of the fire suppression system. The boiling point screening criterion, which was based on this principle, led to the rejection of a large number of otherwise promising candidates.

Real-scale Experimental Approach: The fixture temperature was set above or below the boiling point of either of two chemicals. Chemical portions that had not fully vaporized due to local temperatures below the chemical's boiling point would presumably condense on upstream clutter or pass by the fire zone to some degree in unvaporized state, and hence not contribute to the vapor concentration readings in the local instruments placed around the nacelle. The concentration of the chemical vapor was measured upstream and in the vicinity of potential flame zones. Additional factors varied were the degree of clutter and the air and chemical discharge rates.

**Principle 2: The measured cup burner extinguishing concentration of a candidate extinguishant is an effective predictor of the critical flame suppression concentrations required within the flame recirculation zone of an engine nacelle fire.**

Importance: Virtually all assessments of fire suppression efficiency have been obtained using the cup burner; this is likely to continue. The geometry of the flame and flow field is consistent with exposed flames. In practice, the extinguishing concentration is also dependent on the type of fire and the suppressant residence time in the flame zone. Laboratory experiments and calculations indicate that the flame extinguishment values are the limiting values for extinguishment of pool fires behind obstructions, the most difficult fires to quench.

Real-scale Experimental Approach: For a physically acting and a chemically acting suppressant, the minimum fire zone concentration that caused flame extinguishment was measured. Additional variables included the temperature of the air and extinguisher system, the degree of clutter, the air and chemical discharge rates, and the type of fire (fuel spray and pool).

**Principle 3: Increasing the number of local extinguishant discharge sites increases the dispersion quality in terms of balanced concentration profiles, up to some practical limit.**

Importance: The efficiency of dispersion of a suppressant throughout an engine nacelle or dry bay can be enhanced by the installation of a set of well located and designed agent discharge ports. However, each discharge port, with its associated hardware, increases the mass and complexity of the fire suppression system. Thus, it is important to know the extent to which there is a benefit from adding additional discharge sites.

Real-scale Experimental Approach: A fire suppressant was dispensed into the nacelle test fixture through two contrasting piping designs. The first comprised a single discharge port located far upstream of the fire site. Inside the nacelle, the piping terminated in either two nozzles or two open ends. The other design involved four discharge ports, at four positions spaced angularly around the diameter of the nacelle and at four separate distances downstream, in a helical arrangement to promote balanced flow distribution both radially and axially. The piping through each port again terminated in two open ends or nozzles. Concentration measurements at 12 locations in the nacelle enabled determination of the uniformity of dispersion. Additional variables included the air and chemical discharge rates, the degree of clutter, and the temperature of the test fixture.

**Principle 4: The extinguishant concentration established in the recirculation zone is a function of the injection time and mixing time behind the obstacle (“clutter”) that stabilizes the flame.**

Importance: The NGP correlation, developed at laboratory scale, is the potential basis for designing the preferred time profile of discharge of the suppressant. The correlation holds that the relative quantity of extinguishant entrained from the free stream over a bluff body that anchors a flame into the flame’s recirculation zone is a function of the ratio of the free stream velocity over the clutter to the height of the clutter. The agent discharge time also affects the total time the entrained extinguishant resides in the recirculation zone.

Real-scale Experimental Approach: The concentration of the agent was measured upstream of and within the recirculation zone. The variable was the size of the upstream obstacle.

**Principle 5: The passage of a suppressant through an engine nacelle is significantly affected by the degree of clutter in the nacelle.**

Importance: Prior NGP research efforts had characterized the degree of flow interruption, pressure drop and re-direction through clutter of various idealized configurations, including any condensation of liquid portions of mixed-phase extinguishant flows on the clutter arrays. Most of these studies were performed on idealized, two dimensional clutter representations, and computer models of this behavior were also derived. The complex three-dimensional flows and clutter arrangements in realistic nacelles may challenge these simplified representations.

Real-scale Experimental Approach: Measurements of agent concentration were performed at multiple locations in the test fixture. The standard deviation in those measurements, an indicator of the effect of the clutter on suppressant transport, was determined as a function of rib height and agent discharge rate.

**Principle 6: Assuming that a mix of extinguishant vapor and liquid aerosol reach the flame reaction zone, the sufficient vaporization of liquid particles to enhance extinguishment will be dependent upon, among other parameters, the liquid’s residence time in the recirculation zone.**

Importance: A significant fraction of the suppressant may be discharged in the liquid state. Droplets that do not evaporate fully before or in the flame zone are essentially wasted. If some mixture of liquid aerosol particles is interspersed with the extinguishant vapor as it enters the recirculation zone of the flame, the ability of the particles to evaporate and increase the extinguishant vapor loading in the flame to facilitate extinguishment is dependent upon its vaporization characteristics and residence time in the flame. The evaporation rate is based upon the common heat transfer properties known for these extinguishants, and the droplet diameters (or characterization of their distribution).

Real-scale Experimental Approach: The agent was discharged either through open ended piping or through nozzles that created a fine spray of droplets. Concentrations of agent vapor were measured at 12 locations in the nacelle to identify the total extinguishant mass required to be discharged to reach a given measured concentration just before and in the recirculation zone. Additional factors varied were the air and chemical discharge rates, the degree of clutter, and the temperature of the test fixture. Increases in the extinguishment mass required to reach a given concentration were interpreted as being due to increased collection of liquid portions of the extinguishant on the clutter upstream and prior to reaching the fire site, or passing through the fire site without sufficient vaporization.

**Principle 7: The suppression effectiveness of a non-catalytic extinguishant in a full-scale engine nacelle is determined by its ability to absorb heat as it enters the flame zone.**

Importance: Tests have indicated this is so for a variety of laboratory flames. The degree to which the latent heat can be used to decrease the amount of extinguishant necessary to suppress a fire in a full-scale engine nacelle needs to be verified. Verification under actual engine nacelle conditions will confirm the basis for fire suppression system design equations.

Real Scale Experimental Approach: The minimum concentration of suppressant needed to quench both pool fire and a spray fire were determined. Additional factors varied were the overall flow within the nacelle, the discharge rate of the suppressant, and the temperature of the test fixture.

## 11.7 METHODOLOGY FOR REAL-SCALE TESTING AND VALIDATION

### 11.7.1 Aircraft Engine Nacelle Test Facility (AENTF) Features and Capabilities

### Overall Test Facility

The Aircraft Engine Nacelle Test Facility (AENTF) at Wright-Patterson Air Force Base had been constructed expressly to realistically recreate the environment experienced within a wide range of aircraft engine nacelles, with the capability to conduct repeated, full-scale nacelle fire tests under those conditions. An overall diagram of the facility is shown in Figure 11–1. Figure 11–2 is a photograph of the nacelle section, and Table 11–3 is a cutaway view of the interior.

A primary feature of the facility was the capability to re-create realistic air flow and temperature conditions within the nacelle volume. An atmospheric blower and associated high-pressure bottle farm was used to provide up to 5 kg/s (11.0 lb/s) of air flow, which was more than adequate for the types of aviation platforms currently in operation. An industrial chiller was used to cool the rapidly flowing air. Even with subsequent heating due to insulation limitations between the chiller and the nacelle section, temperatures inside the nacelle of -34 ºC (-30 ºF) or below were achieved. Alternatively, industrial heaters heated the incoming air as hot as 135 ºC (275 ºF). A water quench system was used to cool the effluent from the nacelle fire test section and eliminate some of the combustion by-products, with a scrubber system used to remove the remaining contaminants before the effluent was exhausted to the atmosphere.

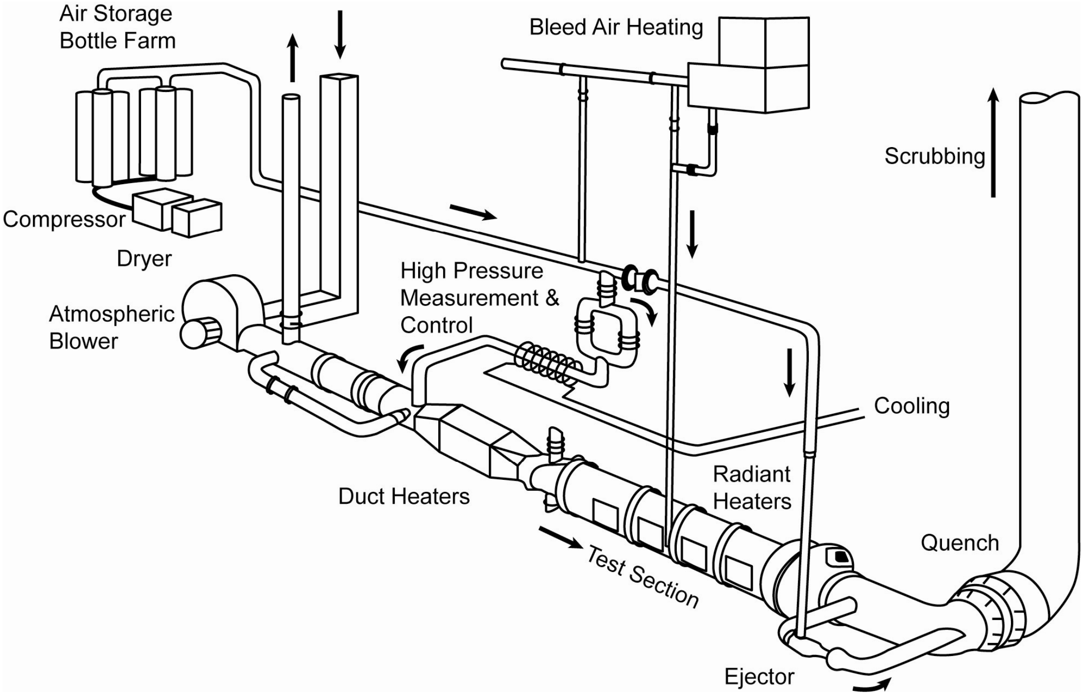

Figure 11–1. AENTF Primary Mechanical Components.

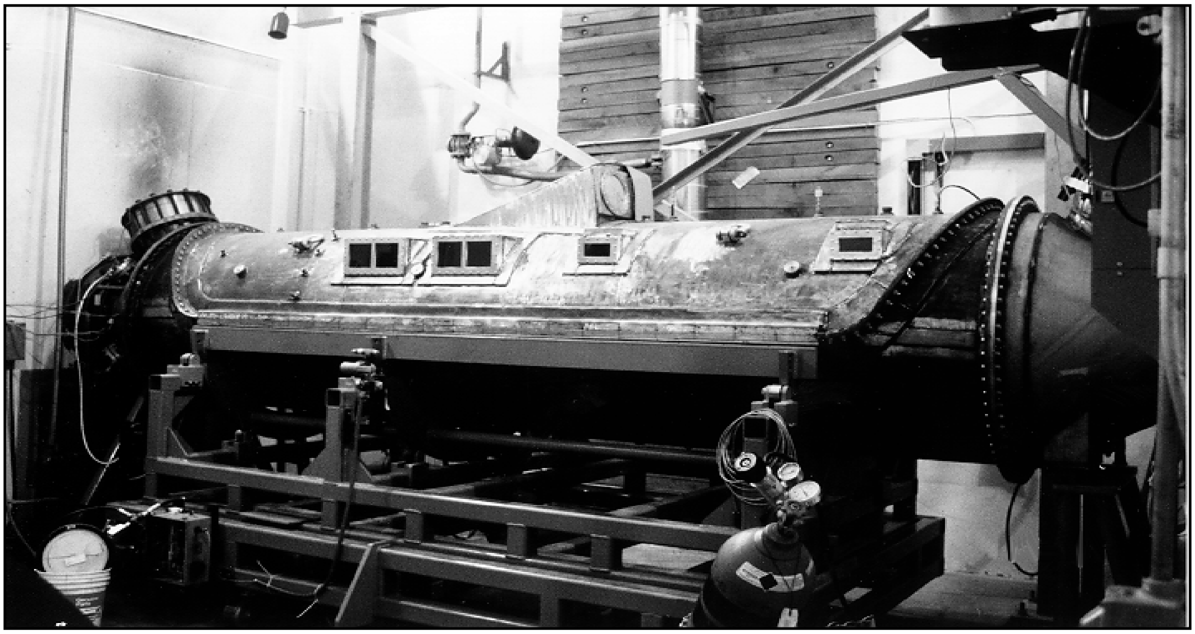

Figure 11–2. Photograph of Universal Test Fixture.

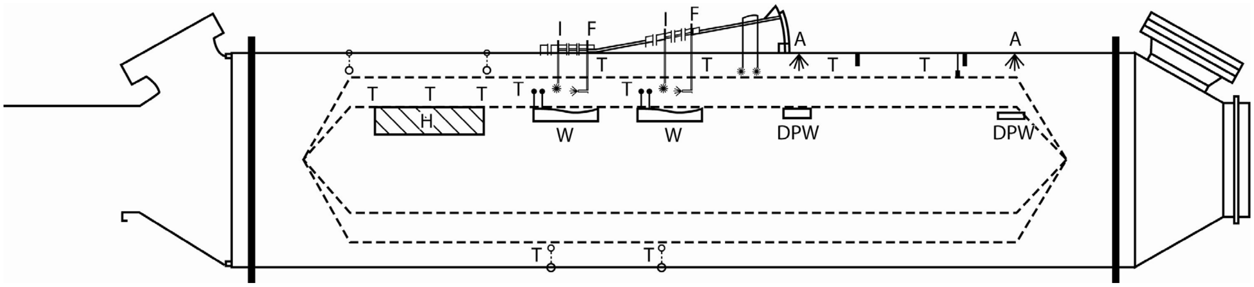

**Figure 11–3. Cutaway View of the Engine Core inside the Nacelle Fixture.** A: Agent Injection Port, F: Fuel Injection Site, I: Igniter, T: Thermocouple site, DPW: Dual Port Window. W: Window.

A remote fuel supply cart was used to supply heated flammable fluids, such as JP-8 jet fuel or an aviation hydraulic fluid, preheating and pressurizing them to their appropriate operating values before introducing them into the nacelle section. A separate extinguisher unit (Figure 11–4) permitted heating or cooling of the fire suppressant. For low temperature tests, the unit was immersed in a dry ice bath, regulated by a heat tape wrap, enabling a container temperature as low as -54 ºC (-65 ºF). A remote control room (Figure 11–5) was used to monitor the internal nacelle air flow, temperature and pressure, as well as fuel and extinguishant conditions, before and during each test. The operation of the fuel release, airflow control, fire and extinguisher initiation, and shutdown procedures were all computer-automated controls.

