VERIFICATION OF NGP FIRE SUPPRESSION PRINCIPLES

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BACKGROUND

TECHNICAL CHALLENGE

The goal of the soon-to-be-completed Next Generation Fire Suppression Technology Program (NGP) is to develop and demonstrate retrofitable, economically feasible, environmentally-acceptable, and user-safe processes, techniques, and fluids that meet the operational requirements currently satisfied by Halon 1301 fire protection systems in aircraft. The results will be specifically applicable to fielded weapon systems, and will provide dual-use fire suppression technologies for preserving both life and operational assets. [1]

The fire suppression principles observed and derived as a result of the many years of research of the Next Generation Fire Suppression Technology Program (NGP) have culminated into an effort (denoted as Project 6-E of the NGP) to quantify and test those principles in the context of a full-scale, or "real scale" engine nacelle environment (such experiments have been performed in 2005 and early 2006 in the Aircraft Engine Nacelle Test Facility (AEN) at Wright Patterson Air Force Base). The principles observed in cup, counter-flow and turbulent spray burners, as well as a myriad of other "bench top" or comparably-scaled specialty intermediate-scale experimental apparati, have isolated the effects of particle or droplet size, chemical and thermal effects, and mixing behavior, amongst many other parameters in a series of controlled, well defined experiments. General principles that govern these processes have been defined by the contributing NGP researchers, in the form of a list of statements of principle, coined "Lessons Learned". A test plan was devised to verify these principles, as best as was feasible, in a full-scale test environment. The challenge of this project was to verify such intricate, interdependent relationships previously identified in previously tightly controlled, highly instrumented and often one or two-dimensional experiments by designing and conducting a series of experiments in a large-scale test simulator with complex three-dimensional, transient airflow patterns, agent release and mixing inhomogeneities, and limited instrumentation capabilities in a large scale fire environment. The skill in translating these fundamental principles in a manner that they can be meaningfully evaluated in a large, "real-scale" environment, including the proper experimental design, measurements and transformation and interpretation of data, thus becomes a critical task in the success of the project, as discussed in this paper.

APPROACH

"LESSONS LEARNED" FROM PRIOR NGP RESEARCH

The list of "Lessons Learned" was developed, comprising principles proposed, reviewed and agreed upon by a group of contributors of research sponsored over the history of the NGP program, as well as other NGP staff. To avoid redundancy, these principles will not be listed here, but will be listed in concert with the new research conducted and documented here, to assess their robustness and applicability to the full-scale fire environment.

METHODOLOGY

The full-scale engine nacelle fire test capabilities of the Aircraft Engine Nacelle Test Facility (AENTF) at Wright-Patterson Air Force Base was used to conduct the experiments. The facility can reproduce most of the environmental conditions an aircraft engine nacelle can experience in flight, including elevated or cold air temperatures, and a wide range of airflow rates (pressure variation to simulate altitude effects was not included in this experimental series). A variety of flammable aircraft fluids can be used to create either pool or spray fires, although only JP-8 fuel was used in this series. No artificial hot surfaces were used to add further re-ignition potential in the experiments, although they are available for use. The configuration of the nacelle, extinguishing system, and fire site can be changed in a standard fashion by rotating the test fixture and originating fires at various sites along the nacelle length, either on the top or bottom (although only bottom fires were used in this series), interchanging the height of ribs that are placed every two feet around the perimeter of the simulated engine core and attached onto the inner nacelle wall, and moving the location of one or more extinguishing agent discharge sites. The extinguishing systems have variable capacities, and can be heated or cooled as well. The test fixture used for this series was the reconfigurable, generic universal nacelle fixture used in thousands of fire experiments in the National Halon Replacement Program or Aviation, and shown installed in the facility in Figure 1.