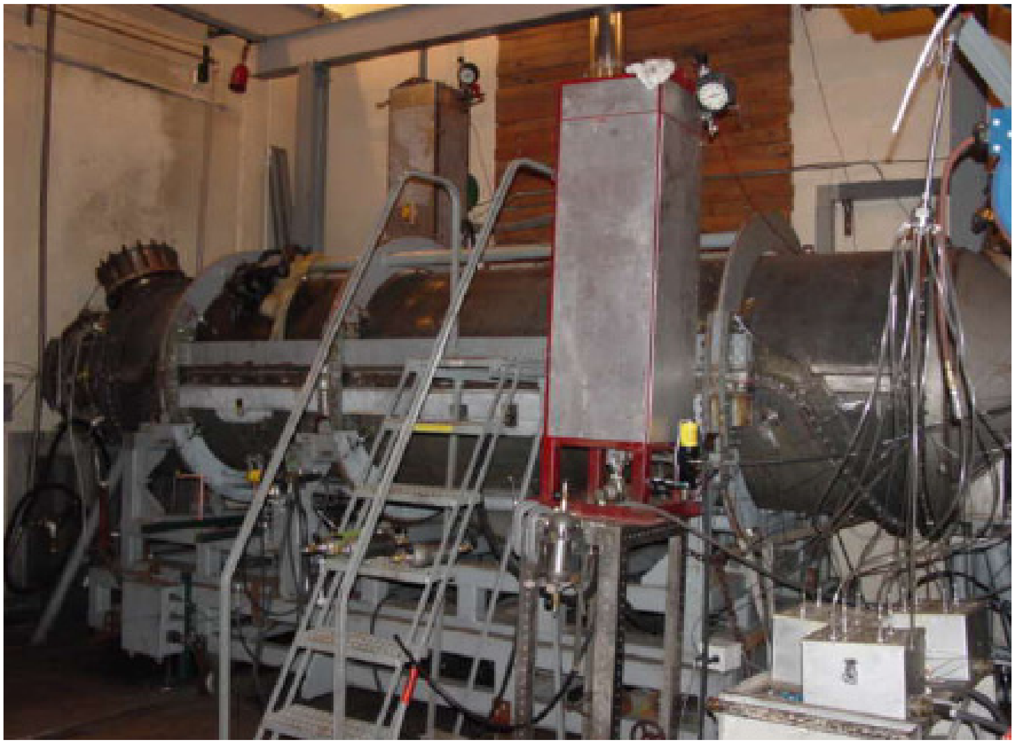

**Figure 11–4. Vertical Extinguisher Unit Attached to the Nacelle Fixture.**

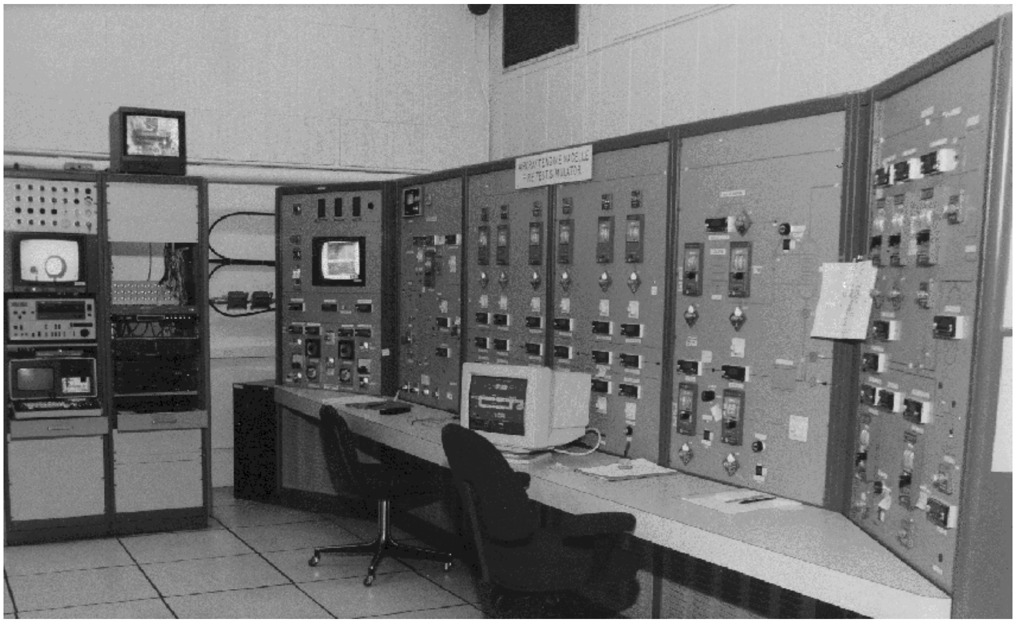

**Figure 11–5. AENTF Control Room.**

## "Generic" Real-scale Nacelle Test Fixture

The test section was a generic (i.e., reconfigurable) engine nacelle previously used in the National Halon Replacement for Aviation Program (conducted from 1992 to 1996)[1], as well as in more recent halon replacement testing for the U.S. Army. It featured the capability to replicate a variety of engine nacelle configurations and operating conditions. It had withstood thousands of full-scale fire tests under extreme thermal loads, and had shown the capability to retain its structural integrity, even when serving as a pressure vessel during fire tests at elevated pressures, due to the unique sliding graphite joint and clamshell design.

The outer nacelle case was a cylinder 1.22 m (4.0 ft) in diameter, and 5 m (16.25 ft) in length, housing a simulated engine core 3.8 m (12.4 ft) in length serving as the effective test section. Conical flow transition sections, each 0.27 m (10.5 in) deep, were attached at each end. Several internal cylindrical simulated engine core sections had been constructed and used in concert with this fixture. Their diameters were 0.61 m (2.0 ft), 0.76 m (2.5 ft), and 0.91 m (3.0 ft). For this program, only the largest diameter core was used, in order to minimize the free volume of the fixture and thus make efficient use of extinguishant for the considerable number of tests conducted. Rather than changing core diameters and the annular air flow clearance area between the nacelle and engine core, which was 0.15 m (6.0 in.) wide for these experiments, the air flow patterns (including local recirculation) were changed by varying the clutter (rib) height. The outer nacelle had multiple ports for making measurements in the nacelle. There were also ports at two distances downstream to mount fuel nozzles and spark ignitors. These enabled varying the distance between the agent discharge sites and the site of the fire, creating, in effect, a "long nacelle" or a "short nacelle." The entire nacelle assembly could be rotated to represent top, side, or bottom fire locations.

Two types of fires were used in these tests – spray fires and pool fires. Figure 11–6 is a semi-transparent view of the internal configuration of the test fixture (with airflow moving from right to left in the illustration). Both the spray fires and pool fires could be created in the bottom of the nacelle (each in their own separate experiments). The pool fire site was 30 cm (1 ft) downstream of the spray fire site. Each flame was stabilized by a variable height rib mounted just upstream of the flame site to act as a flame holder.

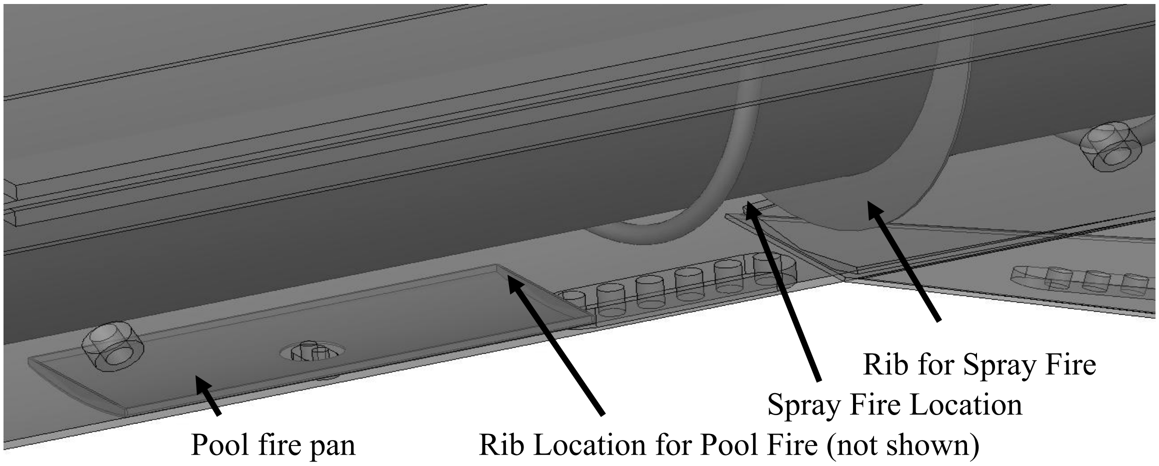

**Figure 11–6. Semi-Transparent View of Components in Fire Section of the Test Fixture.**

Figure 11–7 shows the pool fire pan. Figure 11–8 shows the configuration of components in the fixture interior near the origin of spray fires site, in the upper left quadrant of Figure 11–2.

**Figure 11–7. Pool Fire Pan in Nacelle.**

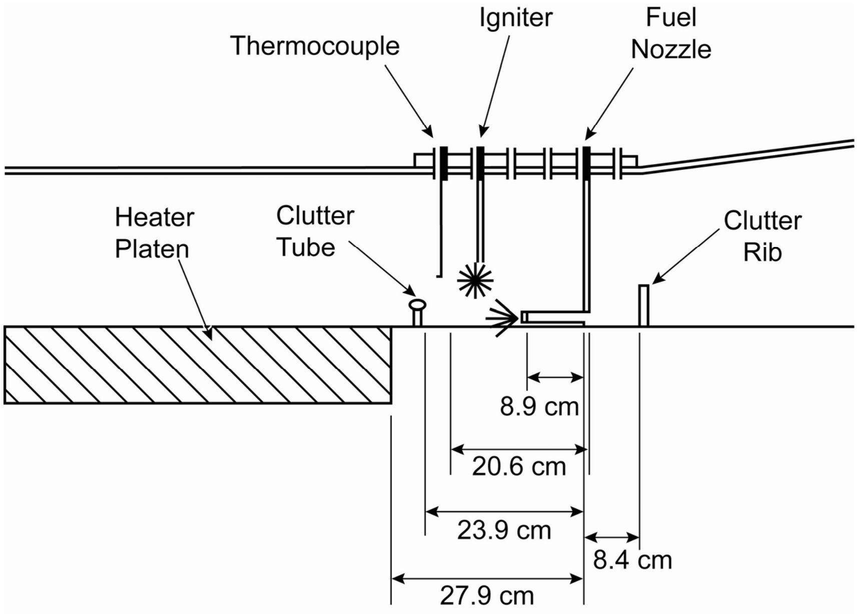

**Figure 11–8. Schematic of Spray Fire Vicinity.**

The agent could be discharged in-line, 90 º off center, or 180 º off center from the site of the fire. This enabled evaluating the ability of the extinguishant to wrap around the nacelle volume to remote sites before it was exhausted from the nacelle.

Annular ribs, simulating structural ribs, supports, and nacelle components, could be mounted on the inside of the outer nacelle and on the inner engine core. The rib heights varied from 2.5 cm (1 in.) to 7.6 cm (3 in.). Spaced at 30.5 cm (12 in.), they alternate between the nacelle surface, extending radially inward, and the engine core, extending radially outward (Figure 11–9). These ribs served to block the flow of extinguishant realistically and served as bluff bodies that shielded the base of the fire and create recirculation zones that made fires stable and resistant to blowout. The reddish material at the rib bases is a sealant to prevent air or fuel seeping under the rib connections.

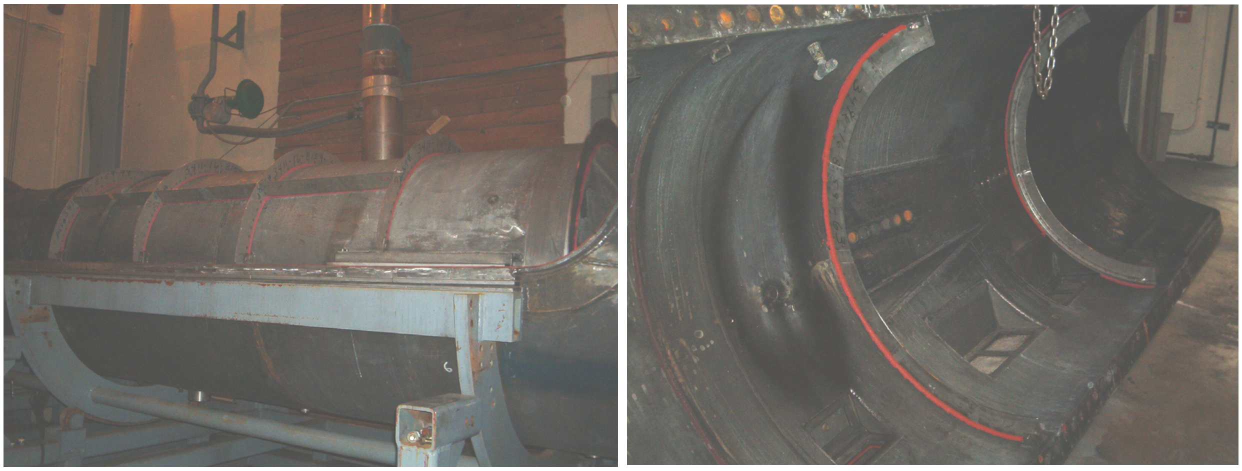

**Figure 11–9. 7.6 cm Ribs Mounted on the Underside of the Nacelle (left) and the Engine Core (right).**

In the flame region, there were also clutter-simulating ribs parallel to the flow. These inhibited the lateral movement of the extinguishant flow around the engine core surface, requiring entrainment over these lengthwise obstructions to enter the recirculation zone of a flame on the other side of the barrier.

A hot surface section, operating at temperature up to 830 ºC (1500 ºF), extended 120 º around the engine core, just downstream of the aft fire origin site. It served as a flame re-ignition source after initial extinguishment. This was not used in the current experimental series, since it decreased the repeatability of the test results.

Side view ports for camera recording were installed (a) downstream of the extinguishant inlets, to observe agent flow in the nacelle during discharge, and (b) near the two possible downstream fire locations, to monitor the flame extinguishing process. An additional port was mounted at an angle to the nacelle axis, permitting an upstream view from the downstream extinguisher port region, past both fire sites, to the aft end of the heater platen on the core, near the very end of the engine core. This permitted the monitoring of the entire agent entrainment and extinguishing process, as well as identification of potential re-ignition sites. Figure 11–3 shows the positioning of the video view ports, extinguisher ports, and other relevant features on and inside the nacelle.

### 11.7.2 Design of Experiments Methodology

A review of the seven fire extinguishing principles to be examined under full-scale testing reveals that a large number of physical parameters are involved in their assessment. A basic set of these included the nacelle air flow, air temperature, clutter height, fire type, whether the agent is chemically active or not, agent boiling point, agent discharge rate, nozzle usage, and discharge location. A test series featuring two extreme settings of each of these nine parameters (or "factors") would entail 512 runs, each with a different combination of the settings. Approximately 20 tests at varying extinguishant masses would need to precede each run to identify the threshold amount needed for extinguishment (as discussed in the next section). This full factorial test matrix of about ten thousand tests was prohibitive.

Fortunately, there existed a statistically valid technique to collect such data with a smaller, specially selected sample of the aforementioned number of different experimental runs, with nearly the same degree of fidelity of the data. It involved a fractional factorial, orthogonal test matrix, developed using a methodology commonly referred to as a statistical Design of Experiments (DOX) approach. The test matrix is termed "fractional factorial" in that it used a small, symmetric sub-set of the full factorial array of tests. ("Symmetric" means that each factor has an equal number of runs represented at each of its extreme settings.) The matrix was "orthogonal" in that it allowed sorting the effect of each individual factor, independent of all the other factors. It also allowed sorting the effect of combinations of individual factors, referred to as "two (or more)-factor interactions."

This type of matrix is formally structured. Thus, for the test series performed here, there was a row for each test to be run and a column for each factor or group of factors. Each cell in the matrix contained the setting for each factor or group of factors for that given "run" or set of experimental conditions. For a column with a discrete, two-value factor, the setting in a cell would be the high or low value.

The associated mathematical analysis protocol for the test results, formally known as Analysis of Variance (ANOVA), provided the ability to assess quantitatively the influence of each factor and multi-factor interaction on a test result, also referred to as a response variable. ANOVA also allowed for comparison of the relative contributions of the factors on the response variables and for comparison with the experimental uncertainty. This latter comparison facilitated determining which factors' influences were so small as to be statistically insignificant, permitting its exclusion from further consideration.

The objective of examining the seven selected NGP principles involved determining the influence of specific factors on the agent discharge and flame extinguishment process. Thus, this analysis approach of confirming the mathematical significance or insignificance of each factor, based upon the test results, was a proper technique to analyze the principles themselves. Success required (a) that both the factors and the response variables (or their post-test, mathematically-transformed derivatives), be properly chosen, defined, measured and analyzed to relate correctly to the principles of interest and (b) use of an orthogonal test array.

The ANOVA procedure also permitted the ability to exploit regression analysis and develop formulas to predict, with a estimable high degree of statistical certainty, values of the response variable for intermediate settings of the factors of interest that were not included in the test matrix. This capability permitted the selection of optimal settings of the design factors (such as extinguisher port location, discharge rate, etc.) that resulted in the most desirable response variable value (such as the minimum mass to extinguish the fire).