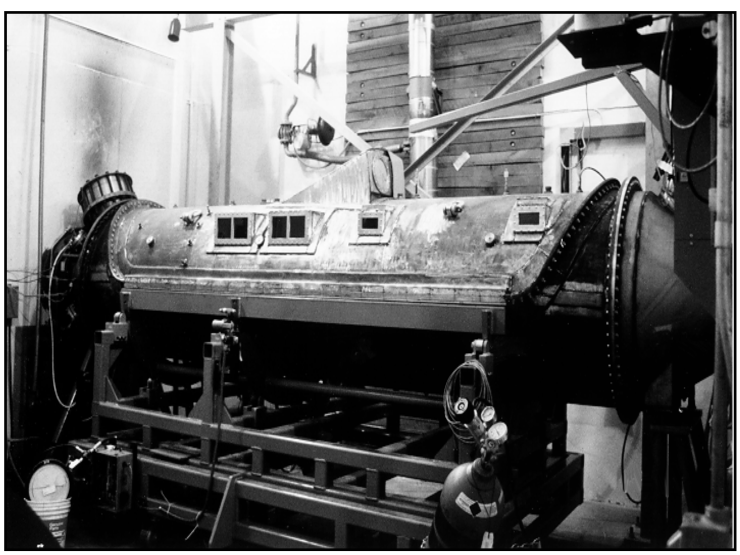

Figure 1. Reconfigurable Nacelle Test Fixture in AENTF.

Figure 2 is a semi-transparent view of the internal componentry and configuration of the test fixture (with airflow moving from right to left in the illustration). As stated, the fire experiments were conducted with the fixture rotated in such a position such that both spray fires and pool fires could be created (each in their own separate experiments), within one foot location of each other (the pool fire being one foot downstream), with each flame stabilized by a variable height structural rib mounted just forward of the flame site to act as a flame holder (the rib just forward of the pool fire pan is not shown).

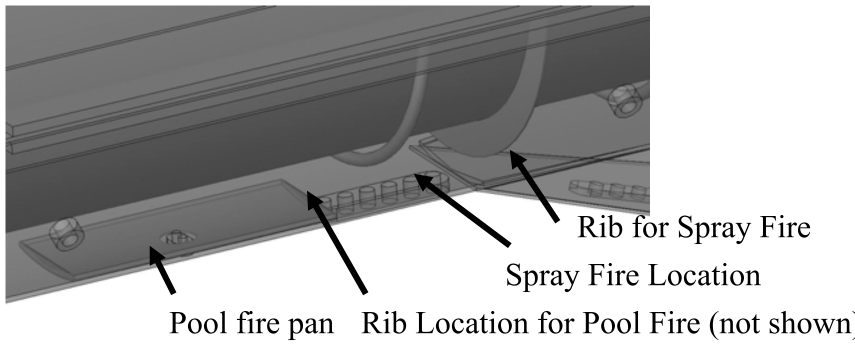

Figure 2. Semi-Transparent View of Components in Fire Section of Fixture.

To conduct experiments involving all of the parameters of interest, with all of the output data desired, and with sufficient repetition and adjustments of agent capacity sufficient to obtain quality data, requires special techniques to collect sufficient data within schedule and cost constraints. This challenge was addressed by employing orthogonal test matrices and statistical experimental design, with the output data processed using Analysis of Variance (ANOVA) techniques. This mathematical technique permits the consideration of many variables (factors) and two-factor interactions (the impact of two factors changed in tandem on the overall results) with only a small fraction of the experiments that would be necessary than if a regular full-factorial experiment series were performed, where only one factor is varied at a time. Using the specific factor setting layout such as that shown in Table 1 (where the -1 and 1 values correspond to two different settings possible for each factor, with the setting varied in a particular pattern for each set of test conditions, or “runs”), the data for each factor is “orthogonal”, meaning that the same output data can be used to analyze the effect of each factor independently, to maximize the use of the output data. The columns in Table 1 represent each factor of interest (with the settings for each run below it), with some columns representing two factor interactions (such as “AB”, which represents the effects of factor A and B in tandem, etc.), in which pairs are “confounded” in this configuration, meaning that the determination of which factor of the pair in a column is statistically significant (if either is) cannot be determined without additional data. The Analysis of Variance (ANOVA) data analysis process can be used to determine which factors significantly contribute to any variance of the output data (and with what percentage of certainty), or whose variance can be explained by inherent experimental error (this feature is a key technique to determine if such factors are significant under certain fire conditions, as stated in many of the principles in the “Lessons Learned”). This technique was used successfully in the thousands of engine nacelle fire tests performed in the National Halon Replacement Program for Aviation.

Since fire experiments are a special situation where the final "answer" (the minimum threshold of agent mass required to extinguish the fire) must be "pre-guessed" before conducting the experiment, then scaled up or down for the next experiments based upon whether the fire was extinguished or not, a special protocol was devised previously to "bracket" in on a final threshold extinguishing quantity for a set of conditions, while retaining a given confidence level and tolerance band. The protocol previously devised and used in this project required five successful extinguishments at a given mass level, to confirm at least an 86% success rate expected at this level in field use. The protocol adjusts the level required for additional tests based upon whether this success rate is observed, continuing to adjust until the next increment to change to is within 10% of the level previously shown to extinguish five out of five fires, resulting in completion.

Table 1. Orthogonal Array Experimental Matrix for Tests

RUN\FACTORS	A	B	EF CD AB	C	BD AC	AD BC	D	E	BF AE	BE AF	F	DF CD			DE 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

The experiments were divided into two phases. In Phase I – "Local Conditions in Fire Zone Required for Extinguishment", the experiments focused on determining how the factors of interest in terms of fire zone configurations or conditions influence the extinguishing concentrations required in the recirculation zone, where the fire is present. After the threshold extinguishing agent mass required is determined for each set of conditions in each run, the extinguisher was run under the same conditions with no fire and using the Halonyzer agent concentration device, to measure local concentrations during discharge within the fire zone, and in the free stream just above the upstream rib stabilizing the flame (since three measurements were made near a given location, a total of six probes were used each for the spray and pool fires). The output data of interest includes the maximum peak concentration measured in the fire zone (the peak is of interest since the theory proposes that chemical reaction times are much smaller than other mixing and transport time scales, thus the required critical extinguishing concentration must only be reached instantly within the fire zone (versus free stream) to achieve extinguishment) and the moles of agent (including stored liquid in the extinguisher) divided by the peak concentration observed. This latter criteria is an indirect method of determining if additional liquid mass is required to achieve a given concentration in a fire zone, such as under cold conditions versus hot, with the excess mass not measured as a gaseous concentration, but presumably condensed onto upstream structural elements, or not vaporized after transport through the flame region. All factors are set at two levels, as seen in Table 2, to meet the requirements of a 16-run, two level experimental design. The airflow rate and temperature settings were limited to levels less than that capable by the facility, since all possible combinations of airflow rate and air temperature must be used in the experimental protocol, and the cold temperature settings tax the airflow capabilities of the facility due to the special sources that must be used for the chiller. It should be noted that the temperature settings for the airflow and extinguisher are "relative" air temperatures, meaning that they are settings at either 10 C below or 60 C above the boiling point of the extinguishing agent tested, so that a similar type of liquid discharge characteristics may be present at cold temperatures with either agent tested (both agents were of very similar boiling point). Extinguishing agents CF_3I and HFC-227ea were chosen as the chemically and non-chemically active candidates respectively, with other comparable physical properties that should behave similarly when exposed to identical operating conditions. The extinguishers were set at a high and low pressure to produce an equivalent high or low mass flow rate from each extinguisher, adjusted for the density of each agent (difficulties in confirming data from the special mass flow meters procured and modified precluded determining the exact mass flow rate values at the date of this publication).

Table 2. Phase I Experimental Factors and Settings.

FACTOR	SETTINGS
Airflow Rate	1.0, 3.0 lbm/sec
Clutter (Rib) Height	1.0", 3.0"
Fire Type	Spray, Pool
Agents	HFC-227ea, CF_3I
Relative Temp/B.P.	-10.0 C, + 60.0 C
Exting. Flow Rate	Low, High

Phase II of testing, "Assessment of Agent Dispersion Optimization", was devised to determine how the nacelle and extinguisher operating conditions control the uniformity of agent concentration profiles throughout the entire nacelle region, and hence the efficiency of discharge (since it is desired to achieve a critical concentration everywhere in the nacelle at a given time, using a minimal amount of agent itself). The output data desired from the experiments include the standard deviation of the concentrations measured at twelve remote points in the nacelle, as a means of assessing the inhomogeneity of extinguisher concentration throughout the nacelle, in a quantitative fashion. This data was collected at multiple extinguisher mass levels, to determine if the effect of the various factors extend over all discharge levels, or varies as the mass changes. Only Halonyzer concentration measurements are made, with no fires. The same factor settings are used as in Phase I, except that either a single, upstream side injection port is used with one extinguisher, or four ports, at the two, four, eight and ten o'clock positions, spaced at four positions downstream and originating from two extinguishers, to assess whether multiple discharge sites improve the homogeneity of concentration profiles in the nacelle. Nozzles were also used in half of the tests, to assess if they break up liquid flows and improve dispersion throughout the nacelle, particularly under cold conditions. A listing of the factors and setting for Phase II is shown in Table 3.