As might be expected, the ability to quantify the effects of numerous factors and two-factor interactions came with a price. For these streamlined orthogonal test matrices, the relative significance of each of the single factors or multiple-factor interactions could be "confounded" with each other to varying degrees in the post-analysis. By "confounding," it is meant that one cannot decipher the role of each factor in the variance of the test results. Confounded factors could be separated by additional testing.

It is helpful to note that experience with DOX protocols in most fields of interest found that three-level or higher interactions were rarely significant and were reasonably dismissed as significant sources of variance. Moreover, in actual practice, few two-factor interactions have been found to be significant, further reducing the requirement for substantial additional tests to decouple interactions to find and isolate the true significant term. These observations were consistent with the findings of the National Halon Replacement Program for Aviation experimental data, where only a couple of two-factor interactions were found to be consistently significant and worthy of consideration in the design and sizing of fire suppression systems.

The degree of confounding present in an orthogonal array experimental matrix of a particular size and with a set number of primary factors is known as the "resolution" of the matrix.

- A resolution 4 design is a full factorial matrix, and all factors and interactions are unconfounded. As noted earlier, this is not feasible for the current test series.
- In a resolution 3 design, all factors and two-factor interactions are unconfounded. While higher-order interaction terms may be confounded with either, this is most likely insignificant for this application, as noted earlier. This is the most desirable resolution.
- In a resolution 2 design, individual factors are not confounded with two-factor interactions, but groups of two-factor interactions may be confounded with each other, requiring future decoupling either experimentally or by engineering judgment for those found to be significant. A resolution 2 design is commonly used when many factors of interest are

present and test resources are limited, with limited additional work to decouple two-factor interactions if only two or three are assigned to each column.

- In a resolution 1 design, individual factors will be confounded with two-factor interactions. As expected, lower resolution designs permit more primary factors in a smaller experimental matrix.

Thus, a test plan is characterized by the number of tests to be performed, the number of factors, and the number of settings for each of the factors. For example (for two settings for each factor):

- A four run array (denoted L-4) is resolution 4 if two factors are being considered, but only resolution 2 with three factors considered.
- An L-8 array is resolution 4 with up to three factors, and resolution 2 with four factors.
- An L-16 array is resolution 3 with five factors, and resolution 2 with up to eight factors.
- An L-32 array is resolution 3 with up to six factors, and resolution 2 with up to 16 factors.

Increasing the number of experiments and the array is not always the most efficient manner for collecting the desired amount of data within a limited time. Splitting a test plan into two matrices may be superior, especially if the global process can be conceptualized as two or more separate and independent sub-processes. Here, "independent" means that the sub-processes are controlled by different sets of factors. (Some, but not all, factors may be common to these different sets, but the settings for these factors can be different for each matrix.) An important benefit of splitting the test plan is that one can select a different critical response variable for each sub-process matrix.

This splitting was deemed preferable for this test program. For the global process of putting out the fire, the two sub-processes were:

- Discharging the extinguishant in an appropriate quantity and manner uniformly throughout the nacelle in an efficient manner.
- Effecting flame extinguishment at the site of the fire zone.

Not only did these two sub-processes have different factors that control each process (with some in common), but they had different required instrumentation needs, and even differed in their need for the presence of a fire. These unique test setup differences suggested that additional experiment and analysis optimization was possible by indeed segregating each of their associated experiments into independent sub-matrices, each of which required its own special test configurations and required procedures, as well as unique measurements. The large number of factors of interest also provided a favorable exploitation of smaller experimental arrays within the limited test schedule period, particularly when factoring in the need for substantial replication and extinguishant mass test quantity "bracketing" to get final run values of their respective response variables, as will be discussed in the next section.

As will be shown in the following sections, the plan for this series of NGP tests involved two L-16 matrices of resolution 2. In each matrix, up to 28 variations of L-16s with six variables assigned in the eight allowed columns were found to be possible. All resulted in columns with either main factors only or a pair of two-factor interactions, with one excepting column having three two-factor interactions, and two columns being empty. (These two columns could be used for a factor with which no other interactions are assured (if possible), and/or for error columns to assess experimental error in the matrix.)

The selection of the array variation and column assignment for each of the factors was dictated by the preference to place a meaningless interaction or one of a high expectation of insignificance in the column with three two-factor interactions, and if possible place similarly likely insignificant interactions in each of the two-factor interaction pairs, to prevent the need for future decoupling experiments.

### 11.7.3 "Bracketing" Procedure for Testing

The testing to appraise the seven principles was divided into two categories. Examination of Principles 2, 4, and 7 required a fire in the test fixture. Principles 1, 3, 5, and 6 applied only to the effective distribution of the fire suppressant and did not require a fire. For efficient design of the experiments for the first group, it was important to know the minimum mass of fire suppressant that will suppress the fire types that were being considered, and the associated concentrations measured in the fire zone. For the second group, it was still necessary to know the concentrations measured throughout the nacelle when discharging various masses of agent, since the experimental factors might have influenced the outcome differently if the extinguishant concentration were of different levels of magnitude.

Determining the exact mass for flame extinguishment was difficult due to the inherent instability and lack of precise repeatability of fire extinguishing tests. This variation resulted from such phenomena as localized and transient air turbulence and thermal instabilities that could not be realistically controlled precisely by the investigator in full-scale tests. Obtaining a high precision was unlikely and would have required a large number of tests for each ensemble of settings of the factors affecting agent dispersion and fire suppression.

Rather, a modest, statistically designed series of tests was conducted to obtain the mass needed to extinguish the flames at a chosen success rate. This process, evolved in the course of the previous National Halon Replacement Program for Aviation, included tests in which the mass quantities were sequentially varied based on the results of prior tests (to converge on a threshold level) and repeated tests at a set quantity (to determine the repeated success rate at that set value).[i] Using the criterion that a true success had to be repeated four times, a test run would iterate until the lowest successful weight and the highest unsuccessful weight were separated only by the defined acceptable maximum convergence criterion, which was 10 % of the lowest successful weight.[ii] With five successful extinguishment repeats without a failure, this process identified the minimum agent mass for an extinguishing success rate of 86 %. This was consistent with the observed success rate of fielded halon systems for the aircraft under consideration.

### 11.7.4 Experimental Approach, Configuration and Procedure

### Phase I – Fire Zone Conditions Required for Extinguishment

This set of tests involved a suppressant being added to the nacelle air flow and observing the effect on a downstream fire. The purpose of these tests was to determine how the local fire zone configuration,

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[i] Earlier bracketing procedures designed to converge on a test mass had relied on the results of a single test to determine the next mass to be tested. Implicit in such a scheme is the assumption that each and every result is perfectly repeatable.

[ii] On fielded aircraft, this convergence criterion must be determined to a high degree of accuracy and precision, due to the severe weight and ultimate cost impacts associated with an inefficient overdesign and the high safety risk associated with an underdesign.

operating conditions, and extinguishant discharge conditions and composition influence the conditions required within the recirculation zone of the fire to result in flame extinguishment. The principles addressed were 1, 2, 4, 6, and 7.

The response variables measured were:

- The peak volumetric extinguishant (vapor) concentration that was reached in the recirculation zone where the flame was present when the minimum mass of extinguishant was discharged from the extinguisher that resulted in flame extinguishment.
- The total mass and moles of extinguishant discharged under those conditions.

The ratio of the number of moles discharged to peak concentration in the fire zone was also used as a measure of the efficiency of the transport of effective fire suppressant.

The experimentally varied factors of interest were:

A. Air Flow. This affects the extinguishant concentration-time profile, the local residence time, fire characteristics, and the degree of entrainment into the flame's recirculation zone. The two settings were 0.45 kg/s (1.0 lb/s) and 1.36 kg/s (3.0 lb/s). These are within the normal operating range of most aircraft, and were at rates that could be cooled to the required temperatures by the existing chiller.

B. Fire Type. Two different types of fires, i.e., spray fires and pool fires, presented different entrainment and flame interaction challenges to the incoming stream of suppressant. As stated previously, the nacelle fixture was turned to locate both types of fires in the bottom portion.

   The spray fires were created using the high-pressure fuel nozzles used for typical AENTF fire tests. The nozzles discharged JP-8 jet fuel at a rate of 0.4 L/min (6 gal/h) at a pressure of 3 MPa (400 psi). As depicted in Figure 11–8, the sprays were ignited with a spark ignitor and allowed to "pre-burn" for 20 s before initiating the extinguisher.[iii] The fuel nozzle and associated spark ignitor (placed several cm downstream of it) were mounted approximately 2.5 m (8 ft) downstream from the extinguisher discharge port (located at the upstream beginning of the 0.9 m (36 in.) engine core), shielded by an engine core rib, which serves as a bluff body flame holder for the resulting flame.

   Since both the pool fire and spray fire could not co-exist at the same location (due to excess fuel from the spray collecting and burning in the pan), the fuel pool pan was shifted 30 cm (1 ft) downstream, and subsequently shielded by the next nacelle rib. The fuel pan was positioned in the bottom of the nacelle (Figure 11–7), as if fuel had leaked and formed a pool there. The pan bottom was beveled to the nacelle curvature. The pan length was 60 cm (27¼ in.) The pan width was limited to 24 cm (9.5 in.), due to (a) the narrowness of the clearance gap between the engine core and the nacelle and (b) the shortness of the flame-stablizing rib jut in front of it, when using the 2.5 cm (1 in.) rib configuration. The fuel surface in the pan needed to be below the rib tip to permit the rib to function as a bluff body flame stabilizer. The pan was filled with about 2 L (0.5 gal) of fuel, with the fuel surface

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[iii] It has been found in previous testing with this fixture that pre-burn times longer than this can heat the surrounding structure sufficiently to create additional hot surface ignition sources (complicating the results of the tests) as well as applying repeated severe thermal stresses to the fixture. This 20 s duration assures a well stabilized, repeatable flame.

being about 0.5 cm (¼ in.) below the pan lip. The fire was ignited by a propane torch and allowed to "pre-burn" for 30 s before discharging the suppressant.

C. Clutter (rib) Height. The height of the bluff body, represented by the rib upstream of the flame, affected the flame structure and recirculation zone dimensions, as well as the degree of entrainment of extinguishant into the recirculation zone. The heights of ribs further upstream impacted air and extinguishant flow patterns, turbulence, and degree of difficulty (and rate) of extinguishant mixing throughout the nacelle, as well as providing potential surfaces for extinguishant condensation during cold (sub-boiling point) conditions. The rib height settings were 2.5 cm (1 in.) and 7.6 cm (3 in.). These dimensions were representative of those in actual aircraft nacelles. These rib heights stabilized flames while permitting some axial flow and minimizing excessive turbulence. The shallower rib height provided a relatively unimpeded flow of 10 cm (4 in) between the opposing ribs (resulting in a slight serpentine flow path as it slaloms past the alternating ribs). The deeper rib height simulated "deep frame" nacelles, where the entire 15 cm (6 in.) clearance distance was blocked by the sum of the core ribs and nacelle ribs, creating a severely serpentine flow path, with large recirculation zones and stagnant flow areas created behind the ribs.

   The ribs were placed on the engine core and interior walls of the nacelle, alternating every 30 cm (1 ft) one foot downstream (thus the ribs on either the core or nacelle exclusively were spaced two feet apart). As mentioned earlier, lengthwise ribs parallel to the core axis were placed on either side of the flame site to simulate components above the core exterior that normally impede the extinguishant from "wrapping" around the core.

D. Flame Reactivity of the Extinguishant. The efficiency of a flame suppressant should be a function of the degree to which it exceeds its flame cooling capacity by catalyzing the removal of the flame-propagating free radicals. Efficiency may also be enhanced by the shorter residence time required for the catalytic reactions, relative to that required for the slower heat absorption process. $CF_3I$ ($T_b$ = -22.5 ºC, -8.5 ºF) was chosen as the chemically active candidate, and HFC-227ea ($T_b$ = -16.3 ºC, -2.7 ºF) as the non-chemically active candidate, for the following reasons:

   - Apparatus temperature limitation. The facility could not reliably cool the air below -34.4 ºC (-30 ºF) for the range of flows of interest, requiring extinguishants with $T_b$ > -24.4 ºC to meet the "-10 ºC" setting criterion. This requirement eliminated many candidates, including halon 1301, HFC-125 and HFC-134a. The "+60 ºC" setting requires a minimum nacelle temperature of 37.5 ºC (92 ºF), which is slightly above ambient. This supports creating consistent test conditions, and was a primary reason for selection of the upper temperature criterion.
   - Similarity of agent boiling points. This allowed similar air and storage bottle temperatures in all tests, reducing the potential for any hidden factor variability due to large air temperature differences.
   - History. Both fluids had been examined previously in the AENTF, with prior performance data thus being available to compare with the NGP data of this project. For instance, in the Army Halon Replacement Program, 0.31 kg (0.69 lb) of $CF_3I$ was sufficient for flame suppression in high ambient temperature tests, while 1.56 kg (3.45 lb) was needed for cold ambient air tests. This showed that an increased mass of $CF_3I$ was required at low temperatures (presumably due to inefficient transport and condensation), but that it could extinguish fires with an amount that was practical for

test purposes. Both extinguishants had been examined previously in the TDP and the NGP, providing further reference performance data.

- Availability. Both extinguishants were readily available in the large quantities required for the planned testing.
- Extinguishant Flow. For a fixed mass of agent, the mass flow affected the peak level and the concentration-time profile of the extinguishant in the nacelle and in the recirculation zone of the flame. The discharge duration also affected whether the extinguishant can reach a flame extinguishing concentration everywhere in the nacelle.

E. Air Temperature, Relative to the Extinguishant Boiling Point. At issue was the extent to which the two-phase fluid suppressant vaporizes before reaching the flame zone. Only the vapor and very fine droplets could be relied upon to contribute to flame extinguishment. Prior NGP experiments had indicated that flash vaporization only occurred for fluids whose boiling point was below the ambient temperature. Evaporation of the agent liquid was slower and would depend on the agent boiling point, and the temperatures of the nacelle surfaces and the ventilation air. To the extent that the agent remained as a liquid, the charged mass of extinguishant (and the total mass of the storage system) would have to be increased to ensure sufficient vapor for flame suppression.

For these experiments, the suppressants were selected for other properties; the air/bottle temperature was set to examine the boiling point importance.[iv] The two values were 10 ºC (18 ºF) below the boiling point of the extinguishant tested, and 60 ºC (108 ºF) above the extinguishant boiling point. (The relative values of these settings were also influenced by facility limitations and other environmental conditions.)

F. Agent Discharge Rate. This was varied by changing the pressure of the nitrogen in the storage bottle after the extinguishant mass had been set and added.[v] Bottle pressures of 1.4 MPa (200 psi) and 5.4 MPa (800 psi) were used for HFC-227ea, and pressures of 0.95 MPa (140 psi) and 3.8 MPa (560 psi) were used for $CF_3I$. The lower $CF_3I$ pressures provided comparable mass flows for the higher molecular weight compound.

The internal volume of the adjustable capacity extinguisher (Figure 11–4) was set for each test condition to maintain a realistic 50 % liquid fill density. The point of discharge was in the bottom of the nacelle, in line and 2.4 m (8 ft) upstream from the spray fire site, and 2.7 m (9 ft) from the pool fire site. The agent was discharged by means of a fast-response solenoid valve into a short, 2.5 cm (1 in.) ID hose leading into the nacelle. Once in the nacelle, it was discharged in opposing directions through a "T"-section, with each end being 1.3 cm (½ in.) in inner diameter, as shown in the upper component in Figure 11–10. (The lower component is the same "T"-section with nozzles added, for use in Phase II). The opposing discharge orifices were centered between the inner nacelle wall and the engine core, spaced 7.6 cm (3 in.) on center from each of them. They discharged upward and downward in the nacelle to promote "wrapping" around the nacelle and helical transport downstream, as is common with fielded systems.

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[iv] The extinguishant storage system was kept at the same temperature as the air temperature for each experimental run. This was to simulate ambient conditions in the flight envelope.

[v] The mass flows varied over the discharge time due to pressure drop as the extinguisher evacuated.