Table 3. Phase II Experimental Factors and Settings.

FACTOR	SETTINGS
Airflow Rate	1.0, 3.0 lbm/sec
Clutter (Rib) Height	1.0", 3.0"
Injection Ports	1, 4 sites (varied downstream, radially)
Nozzle Use	Yes, No
Relative Temp/B.P.	-10.0 C, + 60.0 C
Ext. Flow Rate	Low, High

RESULTS AND ANALYSIS

The following principles were evaluated via analysis of the full-scale experimental data:

PRINCIPLE: "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."

The data revealed (Figure 3) that experiments at colder temperatures (10 C below the agent's boiling point) required about a third more agent to achieve a required fire zone concentration, in terms of moles of agent required to achieve a given concentration, compared to hot conditions. This extra amount is assumed lost due to condensation of liquid agent on the upstream nacelle components, or un-vaporized after passing through the fire zone, thereby providing no benefit.

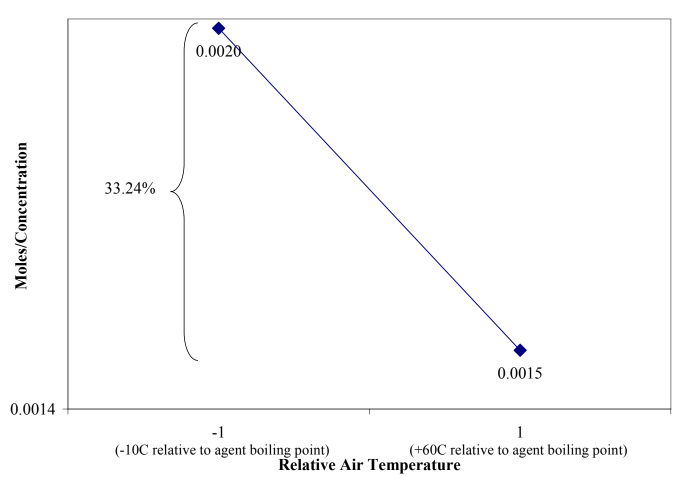

Figure 3. Variation on Moles/Concentration Required With Agent Temperature.

PRINCIPLE: "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 twelve concentration probes (measured at a time when the lowest of the twelve is at its highest amount, as is used for certification testing) by about 22% on average (as seen in Figure 4), when discharging 1.5 lbs (0.68 kg) of agent. It was observed that when discharging 12 lbs., 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.

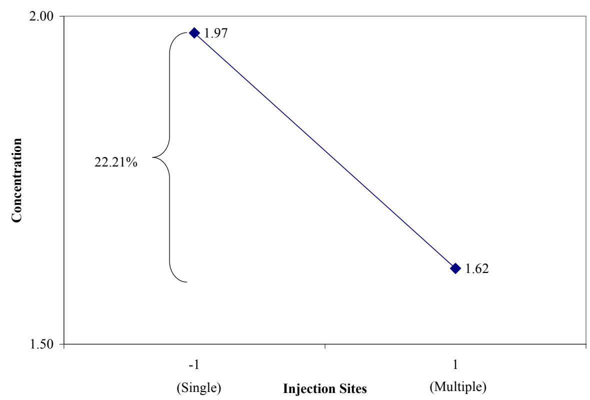

Figure 4. Variation of Concentration Standard Deviation with Number of Discharge Sites.

PRINCIPLE: "The observed behavior by several NGP researchers of extinguishant passage through clutter of various configurations will be verified under full scale, three dimensional conditions."

It was observed that the 3 inch tall rib heights (versus 1 inch) result in a 45% increase in standard deviation of concentration for the 1.5 lb. discharge scenario, and 60% increase for the 12 lb. scenario. Therefore, the height of ribs and other nacelle obstructions are demonstrated to play a significant role in the efficient distribution of extinguishing agent in a nacelle.