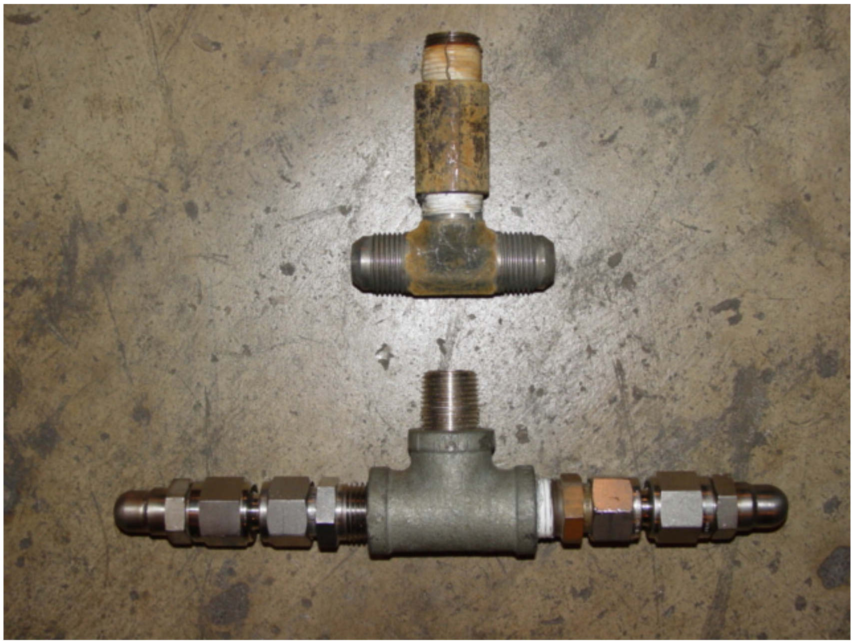

**Figure 11–10. Discharge “T” (top), and with Nozzles Added for Phase II (bottom).**

Fire suppressant concentrations were measured using the 12-probe Halonyzer resident at WPAFB. This device functions by siphoning a sample of the atmosphere, heating and vaporizing the air/agent mixture, measuring the density of the mixture, and comparing it to calibrated mixtures of that extinguishant in air.[vi] The response time of the instrument is about 0.2 s or longer.

Since the probes were not tolerant of the corrosive combustion products generated during suppression of a fire, concentration distribution measurements were made following each Phase I test, under identical conditions, but without igniting the fire. The mass flow of agent was the minimum determined to extinguish the fire. It was recognized that this necessary approach led to some unavoidable flow field modification from omitting the thermal effects of the fire.

Since each test involved either a spray fire *or* a pool fire, the 12 Halonyzer 3 probes were deployed in two sets of six. Six probes were associated with the upstream spray fire, and the next six probes with the pool fire downstream of it. This splitting allowed the conduct of multiple tests without the need to move and re-align the probes. Figure 11–11 is a general illustration of the layout of these Halonyzer 3 probes for either of the fire regions (spray or pool).

For each fire type, three probes were placed just above the rib shielding the flame, between the top of the rib and the top of the nacelle, to measure the free stream concentration of extinguishant as it entered the flame region. One of these probes was mounted in line with the fuel nozzle and the presumed base of the flame, and one probe on either side, approximately 10 cm (4 in.) away, to determine the extent of inhomogeneities in the mixture as it flowed past the rib. Three similarly spaced probes sampled the mixture behind the rib downstream, in a region normally immersed in the flame and in the recirculation zone. Again, probes were placed roughly 10 cm on either side to measure lateral inhomogeneities in the concentration within the recirculation zone. Figure 11–12 shows two views of the probe placements.

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[vi] This device is typically used with twelve probes placed in a dispersed pattern throughout the nacelle. This serves as an FAA-certified method for verifying a uniform concentration of discharged extinguishant in nacelle systems to confirm the sufficiency of balance of the discharge system (Chapter 2).

Combined, the two triads of probes permitted comparison of agent profiles and peak concentration values, to determine what portion of the free stream flow was entrained by the recirculation zone, and the rate at which it changed the recirculation zone concentration. These results could then be compared to prior (and upgraded) models, which will be discussed in detail in the data analysis sections.

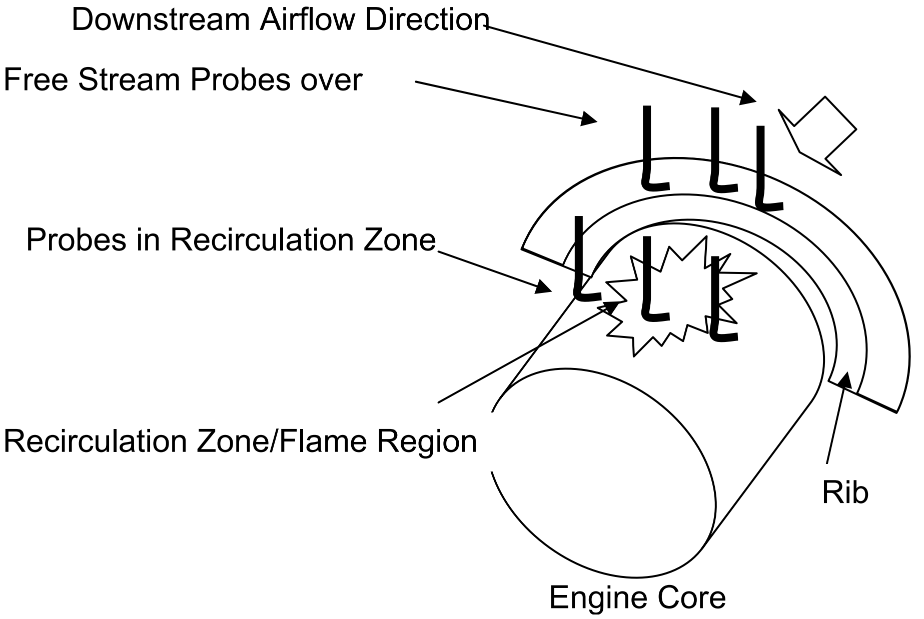

**Figure 11–11. Halonyzer Probe Mounting in Flame Region.**

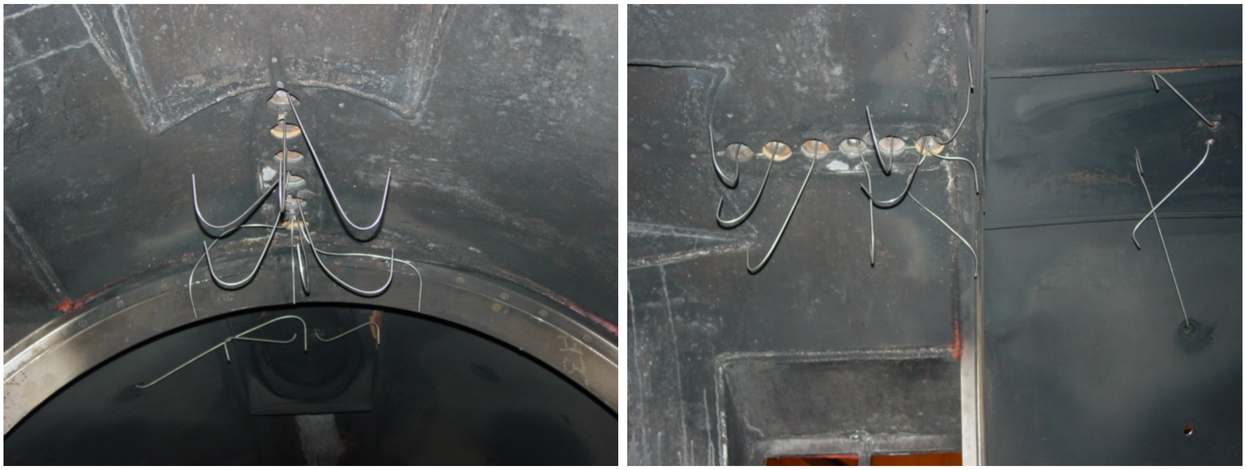

**Figure 11–12. Halonyzer Probes in Nacelle Fixture.**
(left: downstream view; right: side view)

Table 11–1 shows the L-16 test matrix utilized for Phase I. It includes the aforementioned six factors at two levels (Table 11–2) with "-1" indicating the lower level and "1" indicating the higher level. It was assumed that the interaction term, “Chemical Reactivity vs. Rib Height,” was one of the least relevant. Therefore, it was chosen as one of the trio of confounded interaction terms.

**Table 11–1. Local Conditions Fire Test (Phase I) Matrix.**

| Run # | Factors | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | A | B | EF<br>CD<br>AB | C | BD<br>AC | AD<br>BC | D | E | BF<br>AE | BE<br>AF | F | DF<br>CD | | | DE<br>CF |
| 1 | -1 | -1 | -1 | -1 | -1 | -1 | -1 | -1 | -1 | -1 | -1 | -1 | -1 | -1 | -1 |
| 2 | -1 | -1 | -1 | -1 | -1 | -1 | -1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 3 | -1 | -1 | -1 | 1 | 1 | 1 | 1 | -1 | -1 | -1 | -1 | 1 | 1 | 1 | 1 |
| 4 | -1 | -1 | -1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | -1 | -1 | -1 | -1 |
| 5 | -1 | 1 | 1 | -1 | -1 | 1 | 1 | -1 | -1 | 1 | 1 | -1 | -1 | 1 | 1 |
| 6 | -1 | 1 | 1 | -1 | -1 | 1 | 1 | 1 | 1 | -1 | -1 | 1 | 1 | -1 | -1 |
| 7 | -1 | 1 | 1 | 1 | 1 | -1 | -1 | -1 | -1 | 1 | 1 | 1 | 1 | -1 | -1 |
| 8 | -1 | 1 | 1 | 1 | 1 | -1 | -1 | 1 | 1 | -1 | -1 | -1 | -1 | 1 | 1 |
| 9 | 1 | -1 | 1 | -1 | 1 | -1 | 1 | -1 | 1 | -1 | 1 | -1 | 1 | -1 | 1 |
| 10 | 1 | -1 | 1 | -1 | 1 | -1 | 1 | 1 | -1 | 1 | -1 | 1 | -1 | 1 | -1 |
| 11 | 1 | -1 | 1 | 1 | -1 | 1 | -1 | -1 | 1 | -1 | 1 | 1 | -1 | 1 | -1 |
| 12 | 1 | -1 | 1 | 1 | -1 | 1 | -1 | 1 | -1 | 1 | -1 | -1 | 1 | -1 | 1 |
| 13 | 1 | 1 | -1 | -1 | 1 | 1 | -1 | -1 | 1 | 1 | -1 | -1 | 1 | 1 | -1 |
| 14 | 1 | 1 | -1 | -1 | 1 | 1 | -1 | 1 | -1 | -1 | 1 | 1 | -1 | -1 | 1 |
| 15 | 1 | 1 | -1 | 1 | -1 | -1 | 1 | -1 | 1 | 1 | -1 | 1 | -1 | -1 | 1 |
| 16 | 1 | 1 | -1 | 1 | -1 | -1 | 1 | 1 | -1 | -1 | 1 | -1 | 1 | 1 | -1 |

**Table 11–2. Factors and Values for Phase I Fire Test Matrix.**

| Factor | Symbol | Low Value (-1) | | High Value (1) | |
|---|---|---|---|---|---|
| Air flow | A | 0.45 kg/s (1.0 lb/s) | | 1.36 kg/s (3.0 lb/s) | |
| Fire type | B | Pool | | Spray | |
| Rib height | C | 2.5 cm (1 in.) | | 7.6 cm (3 in) | |
| Chemical reactivity | D | No, HFC-227ea | | Yes, $CF_3I$ | |
| Air temperature, relative to Tb | E | -10 ºC, -18 ºF | | 60 ºC, 108 ºF | |
| Discharge rate (controlled by storage bottle pressure) | F | HFC-227ea 1.4 MPa (200 psi) | $CF_3I$ 0.95 MPa (140 psi) | HFC-227ea 5.4 MPa (800 psi) | $CF_3I$ 3.8 MPa (560 psi) |

The test data were analyzed using ANOVA and other established protocols for orthogonal arrays to:

- Determine which factors most influenced the minimum peak concentration required in the fire zone to extinguish the test fires under the range of experimental conditions.
- Assess the efficiency with which the discharged extinguishant resulted in measurable vapor in the fire zone. This was based on the ratio of the moles of extinguishant discharged to the peak concentration measured in the fire zone.
- Verify correlations for predicting the mass of agent entrained into the recirculation zone.

### Phase II – Assessment of Extinguishant Dispersion Optimization

The purpose of these tests was to determine how the nacelle geometry and the discharge/flow conditions determined the speed and uniformity of agent distribution throughout the nacelle volume. This was done for four masses of chemical discharged. There were no fires present. The principles tested were 1, 3, 5, and 6. The response variables were the mean and standard deviation of the extinguishant concentration, measured simultaneously at 12 roughly equally distributed locations throughout the nacelle.

The experimentally varied factors of interest were:

A. Air Flow. See the discussion under Phase I. The two settings were the same.

B. Number of Agent Injection Sites. A larger number of well distributed injection sites decreases the distance over which agent must move laterally to fill the full annulus within the nacelle. Thus, it is more likely that a fire will encounter an extinguishing concentration of suppressant.

   In these tests, two agent injection arrays were used. The first (low value) was the same as used for Phase I: a single extinguisher discharging into a single port in the bottom of the nacelle, located 2.44 m (8.0 ft) and 2.75 m (9.0 ft) upstream of the spray and pool fire sites, respectively. The second setting used two independent extinguishers, fired simultaneously. The flow from each was directed to two separate ports, for a total of four port locations. The second discharge port from the first extinguisher was added on the side of the nacelle, 1.22 m (4.0 ft) and 1.52 m (5.0 ft) upstream of the spray and pool sites, respectively.

   The second extinguisher can be seen behind the left (downstream) end of the test fixture in Figure 11–4. Its first discharge site was on the top of the nacelle, 30 cm (1.0 ft) and 61 cm (2.0 ft) upstream of the spray and pool sites, respectively. Its second discharge site was 61 cm (2.0 ft) and 30 cm (1.0 ft) downstream of the spray and pool sites, respectively, and on the opposing side of the nacelle. Thus, discharge ports were present at the top, bottom and both sides of the nacelle, and at four spaced positions downstream, with each site split into opposing jets once discharged inside the nacelle, for a near optimally mixed (in realistic terms) configuration.

C. Clutter (rib) Height: See the discussion under Phase I. The settings were the same.

D. Nozzle Exploitation. Nozzles can be used to break the liquid flow into much smaller droplets of controlled diameter distribution, compared to the sizes emerging from open pipe ends. For a given total mass of fluid, an array of smaller droplets evaporates faster due to its higher total surface area. A corollary to this is that the smaller droplets will be more likely to evaporate fully before they are transported out the exhaust of the nacelle. This would make more gaseous agent available for quenching flames at cold operating temperatures, when flash vaporization is not possible. The two settings for this factor are shown in Figure 11–10: the presence of nozzles or no nozzles at all.

E. Air Temperature, Relative to the Extinguishant Boiling Point. See the discussion under Phase I. The settings and the chemicals were the same.

F. Agent Discharge Rate. HFC-227ea was used. The settings were flows associated with bottle pressures of 800 psi and 200 psi.

For this series of tests, the Halonyzer probes were spread into 12 distributed locations to measure the uniformity of concentration in the nacelle during and after discharge. Each of three downstream segments of the nacelle was split into quadrants, as illustrated in Figure 11–13. Pre-existing ports on the nacelle fixture were used to insert Halonyzer probes to make readings in these 12 quadrants. The axial locations of the planes of these port sites were 0.23 m (0.75 ft), 2.21 m (7.2 ft), and 3.50 m (11.5 ft) from the upstream edge of the engine core, with the far upstream and downstream port planes being the same distance from the front and aft ends of the nacelle, respectively. The middle port plane was slightly upstream of the middle of the nacelle. At each of these axial distances, the four ports existed at the approximate "two o'clock," "four o'clock," "eight o'clock," and "ten o'clock" positions on the nacelle perimeter, comprising four fairly even spaced quadrant positions. Figure 11–14 indicates the port locations.

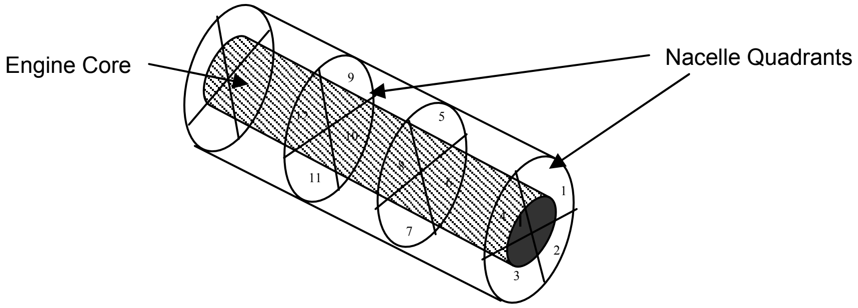

**Figure 11–13. Phase II Nacelle Concentration Measurement Quadrants.**

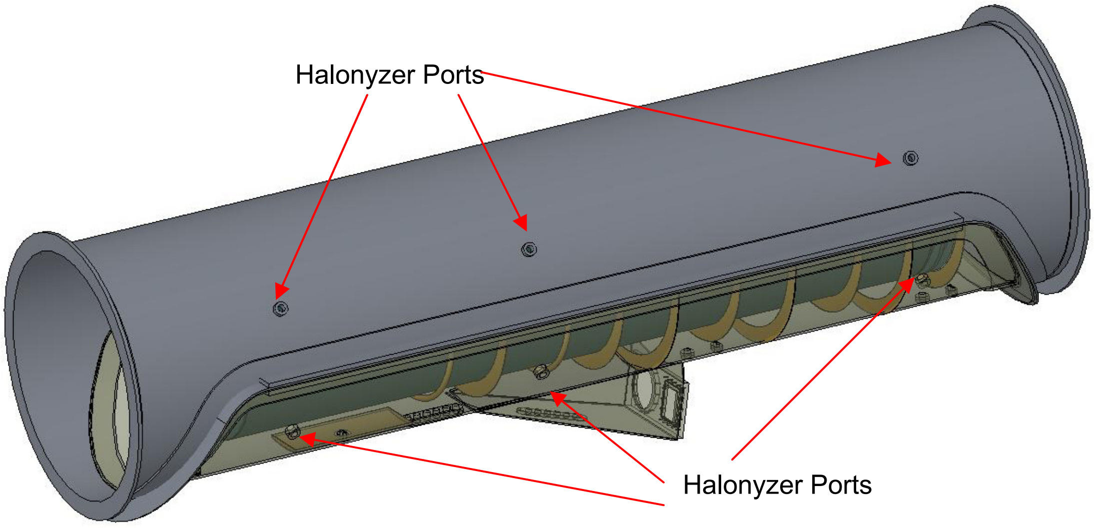

**Figure 11–14. Layout for Multi-Port Discharge.**

The following L-16 test matrix (Table 11−3) was used for Phase II experiments, with six factors at two levels (Table 11−4). It was assumed that the interaction term, "Nozzles vs. Rib Height," was one of the least relevant. Therefore, it was chosen as one of the trio of confounded interaction terms.

**Table 11–3. Extinguishant Dispersion Optimization (Phase II) Test Matrix.**

| | Factors | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Run # | A | B | EF<br>CD<br>AB | C | BD<br>AC | AD<br>BC | D | E | BF<br>AE | BE<br>AF | F | DF<br>CD | | | DE<br>CF |
| 1 | -1 | -1 | -1 | -1 | -1 | -1 | -1 | -1 | -1 | -1 | -1 | -1 | -1 | -1 | -1 |
| 2 | -1 | -1 | -1 | -1 | -1 | -1 | -1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 3 | -1 | -1 | -1 | 1 | 1 | 1 | 1 | -1 | -1 | -1 | -1 | 1 | 1 | 1 | 1 |
| 4 | -1 | -1 | -1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | -1 | -1 | -1 | -1 |
| 5 | -1 | 1 | 1 | -1 | -1 | 1 | 1 | -1 | -1 | 1 | 1 | -1 | -1 | 1 | 1 |
| 6 | -1 | 1 | 1 | -1 | -1 | 1 | 1 | 1 | 1 | -1 | -1 | 1 | 1 | -1 | -1 |
| 7 | -1 | 1 | 1 | 1 | 1 | -1 | -1 | -1 | -1 | 1 | 1 | 1 | 1 | -1 | -1 |
| 8 | -1 | 1 | 1 | 1 | 1 | -1 | -1 | 1 | 1 | -1 | -1 | -1 | -1 | 1 | 1 |
| 9 | 1 | -1 | 1 | -1 | 1 | -1 | 1 | -1 | 1 | -1 | 1 | -1 | 1 | -1 | 1 |
| 10 | 1 | -1 | 1 | -1 | 1 | -1 | 1 | 1 | -1 | 1 | -1 | 1 | -1 | 1 | -1 |
| 11 | 1 | -1 | 1 | 1 | -1 | 1 | -1 | -1 | 1 | -1 | 1 | 1 | -1 | 1 | -1 |
| 12 | 1 | -1 | 1 | 1 | -1 | 1 | -1 | 1 | -1 | 1 | -1 | -1 | 1 | -1 | 1 |
| 13 | 1 | 1 | -1 | -1 | 1 | 1 | -1 | -1 | 1 | 1 | -1 | -1 | 1 | 1 | -1 |
| 14 | 1 | 1 | -1 | -1 | 1 | 1 | -1 | 1 | -1 | -1 | 1 | 1 | -1 | -1 | 1 |
| 15 | 1 | 1 | -1 | 1 | -1 | -1 | 1 | -1 | 1 | 1 | -1 | 1 | -1 | -1 | 1 |
| 16 | 1 | 1 | -1 | 1 | -1 | -1 | 1 | 1 | -1 | -1 | 1 | -1 | 1 | 1 | -1 |

**Table 11–4. Factors and Values for Phase II Agent Distribution Test Matrix.**

| Factor | Symbol | Low Value (-1) | High Value (1) |
|---|---|---|---|
| Air flow | A | 0.45 kg/s (1.0 lb/s) | 1.36 kg/s (3.0 lb/s) |
| Injection Sites | B | 1 | 4 |
| Rib height | C | 2.5 cm (1 in.) | 7.6 cm (3 in.) |
| Nozzles | D | No | Yes |
| Air temperature, relative to $T_b$ | E | -10 ºC, -18 ºF | 60 ºC, 108 ºF |
| Agent discharge rate | F | 1.4 MPa, 200 psi | 5.4 MPa, 800 psi |

The test data were analyzed using ANOVA and other established protocols for orthogonal arrays to determine which factors most influenced the average value and standard deviation of the extinguishant concentration measured simultaneously at all 12 Halonyzer probe locations at the time that all 12 probes met or exceeded the same concentration level at its highest value during discharge (as with certification tests), for a given mass of extinguishant.

### Phase III – Additional Fire Extinguishment Tests

As an additional dimension to Principle 2, the test series briefly examined the performance of a brominated fire suppressant other than halon 1301. As mentioned in Chapter 7, 2-bromo-3,3,3-trifluoropropene ($CF_3CBr=CH_2$), BTP, has a boiling point of 34 ºC (93 ºF) and thus did not meet this screening criterion for effective dispersion at cold in-flight operating conditions. However, it had a cup burner flame extinguishment value of 2.6 % by volume, which is characteristic of brominated compounds. It has a short atmospheric lifetime due to tropospheric attack at the double bond.

It was intended to perform a series of experiments under conditions identical to those under which HFC-227ea had been tested. However, the high boiling point of BTP required conducting experiments at a "cold" air flow and agent storage temperature of 24 ºC (75 ºF) and a "hot" temperature of 94 ºC (200 ºF), to maintain the same temperature conditions, relative to boiling point, as with the other agents tested. These notably hotter temperatures significantly increased the flame stability and strength, which required larger amounts of extinguishing agent, and required re-testing HFC-227ea under the same conditions to facilitate comparison.

Experiments with two condition variations, simulating two prior HFC-227ea run conditions (except at higher temperatures), were conducted to determine the threshold of agent mass required to extinguish the fires generated under the conditions cited, using a traditional agent mass "bracketing" method. Due to a limited quantity of agent available, in some cases fewer repeats (relative to the earlier test series) at the same mass level were conducted. The experimental conditions for the two experiment variations were:

> Test Condition 1: 1.36 kg/s (3.0 lb/s) air flow, 24 ºC (75 ºF) agent/air temp (10 ºC below boiling point), 5.1 MPa (750 psi) extinguisher pressure, spray fire, with nozzles.
>
> Test Condition 2: 0.45 kg/s (1 lb/s) air flow, 94 ºC (200 ºF) agent/air temp (60 ºC above boiling point), 5.1 MPa (750 psi) extinguisher pressure, pool fire, with nozzles

## 11.8 RESULTS AND ANALYSIS

### 11.8.1 Summary of General Data Collected

The ANOVA analyses can provide a rich assessment of the relative importance of the test factors on the response variables. The following results focus on the specific analyses that cast light on the validity of the principles being tested.

Table 11–5 summarizes the data collected in Phase I, including the minimum mass required for extinguishing in each run and the resultant peak concentration measured in the fire zone (averaged of three repeats). The data from adjacent probes were similar enough to use peak data readings in the analysis. (It did not affect the ANOVA analysis.) Table 11–6 summarizes the Phase II data, including the standard deviation data of the concentrations measured in each of the remote twelve probe locations, for both extreme mass discharge levels of 0.68 kg (1.5 lb) and 5.44 kg (12.0 lb). These aforementioned data were used for all ANOVA and other data analyses, including transformations of these data.

Table 11–5. Phase I Summary Data.

| Run | Mass (kg, lb) | Peak Concentration, % by volume | Run | Mass (kg, lb) | Peak Concentration, % by volume |
|---|---|---|---|---|---|
| 1 | 1.70, 3.75 | 14.8 | 9 | 1.42, 3.13 | 10.4 |
| 2 | 1.77, 3.90 | 13.5 | 10 | 1.24, 2.73 | 12.7 |
| 3 | 1.13, 2.50 | 6.3 | 11 | 1.24, 2.73 | 11.2 |
| 4 | 0.85, 1.88 | 6.4 | 12 | 0.71, 1.56 | 11.2 |
| 5 | 0.85, 1.88 | 3.3 | 13 | 0.99, 2.19 | 6.5 |
| 6 | 0.57, 1.25 | 3.0 | 14 | 0.99, 2.19 | 7.7 |
| 7 | 0.57, 1.25 | 2.4 | 15 | 0.29, 0.63 | 2.0 |
| 8 | 0.43, 0.94 | 2.6 | 16 | 0.21, 0.47 | 2.4 |

Table 11–6. Phase II Summary Data.

| Run | Concentration Standard Deviation (0.68 kg released), % by volume | Concentration Standard Deviation (5.44 kg released), % by volume | Run | Concentration Standard Deviation (0.68 kg released), % by volume | Concentration Standard Deviation (5.44 kg released), % by volume |
|---|---|---|---|---|---|
| 1 | 2.3 | 10.9 | 9 | 1.4 | 5.0 |
| 2 | 1.5 | 3.5 | 10 | 1.1 | 3.5 |
| 3 | 1.4 | 5.9 | 11 | 2.9 | 14.2 |
| 4 | 2.3 | 9.4 | 12 | 2.9 | 13.6 |
| 5 | 1.0 | 5.0 | 13 | 1.5 | 9.9 |
| 6 | 1.5 | 6.5 | 14 | 1.5 | 8.6 |
| 7 | 2.4 | 12.3 | 15 | 1.4 | 6.6 |
| 8 | 2.5 | 15.4 | 16 | 1.2 | 7.0 |

### 11.8.2 Principle 1

*Extinguishants with boiling points higher than the local engine nacelle airflow and surface temperatures do not disperse sufficiently in time for engine nacelle fire mitigation, whereas those with boiling points below the prevailing temperature can disperse sufficiently if properly applied.*

Figure 11–15 plots the ratio of the g-moles of agent injected into the test fixture to the volume percent of agent measured in the fire zone. The data showed that experiments at colder temperatures (below the agent's boiling point) required about a third more moles of agent to achieve a required fire zone concentration compared to hot conditions. This extra amount was assumed lost due to condensation of liquid agent on the upstream nacelle components, or unvaporized after passing through the fire zone, thereby providing no benefit.

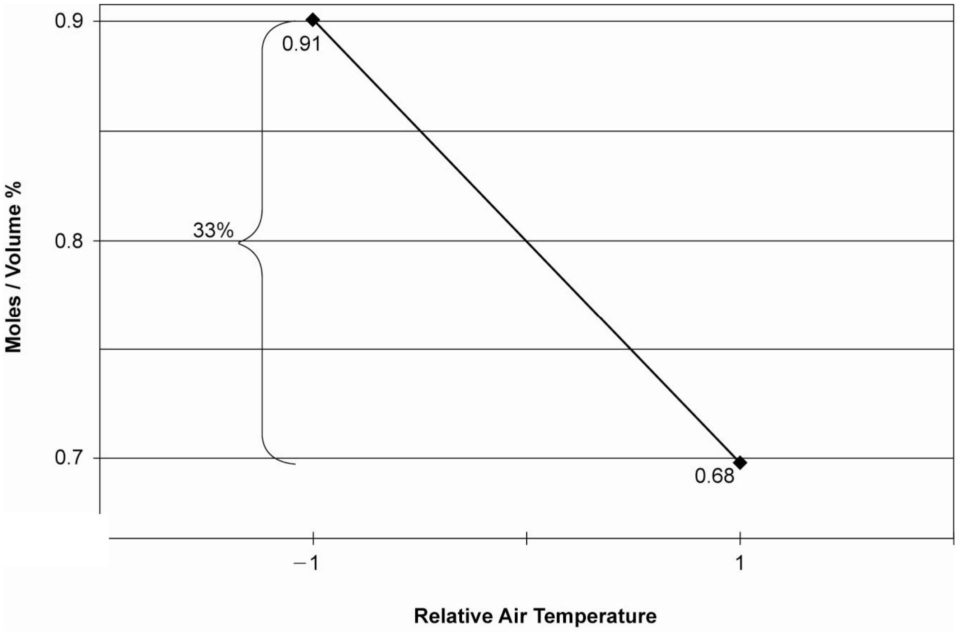

**Figure 11–15. Variation of Moles of Injected Chemical per Fire Zone Volume Percent with Relative Air Temperature.** ("-1" is 10 ºC below the agent boiling point; "1" is 60 ºC above the agent boiling point.)

### 11.8.3 Principle 3

*Increasing the number of local extinguishant discharge sites increases the dispersion quality in terms of balanced concentration profiles, up to some practical limits.*

It was found that increasing the number of injection sites from one to four (well distributed) reduced the standard deviation of the 12 concentration probes (measured at a time when the lowest of the 12 is at its highest amount, as is used for certification testing) by about 22 % on average (as seen in Figure 11–16), when discharging 0.68 kg (1.5 lb) of agent. It was observed that when discharging 5.4 kg (12 lb), the effect of injection sites was not statistically significant. It may be that discharging excessive quantities of agent may saturate the nacelle, even with only one discharge port, as well as discharge longer and let the nacelle concentration even out, and hence dilute the benefits of distributed discharge.