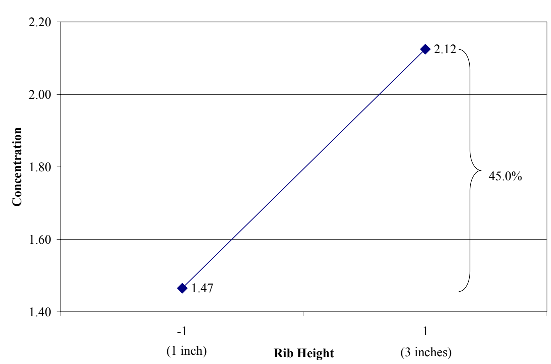

Figure 5. Variation of Concentration Standard Deviation with Rib Height.

PRINCIPLE: "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 the aerosol particle sizes, the liquid's heat transfer characteristics, residence time in the recirculation zone, and other related parameters."

This type of full-scale testing is not an ideal means to assess the particle size of liquid aerosols, and the heat transfer aspect is addressed in the next principle. However, the residence time in the recirculation zone may be estimated indirectly. Hamins [2] states 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 detail in the evaluation of one of the later principles. An estimate of the characteristic time has been calculated for each of the sixteen sets of conditions represented in the sixteen test runs, and the influence of individual parameters on these calculations (using actual agent concentration data) has been evaluated using the ANOVA process. Figure 6 is a plot of the moles divided by peak fire zone concentration, as a function of this characteristic time (represented by the Greek letter "tau"), for those runs of spray fires under cold conditions (having the smallest "tau" values). This demonstrates that, if in fact the residence time increases with the increase in the value of "tau", then increased residence times reflect a reduced amount of moles of agent needed to provide a given fire zone concentration, suggesting that more of the liquid aerosol in the fire zone is indeed vaporizing in the fire zone and contributing to the local concentration, thereby increasing efficiency. This effect diminishes with further increases in tau, such as under hotter air conditions, presumably because vaporization in the fire zone is nearly complete under less benign conditions.

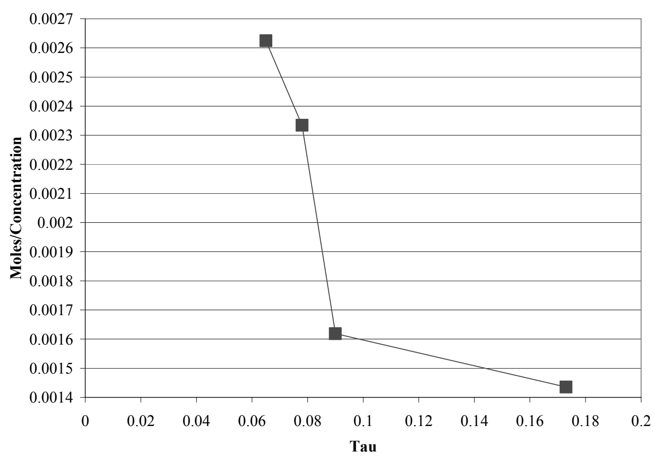

Figure 6. Reduction in Excess Moles/Concentration With Increasing Tau, Residence Time

PRINCIPLE: "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."

The only output data deemed to be relevant to this principle was the measure of variability in required concentration with cold operating temperature versus hot temperatures. The idea behind this approach was that an agent at colder temperatures in or approaching the fire zone may possibly extract additional heat due to the larger temperature difference from the flame, as well as some possible phase change heat of vaporization component to further enhance its cooling effects, resulting in a lower extinguishing concentration required. Figure 7 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-227 ea. It can be seen that neither agent exhibits any notable difference in required concentration between the hot and cold conditions – certainly well within the variability due to experimental error alone (the influence on both agents was nearly identical, although HFC-227ea has a much larger specific heat than CF_3I, although CF_3I's chemical capabilities may offset its more limited thermal cooling properties). This cannot readily be explained, other than for the fact that the cold temperature levels tested may not be cold enough to capture this influence, with insufficient liquid portions to significantly influence it, and in any case, the impact of agent temperature on required extinguishing concentration may be modest in general, compared to more significant factors. The influence of an extinguishing agent in absorbing heat may best be captured in separate smaller scale and more tightly controlled experiments, where the large body of literature data on the effects of extinguishing agents on influencing critical flame temperatures can be more easily reinforced.