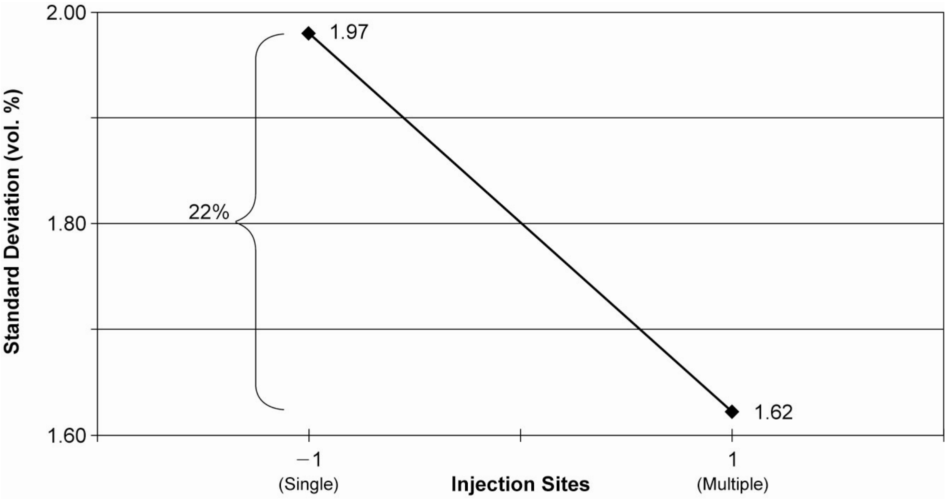

**Figure 11–16. Variation of Concentration Standard Deviation with Number of Discharge Sites.**

### 11.8.4 Principle 5

*The passage of a suppressant through an engine nacelle is significantly affected by the degree of clutter in the nacelle.*

Figure 11–17 shows that the 7.6 cm (3 in.) tall rib heights resulted in a 45 % increase in standard deviation of concentration for the 0.68 kg (1.5 lb) agent discharge, compared to the same discharge with 2.5 cm (1 in.) rib height. The increase was 60 % for the 5.44 kg (12 lb) discharge. Therefore, the height of ribs (and, by analogy, other nacelle obstructions) was demonstrated to play a significant role in the efficient distribution of extinguishing agent in a nacelle.

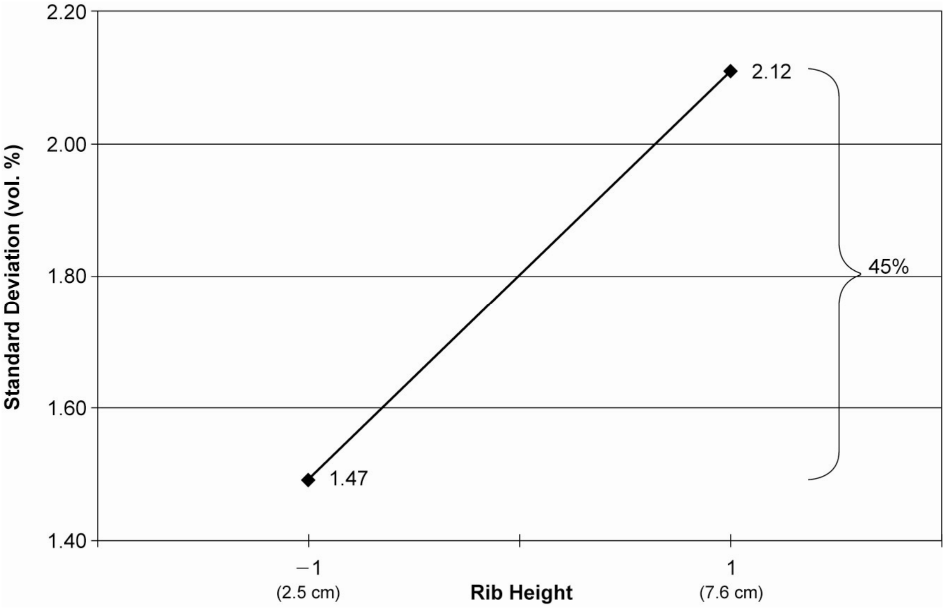

**Figure 11–17. Variation of Concentration Standard Deviation with Rib Height.**

### 11.8.5 Principle 6

*Assuming that a mix of extinguishant vapor and liquid aerosol reach the flame reaction zone, the sufficient vaporization of liquid particles to enhance extinguishment will be dependent upon, among other parameters, the liquid's residence time in the recirculation zone.*

This type of full-scale testing was not an ideal means to assess the particle size of liquid aerosols, and the heat transfer aspect was addressed in the next principle. However, the residence time in the recirculation zone was estimated indirectly. Hamins et al.[2] stated that the characteristic entrainment or mixing time is equal to the residence time in the recirculation zone. This "characteristic mixing time" will be defined and estimated in Section 11.8.7. An estimate of the characteristic time has been calculated for each of the 16 sets of conditions represented in the 16 test runs, and the influence of individual parameters on these calculations (using actual agent concentration data) has been evaluated using the ANOVA process. Figure 11–18 is a plot of the g-moles of extinguishant discharged, divided by peak volume fraction of extinguishant in the fire zone, as a function of this characteristic time, τ, for those runs of spray fires under cold conditions having the smallest τ values.

These data showed a drop in the required moles of extinguishant as τ increases. This finding was consistent with the hypothesis that, if the residence time increased with the increase in the value of τ, then increased residence times reflect a reduced amount of moles of agent needed to provide a given fire zone concentration. This, in turn, suggested that during longer residence times in the fire zone, more of the liquid aerosol was indeed vaporizing in the fire zone and contributing to the local concentration, thereby increasing efficiency. This effect diminished with further increases in τ, such as under hotter air conditions, presumably because vaporization in the fire zone was nearly complete under less benign conditions.

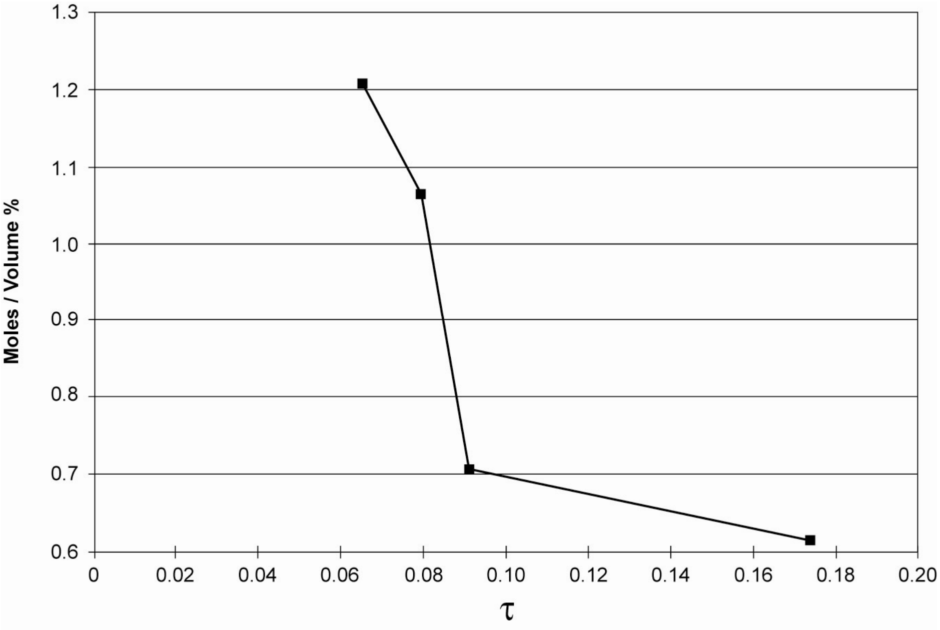

**Figure 11–18. Reduction in Moles/Concentration with Increasing τ, Residence Time.**

### 11.8.6 Principle 7

*The suppression effectiveness of a non-catalytic extinguishant in a full-scale engine nacelle is determined by its ability to absorb heat as it enters the flame zone.*

There are three sources of information that collectively indicate support for this principle.

- Figure 11–19 is a plot of required extinguishing concentration as a function of air and agent storage temperature (either above or below the agent's boiling point) for both the catalytic $CF_3I$ and the non-catalytic HFC-227ea. Neither agent exhibited any notable difference in required concentration between the hot and cold conditions, given the experimental uncertainty in the measurements. The lower inflow of agent and air in the "cold" temperature tests resulted in a lower flame temperature and a higher aerosol fraction of the agent. The minimal temperature dependence in this Figure shows that these two factors, and the resulting possible difference in heat extraction, were not important in these tests.

- Other data provide further evidence that HFC-227ea was fully vaporized in the fire zone in these tests. Figure 11–15 shows that HFC-227ea volatility was significantly dependent on the environmental temperature for a non-fire test. Figure 11–19 indicates that the same chemical showed no temperature dependence of volatility in a fire test. In the tests with a fire, all the HFC-227ea was effective. This likely means that the temperature in the fire zone was high enough <u>and</u> the agent residence time was long enough for all of the HFC-227ea to volatilize. Alternatively stated, at even the lower temperature, none of HFC-227ea was surviving as an aerosol through the fire zone.
- In cup burner tests, the suppressant fluids were fully vaporized. For HFC-227ea, the extinguishing values were ca. 7 volume %; for $CF_3I$, the value is ca. 3 volume %. The relative effectiveness of the two compounds was about the same as in the engine nacelle experiments. (The consistently higher extinguishing concentrations for the two agents in the nacelle tests likely reflected the effect of clutter and agent residence time in the real-scale tests relative to the open geometry in the cup burner. See the discussion under Principle 5.) Certainly, there was no indication of a significant contribution beyond the thermal effects seen in the cup burner for the HFC-227ea vapor.

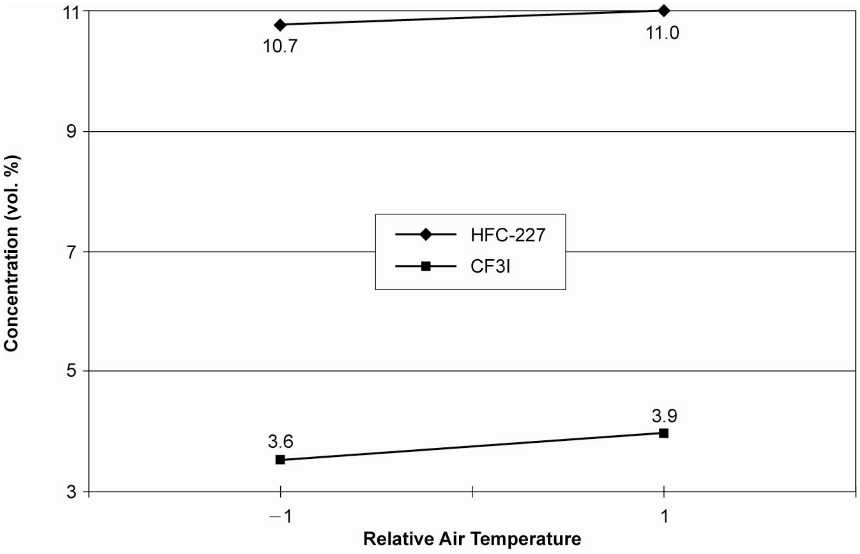

**Figure 11–19. Effect of Agent Type and Relative Temperature on Extinguishing Concentration.** (“-1” is 10 ºC below the agent boiling point; “1” is 60 ºC above the agent boiling point.)

### 11.8.7 Extinguishing Mixing Models

#### Basic Mixing Model

Before proceeding to the next principles, several basic concepts related to extinguishing baffle-stabilized fires need to be established:

Longwell et al.[3] developed a model to explain the blow off of pre-mixed flames by treating the air flow recirculation zone created by a bluff body stabilizing a flame as a well-stirred reactor. The key parameter in this model is the characteristic mixing time for reactants to entrain from the free stream into the recirculation zone. Mestre[4] also found that the blow-off velocity was related to the characteristic time for entrainment into the recirculation zone. Bovina[5] found that the characteristic time ($\tau$) is related to a baffle diameter (assuming it is suspended in a tube and serves to stabilize a flame), divided by the upstream velocity. Winterfeld[6] also found that τ was inversely proportional to the upstream velocity for both combusting and non-combusting cases, as well as the geometry of the flame holder. Importantly, he found that τ was approximately a factor of two larger for a combustion situation relative to isothermal conditions. Additional details of this prior research can be found in Reference 2.

Hamins et al.[2] extended the model to explain the mixing process of an extinguishing agent discharged upstream into an air flow, resulting in a steady and constant concentration of the agent. A portion of this stream is entrained into the flame's recirculation zone, where it is perfectly and instantaneously mixed with the existing species. The process is characterized by the following governing equation:

$$X_f = X_\infty / (1 - e^{-\Delta t/\tau}) \qquad (11\text{-}1)$$

where:

$X_f$ is the free stream volume fraction of agent, held for the time $\Delta t$,

$X_\infty$ is the volume fraction of agent needed in the fire zone to accomplish extinguishment, and

$\tau$ is the volume fraction mixing time for the flame holder configuration and conditions of interest.

This expression demonstrates that the free stream volume fraction must be higher than the minimum volume fraction required to extinguish a fire within the recirculation zone unless the time that the agent is applied is significantly longer than the characteristic time. This time condition is met for a cup burner flame (although there is no recirculation zone), but is not met for an agent typically discharged into an aircraft engine nacelle.

Takahashi et al.[7] determined that the coefficient relating τ to the ratio of rib height to free stream velocity was 22.79 for the two-dimensional bluff body/rib stabilizing a pool fire in their experiments. Literature values of $X_\infty$ and τ for both baffle-stabilized spray (centered in a stream) and pool fires (with the baffle against the flow chamber floor) for the agents of interest, with their associated references are shown in Table 11–7.

**Table 11–7. Values of $X_\infty$ and τ from Prior Experimentation.**

| Fire Type | $X_\infty$ (HFC-227ea, $CF_3I$), % by volume | τ, s |
|---|---|---|
| Spray | 0.062, 0.032 | 0.1, 0.04 |
| Pool | 0.11, 0.068 | 0.7, 1.0, 0.04 to 0.4 [7], 0.1 to 0.2[8], 0.1 to 1.0[9] |

Data from Reference 2, except as noted.

### Detailed Mixing Model

Hamins et al.[2] also reported the following differential equation expression for the mixing process behind a bluff body in general:

$$\tau\,(dX(t)/dt) = X_f(t) - X(t) \qquad (11\text{-}2)$$

where:

$X_f(t)$ is the free stream volume fraction of agent at time t (at least at one point on a streamline, preferably just over the top of the bluff body stabilizing the fire),

$X(t)$ is the recirculation zone volume fraction of agent at time t (along the same streamline), and

$\tau$ is the characteristic mixing time of the recirculation zone.

This more general model permitted consideration of the types of complex realistic concentration profiles associated with Halonyzer "no fire" concentration measurements in real engine nacelles. This model did not require a two-dimensional flow pattern of uniform velocity magnitude and direction. It also obviated the requirement of a simplified bluff body geometry, since measured concentration data in both locations determined an empirical value of $\tau$.

Note that if the flow was expected to come from multiple directions, one should determine a volumetric, flow-adjusted, average flow free stream concentration profile external to the recirculation zone. If concentration measurements were made in only one location in the recirculation zone, then one must assume that mixing is uniform and complete there. Otherwise, an average from multiple probe sites in the recirculation zone would be necessary.

Equation (11-2) was functionally similar to that used to determine the extinguishant mass required to totally flood a room to a given volume fraction, accounting for leakage, as prescribed in NFPA 2001.[10] That model simulated mixing and local volume fraction changes of an additive in a fluid (such as air) in a fixed volume. It included an air inflow with an additive of volume fraction, $X_f$ , (between 0 and 1) in the fluid, and an outflow of the room mixture, maintaining a constant pressure within the volume. In the case of the design equation used in NFPA 2001, the inflow value of $X_f$ was 1.0, since pure extinguishant was coming out of the tank, resulting in the simplified structure shown in that publication. Although the enclosure volume fraction changes during the discharge, it peaks as the extinguisher completes its discharge. With no further influx, the agent volume fraction remains nominally constant at that value if there were no ventilation forcing flow from the enclosure. If the influx volume fraction were a constant value other than 1.0, then Equation (11-2) simplifies to the structure of Equation (11-1), used in the NGP as the a simplified case of a free stream influx of a constant volume fraction for a set period of time, $\Delta t$. For application to an engine nacelle, Equation (11-2) can be adapted to include the introduction of extinguishant and air, assuming that the density of the flow across the recirculation zone remains constant. The characteristic time, $\tau$, can be seen to be the ratio of volume of the recirculation zone, $V_R$, divided by the volumetric flow, $V_{in}$, into the recirculation zone. The recirculation zone volume is a function of the fire type (spray vs. pool) and local geometry. $V_{in}$ is a function of the free stream volumetric flow and the local bluff body geometry.