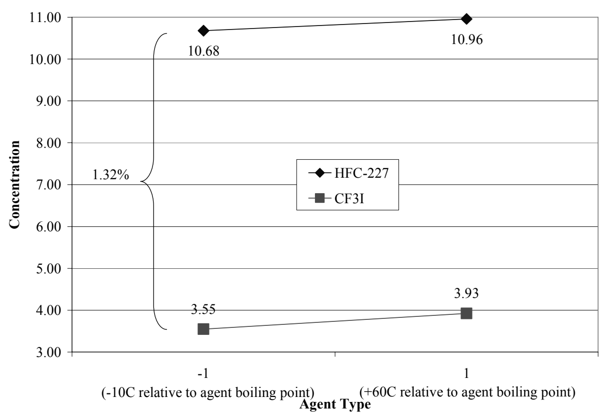

Figure 7. Effect of Agent Type and Relative Temperature on Extinguishing Concentration.

EXTINGUISHING MIXING MODELS

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

Basic Mixing Model

Hamins [2] proposed a basic mixing model, expanding upon the work of Longwell, et al [3], who 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 of 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 (τ) 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 versus isothermal conditions. Additional details of this prior research can be found in the work of Hamins [2].

Hamins extended the model to explain the mixing process of an extinguishing agent discharged upstream into an air flow, a portion of which is entrained into the flame's recirculation zone, according to the following governing equation:

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

Where X_f is the free stream concentration, held for the time Δt, X_∞ is the concentration needed in fire zone to accomplish extinguishment, and τ (tau) is the characteristic mixing time for the configuration and conditions of interest. This expression demonstrates that the free stream concentration X_f must be to some extent higher than the minimum concentration X_∞ (the minimum concentration required if held indefinitely, such as in a cup burner test) required to extinguish fires within the recirculation zone if the time Δt that it is applied is not significantly longer than the characteristic time τ. The extent that the free stream concentration must exceed the required fire zone minimum concentration is governed by the preceding equation, and the value of the characteristic time τ, which is determined as a result of the flame holder size and configuration, and the local free stream velocity. This model, like that which it is built upon, assumes instant and perfect mixing within the recirculation zone, resulting in a homogeneous composition, as well as a constant, steady concentration of extinguishing agent within the free stream that is introduced into the recirculation zone (which is significant departure from actual nacelle discharge conditions), which permits the simplification of the expression shown above. Takahashi et al [7] noted that prior studies had shown that the proportion coefficient relating the value of τ to the ratio of rib height to free stream velocity was 22.79, for his two-dimensional bluff body/rib stabilizing a pool fire in his experiments.

The literature values of X_∞ 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 4.

Table 4. Literature Values of X_∞ and τ from Prior Experimentation.

FIRE TYPE	X_∞ (HFC-227ea/CF_3I)	Tau
Spray Fires	.0062[2]/0.032[2]	0.1 [2], 0.04 [2]
Pool Fires	0.11 [2]/0.068[2]	0.7 [2], 1.0 [2], 0.04 – 0.4 [7],0.1-0.2 [8], 0.1-1.0 [9]

Detailed Mixing Model

Hamins also reported the following differential equation expression for the mixing process behind a bluff body in general:

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

where $X_f(t)$ is the free stream concentration 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 concentration at time t (along the same streamline), and τ is the characteristic mixing time of the recirculation zone. It can be seen that it reflects a more general model than that discussed in the last model and in Equation (1), permitting consideration of the types of complex realistic concentration profiles associated with “real world” Halonyzer “no fire” concentration measurements in real engine nacelles. This more general model also does not require a two-dimensional flow pattern of uniform velocity magnitude and direction, nor a simplified bluff body geometry, since actual measured concentration data can be used in both locations, which dictates the global value of tau, regardless of flow direction or geometrical construction. If feasible, a volumetric flow-adjusted average flow profile of the “free stream” concentrations from multiple sites and directions external to the recirculation zone should be measured, if the flow is expected to come from multiple directions. If only one location of concentration measurements are made over time in the recirculation zone, then one must assume that mixing is uniform and complete in the recirculation zone, otherwise an average from multiple probe sites in the recirculation zone would be necessary.