Equation (11-2) was used to predict the influence of many operating parameters on the extinguishing concentrations to be required in the free stream and measured under "no fire" conditions. The most common profiles of extinguishant concentration in the free air stream of an engine nacelle were somewhat Gaussian in shape, such as shown above, with a rise, peak and decay. (This neglected fluctuations and even second peaks that occurred due to agent flashing or other surging behavior during discharge, or due to other perturbations to the upstream flow.) Figure 11–20 illustrates realistic notional concentration profiles that might be measured in an engine nacelle in both the free stream, such as over a bluff body, and behind the bluff body in the flame's recirculation zone, using a Halonyzer device.

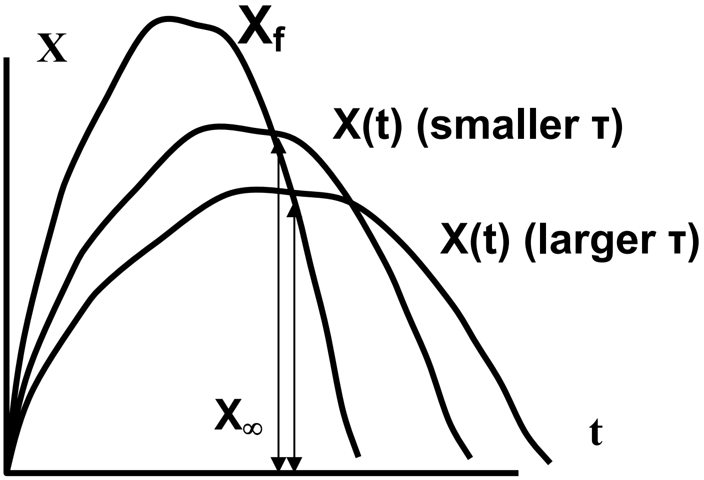

**Figure 11–20. Notional Graphs of Concentration in the Free Stream and Recirculation Zone.**

The agent concentration in the recirculation zone rose and fell more slowly than the free stream concentration. In effect, the recirculation zone volume exhibited a type of mass transfer concentration inertia, taking time to build up a concentration (depending upon the ratio of the volume to the incoming volumetric flow), then taking time to offload the agent as fresh air is entrained. In Equation (11-2), the peak of the agent concentration in the flame's recirculation zone occurred when the free stream concentration decayed to the level already in the recirculation volume, i.e., $dX/dt = 0$ when $X_f = X$.

The decrease in slope of $X(t)$ relative to that of $X_f(t)$ was controlled by the characteristic mixing time, $\tau$, which reflected the relative incoming flow in proportion to the recirculation zone volume. As shown in Figure 11–20, as $\tau$ increased,

- The rise and fall of the agent concentration in the recirculation zone decreased;
- The peak value, $X_p$, occurred is at a later time; and
- The peak concentration in the recirculation zone was relatively lower, because the concentration curve for $X_f(t)$ had decayed further during that extended time before it intersected the peak.

Thus, flame regions with larger characteristic times (due to local geometries and velocities) required a greater excess agent peak in the free stream to reach a desired concentration within the recirculation zone. This feature impacted the interpretation of "no fire" concentration measurements and provided a guide to estimating conditions under actual "fire" conditions, as will be shown later.

Actual values of the characteristic mixing time were estimated for real engine nacelle regions by discretizing the free stream and recirculation zone concentration data collected, and using a discretized form of Equation (11-2), as shown in Equation (11-3). $t_1$ is any time when a concentration is measured.

$$\tau = (X_f(t_1)-X(t_1)) / (\Delta X/\Delta t) \qquad (11\text{-}3)$$

This approach can be illustrated using actual Halonyzer concentration data collected in the nacelle simulator in this experimental program. At a point in time, $t_1$, the concentrations from both the free stream (just above the rib that stabilizes the flame) and recirculation (behind the rib) probe data traces were selected. This time was during the rising segment of the concentration curves, which was generally the most stable segment for all test conditions.[vii] Figure 11–21 shows 12 Halonyzer traces for a test in which the minimum mass of extinguishant to extinguish the fire was discharged. Three replicate tests were analyzed separately and the results averaged.

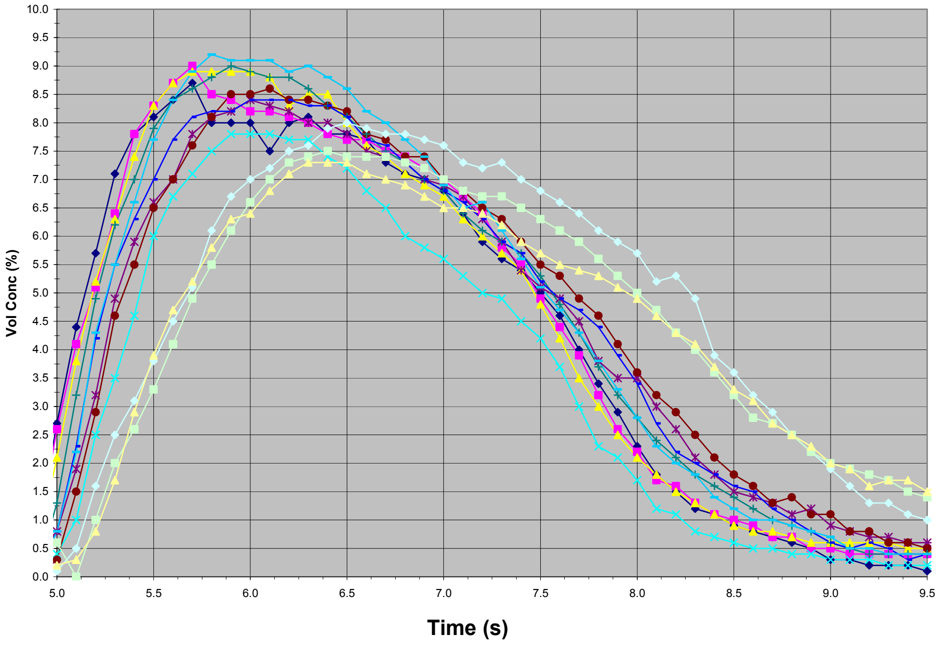

**Figure 11–21. Sample Halonyzer Traces.**

The denominator of Equation (11-3) was calculated from the recirculation zone concentrations 0.1 s before and 0.1 s after the selected point. This gave the shortest data collection interval possible with the Halonyzer on either side of $t_1$, a total $\Delta t$ of 0.2 s. Using this approach for each of the sets of Halonyzer data for each run, the $\tau$ values for all of the runs were calculated to range from 0.024 s to 0.17 s for the spray fires and 0.25 s to 0.54 s for the pool fires. This range correlates well with that in Table 11–7, thereby suggesting that this approach may have some merit for estimating $\tau$ values for fire suppression using data from non-fire tests.

### 11.8.8 Principle 4

*The extinguishant concentration established in the recirculation zone is a function of the mixing time behind the obstacle ("clutter") that stabilizes the flame.*

Mixing times for the 16 tests in Phase I were calculated using (a) Takahashi's correlation, with AENTF nacelle velocity measurements by Davis and Disimile[11] and (b) Equation (11-3), with Halonyzer

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[vii] Under some conditions, various mixing phenomena resulted in erratic concentration traces in the recirculation zone after the peak was reached. Some traces showed great turbulence, and some have profiles with two peaks.

concentration data measured over the top of the bluff bodies stabilizing the flame and within the flame recirculation zone region. Table 11–8 compares the values of τ for both approaches. Since the velocity and rib height approach does not define a proportionality constant, the runs were rank ordered in terms of their value of τ, from lowest to highest. (When the proportionality constant of 22.79 was used, then τ values of 0.13 to 0.71 were observed, which was consistent with prior literature.) The data were segregated by rib height and fire type, since these two factors largely influenced the test results.

**Table 11–8. Rank Order of τ Values in All Test Run Conditions for Both Mixing Models.**

| 2.5 cm Clutter (Runs 1 to 8) | | | | 7.6 cm Clutter (Runs 9 to 16) | | | |
|---|---|---|---|---|---|---|---|
| Pool Fires | | Spray fires | | Pool fires | | Spray Fires | |
| Correlation | Eq. (3) | Correlation | Eq. (3) | Correlation | Eq. (3) | Correlation | Eq. (3) |
| 5 | 2 | 7 | 8 | 9 | 14 | 11 | 12 |
| 2 | 1 | 4 | 4 | 14 | 10 | 16 | 16 |
| 1 | 6 | 3 | 7 | 13 | 9 | 15 | 15 |
| 6 | 5 | 8 | 3 | 10 | 13 | 12 | 11 |

The two sets of results did not correlate well. It was hypothesized that the calculated values using only the free stream, steady state velocity and fixed rib height may have deviated from those using actual concentration data for at least two reasons:

- The local velocity was greatly perturbed and changed in a transient manner during the extinguisher discharge period. This was due to the entrainment and mixing into the free stream of a high mass, high momentum flow of extinguishant. Provisions to artificially adjust the air velocity to accommodate and dampen this perturbation, made in some laboratory scale tests, were not practical under these full-scale conditions.
- The velocity-and-rib height approach did not consider that different types of fires created different thermally influenced dimensions of the recirculation zone. These, in turn, resulted in different mixing and concentration dilution rates as well as local velocity changes. To the extent that the different character of the recirculation zones required larger agent mass discharges, there were secondary effects on the mixing rate, as discussed later.

Therefore, it was not surprising to find that the simple correlation, when applied to the complex flow fields associated with real engine nacelle geometries and conditions, did not provide satisfactory prediction of the test results. The veracity of the approach of using Halonyzer concentration curves and Equation (11-3) will be supported further with additional analysis discussed later in this chapter.

It was then of interest to determine what impact the various physical parameters of the nacelle had on the calculated values of τ, as determined from the fire test data and concentration measurements, using the ANOVA data analysis technique.

- The calculated values of τ for the 7.6 mm (3.0 in.) ribs were nearly double those for the 2.5 cm (1.0 in.) ribs, as seen in Figure 11–22. Thus, the increase in τ with rib height (the "L" of L/U) in the correlation was justified, although the magnitude of the effect was not predicted to be so large. This was likely due to the influence of other factors, such as fire type.
- The calculated values of τ for the pool fires were nearly four times those for the spray fires, as shown in Figure 11–23. This appeared logical, given that pool fires created larger, less

turbulent recirculation zones than spray fires. However, the Halonyzer data were collected under non-fire conditions. The question then became whether the Halonyzer data somehow retained some influence of fire type in its non-fire data. Larger extinguishing agent masses were required to extinguish the pool fire tests, and the same amounts were used in the Halonyzer tests. These larger masses were injected at higher mass flows. There were several possible hypotheses for this mass effect to increase τ, but additional data were needed to appraise them.

- Figure 11–24 shows 50 % larger values of τ for colder air and agent temperature. This may have been due to increased agent and air density at constant mass flows, which could have decreased the velocity and volumetric flow. It is also possible that some of the agent may have remained in a liquid state, which reduces the agent's contribution to the velocity and flow, relative to hotter conditions.

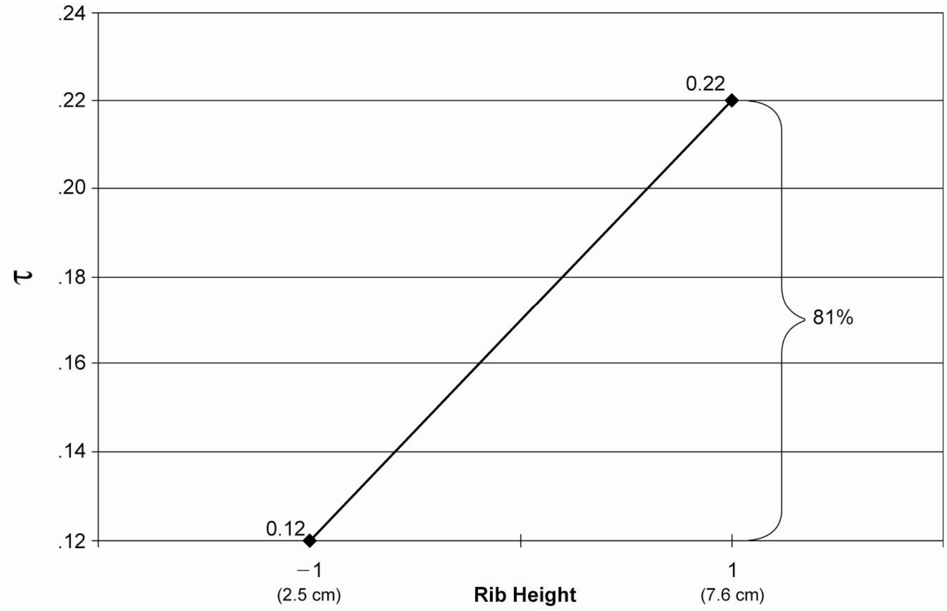

**Figure 11–22. Influence of Flame Stabilizing Rib Height on Value of τ.**

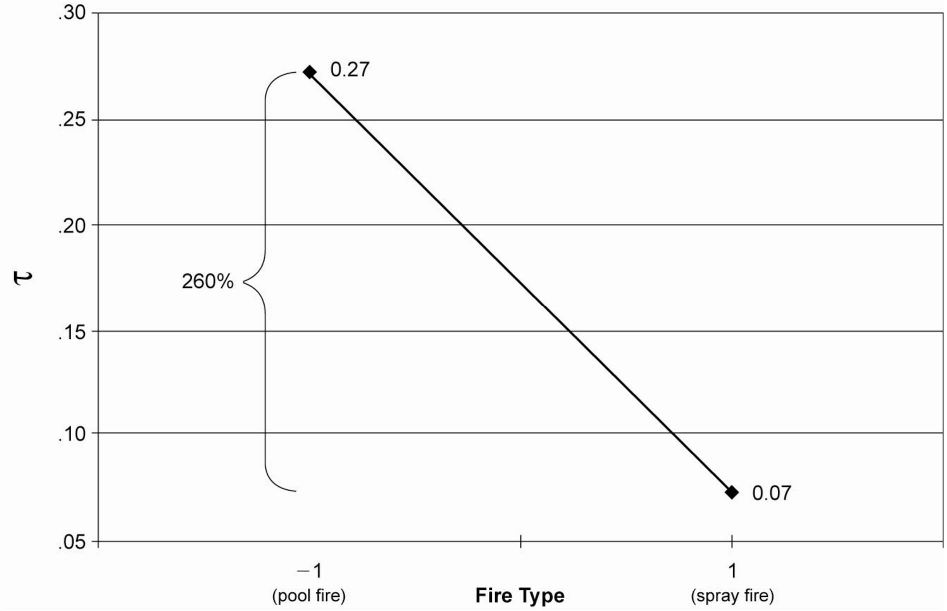

**Figure 11–23. Influence of Fire Type on Value of τ.**

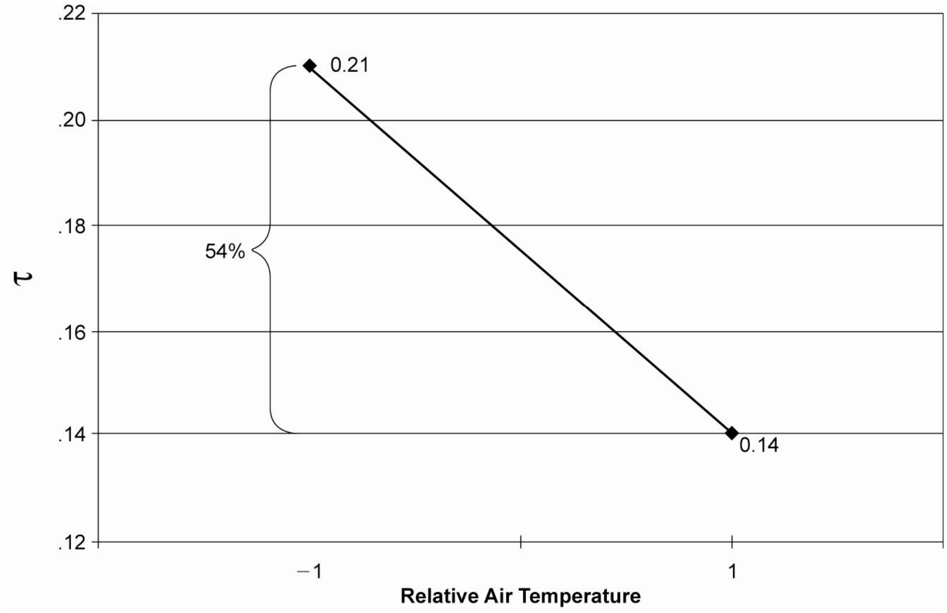

**Figure 11–24. Influence of Agent and Air Temperature on Value of τ.** ("-1" is 10 ºC below the agent boiling point; "1" is 60 ºC above the agent boiling point.)

### 11.8.9 Principle 2

*The measured cup burner extinguishing concentration of a candidate extinguishant is an effective predictor of the critical flame suppression concentrations required within the flame recirculation zone of an engine nacelle fire.*

Table 11–9 is a summary of the Phase I fire extinguishing data. For each of the 16 run conditions, the minimum agent mass for flame extinguishment was determined, with an estimated uncertainty of ± 0.005 kg (0.01 lb). The minimum agent discharge was then repeated with no fire, to enable making Halonyzer 3 measurements of agent concentration above the rib stabilizing the flame in the region, and where the flame's recirculation zone had been. For each run, the value used for further analysis was the highest concentration in the recirculation zone. This value was selected because the reaction rate time scale was so much shorter than the residence time scale, that the quenching process was estimated to be immediate. The concentrations in the table were derived from this group of 16 data points.

**Table 11–9. Flame Extinguishment Concentrations.** (% by Volume)

| | **HFC-227ea** | **$CF_3I$** |
|---|---|---|
| Minimum and maximum values of the 8 sets of conditions for each agent | 6.3, 14.8 | 2.4, 7.7 |
| Mean value and std. dev. of the 8 sets of conditions for each agent | 10.8 ± 3.1 | 3.7 ± 2.1 |
| Mean value (of 4 runs) for spray fire extinguishment | 8.9 ± 2.8 | 2.5 ± 0.25 |
| Mean value (of 4 runs) for pool fire extinguishment | 12.9 ± 1.8 | 5.1 ± 2.3 |
| Cup burner value | 6.2 | 3.2 |
| Flammability limit | 11.0 | 6.8 |

The first two rows show a considerable spread in the extinguishing concentrations for both agents. The three mean values correlated with the cup burner values, but were numerically larger, i.e., it generally appeared to require more chemical to quench the real-scale fires.

The results for spray fire and pool fire extinguishment (rows 3 and 4) were not likely to have been in error. They were consistent with the results of Hamins et al.,[2] who obtained 6.2 % and 11 % for HFC-227ea and 3.2 % and 6.8 % for $CF_3I$. The differences were within the combined experimental uncertainties.

It was therefore important to determine whether the real-scale fires were more difficult to suppress than small diffusion flames or whether a smaller concentration of extinguishant was actually reaching the fire. Since the flow patterns and thermal conditions were different between the tests with a fire and the equivalent test without a fire, it was beneficial to obtain $X_{fire}(t)$, the extinguishant concentration in the recirculation zone, for the former using data from the latter. The following is a proposed protocol for obtaining an estimate.

Equation (11-4) is a reasonable fit to the rising portion of the time-dependent agent concentration in the recirculation zone area, but with no fire present:

$$X_{nf}(t) = X_{\infty nf} e^{-a_{nf}(t-t_{p_{nf}})^2} \tag{11-4}$$

where:

$X_{nf}(t)$ is the concentration in the non-fire region at time t,
$X_{\infty nf}$ is the peak concentration measured in the fire zone,
$a_{nf}$ is an exponential coefficient, and
$t_{p_{nf}}$ is time corresponding to the peak of the Halonyzer trace in the fire zone (with the beginning of the concentration rise defined as t = 0).

The exponent has been raised empirically to the second power. Although it would have been preferable to adjust it based on the data, the limited number of independent boundary conditions required that one of the parameters be fixed.

1. Using an extra intermediate data point prior to the peak on the concentration trace, and measured values of $X_{\infty nf}$ and $t_{p_{nf}}$, calculate $a_{nf}$.
2. Assume that the value of $\tau$ for the "fire" condition is twice that for the equivalent "non-fire" condition, consistent with the findings of Winterfeld.[6] Hamins et al. also published data from which such an assumption could be drawn.[2]
3. Use Equation (11-2), twice, to express $X_f$ as a function of either $X_{nf}$ or $X_{fire}$..
4. The free stream concentration $X_f$ is expected to be roughly the same whether a fire existed or not. Therefore, set the two expressions for $X_f$ equal to each other. Use the previously calculated value of $\tau$ for the conditions of interest, and use (2 $\tau$) to replace $\tau$ in the expression using $X_{fire}$ Set the values of $X_{nf}$, $X_{fire}$ and $X_f$ to be equal at t = 0.
5. Using Equation (11-5), calculate the exponential coefficient for the fire condition.

$$a_{fire} = (a_{nf} \text{ x } t_{p_{nf}})/(2 \text{ x } t_{p_{fire}}) \tag{11-5}$$

6. Solve the expression $X_{nf}(0) = X_{fire}(0)$. The former term can be calculated directly, permitting one to calculate $X_{\infty fire}$ as an expression of only $t_{p\,fire}$.
7. Apply the boundary condition $X_f(t_{p\,fire}) = X_{\infty fire}$, since the free stream concentration curve crosses the fire zone curve at its peak.
8. Solve the equation for $t_{p\,fire}$ using iterative techniques.
9. Using an equation of the form of Equation (11-4), calculate $X_{\infty fire}$, $a_{fire}$ and $X_{fire}(t)$ to obtain a theoretical concentration profile under fire conditions.

This somewhat complex approach was used to calculate theoretical peak concentration profiles for two extremely different sets of experimental run conditions, using different extinguishing agents, fire types and air flows, and with widely varying τ values, as examples to test the "robustness" of this proposed approach. The calculated peak concentrations expected under fire conditions and threshold agent mass requirements are shown in Table 11–10.

**Table 11–10. Calculated Peak Concentrations under Fire Extinguishment Conditions.**
(% by Volume)

| Run Conditions | τ | $X_{\infty nf}$ | $X_{\infty fire}$ |
|---|---|---|---|
| Run 13: $CF_3I$, pool fire, 7.6 cm rib height, low air flow | 0.54 | 6.3 | 3.0 |
| Run 11: HFC-227ea, spray fire, 7.6 cm rib height, high air flow | 0.17 | 11 | 5.8 |

The peak concentrations in the far right column are very close to the cup burner flame extinguishment values for the two agents, even with all of the approximations and assumptions used in this analysis. These limited results suggested:

- Cup burner values may be widely applicable indicators of peak agent concentrations in the fire zone at flame extinguishment.
- The preceding estimation protocol may be of some utility in estimating threshold flame extinguishing concentrations using only non-fire Halonyzer data. Further experiments and theoretical analysis are needed to establish the reliability of the protocol.

An alternative representation of the agent concentration profile assumed that the nacelle portion upstream of the fire zone was well mixed, as shown in Equation (11-6):

$$X_f(t) = \frac{Q_E}{(Q_E + Q_A)}\left[1 - e^{\frac{-(Q_A+Q_E)}{V_T}t}\right] \tag{11-6}$$

where:

$X_f(t)$ is the free stream concentration just upstream of the fire zone,

$Q_E$ is the volumetric flow of the extinguisher during discharge,

$Q_A$ is the volumetric flow of the ventilation air inflow, and

$V_T$ is the total volume of the nacelle upstream of the fire location.

After the extinguisher flow subsides, the upstream concentration gradually decays, as represented by the following upstream concentration model:

$$X_f(t) = X_{f_D} e^{\frac{-Q_A}{V_T}(t-t_D)} \tag{11-7}$$

where $X_{fD}$ is the free stream concentration at the time ($t_D$) that extinguishant stops flowing (actually the peak concentration). This rendition was not used in the preceding analysis, but warrants further study.

As noted above, this analysis suggested that, for each fire suppressant and fire type, a single concentration in the fire recirculation zone may lead to extinguishment under all engine nacelle operating conditions. Therefore, it was valuable to examine the extent to which the test factors affected the response variable. This ANOVA analysis used the Halonyzer peak concentration reached in the fire zone at the threshold extinguishing mass for each set of run conditions in the experimental series.

- The agent flow, determined by the extinguisher storage pressure, had only a modest influence, as shown in Figure 11–25. A change of a factor of 4 in storage pressure resulted in a 30 % change in the response variable.
- As shown in Figure 11–26, increased clutter (taller rib heights decreased the response variable by about 20 %.
- No other parameters (or “factors”) were shown to have statistically significant influences.

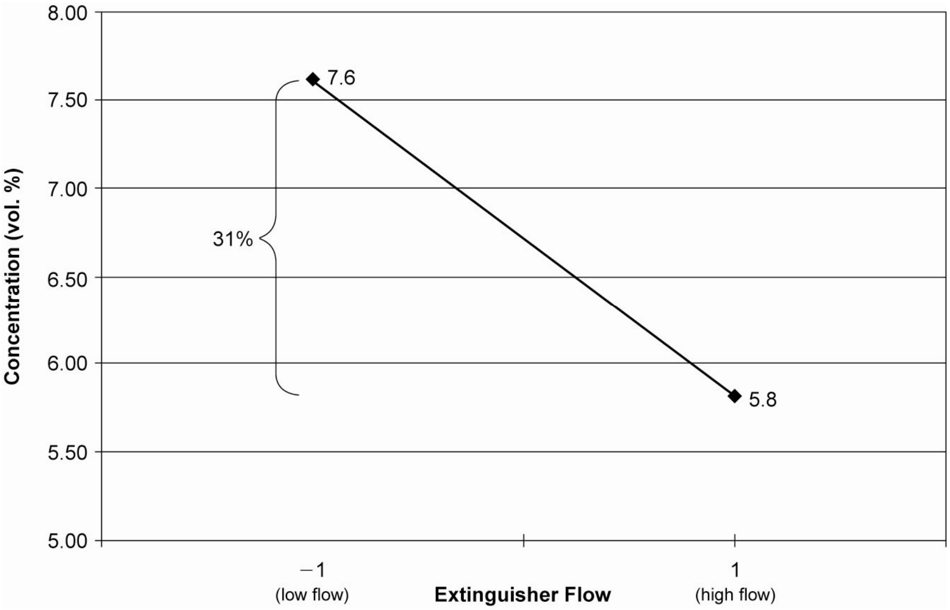

**Figure 11–25. Variability in Peak Concentration Required Due to Extinguisher Flow.**

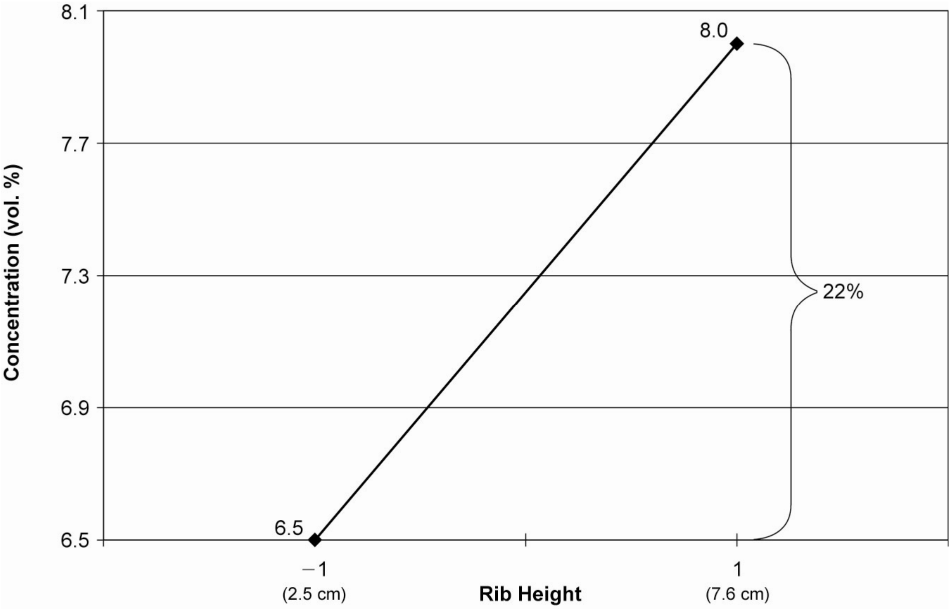

**Figure 11–26. Variability in Peak Concentration Required Due to Rib Height.**

### 11.8.10 Phase III Results

The results of the Phase III experiments are compiled in Table 11–11. The limited data showed that on a mass basis, BTP was at least as effective at flame suppression as HFC-227ea. This indicated at least some benefit from the presence of the bromine atom. Since BTP extinguished the fires in essentially all the tests, additional testing with lower discharged BTP mass would be needed to (a) ascertain the magnitude of the improvement in efficiency and (b) determine whether the magnitude was comparable to the improvement over HFC-227ea in the cup burner apparatus.

**Table 11–11. Results of Fire Experiments with HFC-227ea and 2-bromo-3,3,3-trifluoropropene.**

| | HFC-227ea | | 2-bromo-3,3,3-trifluoropropene | |
|---|---|---|---|---|
| Test Conditions | Mass Discharged kg (lb) | Flame Suppressions/Number of Tests | Mass Discharged kg (lb) | Flame Suppressions/Number of Tests |
| 1 | 1.06 (2.34) | 4/5 | 1.0 (2.2) | 1/1 |
| 1 | 0.91 (2.00) | 0/4 | 0.91 (2.0) | 3 /4 |
| 2 | 1.24 (2.73) | 0/5 | 1.24 (2.73) | 4/4 |
| 2 | | | 1.06 (2.34) | 3/3 |

## 11.9 SUMMARY

In its 10 years of research, the Department of Defense's Next Generation Fire Suppression Technology Program:

- Developed new understanding of the fire suppression process,

- Established sound tools for screening and evaluating large numbers of alternate fire suppressant fluids,
- Screened tens of thousands of compounds, and
- Developed technology for obtaining the best fire suppression system performance for a given suppressant.

Most of the research was performed using laboratory apparatus. In the process of compiling the copious knowledge that resulted from the research, seven principles were identified that were appraised using a fully complex, real-scale engine nacelle test facility. The following principles were confirmed:

- In general, 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. Should the suppressant be efficiently transported through the nacelle annulus and spend sufficient time in the fire zone, local vaporization may allow full efficiency for a suppressant with a boiling point slightly below the engine nacelle temperature.
- The measured cup burner extinguishing concentration of a candidate extinguishant can be a predictor of the critical flame suppression concentrations required within the flame recirculation zone of an engine nacelle fire.
- When deploying near-minimal masses of agent needed to suppress a fire, increasing the number of extinguishant discharge sites increases the uniformity of suppressant concentration throughout the nacelle. As with all the mixing-related principles, discharging sufficient additional suppressant can result in an extinguishing concentration throughout the nacelle.
- Obstructed pool fires require more agent for flame extinguishment than do spray fires.
- The extinguishant concentration established in the recirculation zone is a function of the free stream concentration, the magnitude of the obstacle (“clutter”) that stabilizes the flame, and the mixing time behind that obstacle.
- The degree of clutter typically present in an engine nacelle can significantly hinder the uniform distribution of a fire suppressant.
- Assuming that a mix of extinguishant vapor and liquid aerosol reach the flame reaction zone, the sufficient vaporization of liquid particles to enhance extinguishment will be dependent upon, among other parameters, the liquid’s residence time in the recirculation zone.
- The suppression effectiveness of a non-catalytic extinguishant in a full-scale engine nacelle is determined by its ability to absorb heat as it enters the flame zone.
- 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.

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