If one examines the differential Equation (2), one can see a mathematical structure akin to that used to determine the absolute mass required in extinguishers to “total flood” rooms to a given concentration, accounting for leakage, as prescribed in NFPA (National Fire Protection Association) Standard 2001. This mathematical structure models mixing and local concentration (of an additive in a fluid such as air) change and values in time in a fixed volume, with an inflow with an additive of a concentration X_f (less than or equal to 1.0) in the fluid, and an outflow of concentration X (the same as within the volume) to maintain constant pressure within the volume. In the case of the design equation used in NFPA 2001, the inflow concentration X_f is 1.0, since it pure extinguishant coming out of the extinguisher, resulting in the simplified structure shown in that publication. Although the protected volume concentration will change in time during discharge, it will reach a peak as the extinguisher completes its discharge after a finite period, and remain since leakage will end, since no new influx necessitates it to maintain a pressure balance with the space external to the volume. If the influx concentration is a constant value other than 1.0, then the differential equation (2) will simplify to the structure of Equation (1), used by Hamins and other NGP researchers as a simplified case, where they introduced a free stream influx of a constant concentration, as a “plug” of a set period of time Δt. Differential Equation (2) is constructed as an expression of the Conservation of Mass for the physical configuration of a volume (the recirculation zone in this fire case) with an inflow and outflow, with a separate equation possible for both the extinguishant and air, since both species are conserved. If one assumes that the density of either the air or agent respectively remains constant from the inflow, through the recirculation zone and outflowing from it (or the recirculation zone adjusts its volume due to the density difference of its hotter reaction zone versus the cooler incoming flow), then both equations can be simplified and considered solely in terms of volumetric flows, and one equation can be incorporated into the other to simplify and result in the structure of Equation (2). For this mathematical structure representing this physical system, the coefficient expressed as the “characteristic time” τ can be seen to be the ratio of volume of the recirculation zone, V_R, divided by the volumetric flow rate of the incoming flow

$\underline{V}_{in}$ into the recirculation zone. The recirculation zone volume will be a function of the fire type (spray versus pool) and local geometry, and its effect on stable flame zones and local flow influences. The volumetric inflow $\underline{V}_{in}$ is a function of the total volumetric flow $\underline{V}_T$ in the free stream (where concentration X_f is measured, such as above the bluff body stabilizing the flame), and influences of the local bluff body geometry, which governs the portion of the total volumetric flow that is entrained into the recirculation zone as $\underline{V}_{in}$, as well as the size and shape of the recirculation zone. As stated in the previous section, for the case of a rib of uniform height oriented perpendicular to a horizontal flow, this is expressed a ratio of the rib height divided by the velocity of the flow over the rib (note that this ratio has dimensional units of time, as with the ratio of recirculation zone volume to volumetric inflow rate). It should be noted that such free stream velocities become greatly perturbed and thus difficult to characterize in many cases when extinguishing agents are discharged at a high mass flow rate into the incoming flow, with high variabilities in overall velocity often experienced locally and over time during discharge.

The fundamental Equation (2), which when analyzed can be 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, sheds further light on the overall behavior of the system and influence of various parameters when the concentration profiles over time for which it governs are expressed graphically in a notional form, as in Figure 8.

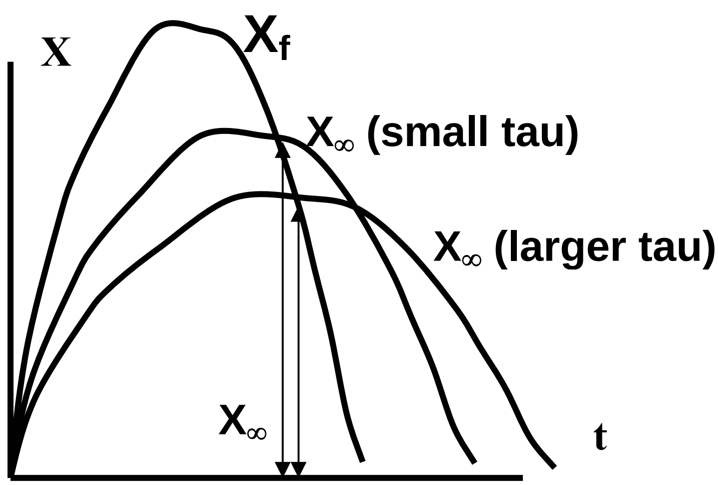

Figure 8. Notional Graphs of Concentration in the Free Stream and Recirculation Zone.

Figure 8 illustrates realistic notional concentration profiles that might be measured in an engine nacelle in both the free stream, such as over a bluff body (X_f), and behind the bluff body in the flame's recirculation zone (X), using a Halonyzer device. The most common profile of extinguishant concentration measurements over time in the free air stream are somewhat Gaussian in shape, such as shown above, with a rise, peak and decay, since an extinguishant is discharging into an upstream volume until its flow subsides and the volume concentration then decays, although other curve features such as fluctuations and even second peaks can occur, due agent flashing or other surging behavior during discharge, or other perturbations to the upstream flow. The governing Equation (2) dictates that the peak of the agent concentration X in the flame's recirculation zone must reach a peak when the free stream concentration decays to intersect the recirculation volume rising concentration (since $dX/dt = 0$ when $X_f = X$). This relationship makes intuitive sense; when the incoming airflow is no longer a higher concentration than that of the recirculation zone, then the concentration within the recirculation zone can no longer rise. Notice that a reduced rise time of the recirculation zone curves (X), and hence lower slope or dX/dt versus that for X_f, is governed by Equation (2) which satisfies that X_f, will be higher than X while the curve for X(t) rises, while the reverse is true as X(t) decays, falling slower than that of X_f,. In effect, the recirculation zone volume exhibits a type of mass transfer concentration "inertia" that takes time to build up a concentration (depending upon the ratio of the volume to the incoming volumetric flow rate), then in turn time to decay in concentration long after the incoming flow concentration has dropped comparably. The relative decrease in slope of X(t) versus that of X_f (t) is controlled by the characteristic mixing time τ, which dictates the relative incoming flow rate in proportion to the recirculation zone volume. As τ increases, the slope of X(t) further decreases. The second curve of X(t) illustrated in Figure 8 exhibits a larger value of τ, and correspondingly a smaller valued slope on rise. It should be noted that, if a larger value of τ does occur, several things also follow: (1) the time at which the peak (X_∞) occurs is at a later time, and (2) the peak value (X_∞) in the recirculation zone is relatively lower, because the concentration curve for X_f (t) has decayed further during that extended time before it intersects the peak. **Thus, flame regions with larger characteristic times (due to local geometries and velocities) will require a greater excess agent peak in the free stream to reach a desired concentration within the recirculation zone**. This feature will impact the interpretation of "no fire" concentration measurements and provide a guide to estimating conditions under actual "fire" conditions, as will be shown later.

Actual values of the characteristic mixing time can be estimated for real engine nacelle regions, by discretizing the free stream and recirculation zone concentration data collected, and using a discretized form of Equation (2), as shown in Equation (3).

$$\tau = (X_f(t_1)-X(t_1)) / (\Delta X/\Delta t) \qquad (3)$$

In this expression, t_1 is any given point in time where concentration data is collected. This approach can be illustrated using actual Halonyzer concentration data collected in the nacelle simulator in this experimental program. In this case, a point in time t_1 is selected to record the measured concentration level from both the free stream (just above the rib that stabilizes the flame) and recirculation (behind the rib) probe data traces. It was determined to select such data from the initial rise time of the curves, which was generally the most stable curve segment for all of the different test conditions, because under some conditions various mixing phenomena result in erratic concentration traces at various locations in the recirculation zone, after the initial peak is reached (which is not critical since the period up to reaching the critical extinguishing concentration is the period of value in determining the extinguishing process). Three repeat Halonyzer runs, discharging the threshold minimum mass from the extinguisher required to extinguish the fires for each set of run conditions, were analyzed separately and averaged using this approach. The denominator of Equation (3) was calculated by recording the recirculation zone concentrations at each data point either 0.1 second before or after the selected point t_1, corresponding to the shortest data collection interval possible with the Halonyzer device, for a total Δt of 0.2 seconds. Using this approach methodically for each of the sets of Halonyzer data for each run, it was found that the τ values for all of the runs were calculated to range from 0.024 to 0.173 for the spray fires, and 0.15 to 0.54 for the pool fires. This range correlates well with that reported by other investigators, thereby suggesting that this "real data" approach may have some merit.

PRINCIPLE: "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."

The injection time parameter cannot be estimated in any significant way, since the injection time is actually coupled with the agent concentration at the time in the injection profile, which varies over time in this "real world" case. This parameter had been of interest to other NGP investigators based upon their prior laboratory scale experiments whereby they could inject a constant extinguishing concentration over a set injection interval, and using Equation (1) estimate that concentration obtained behind the bluff body, however such a uniform flow concentration over time is not realistic representation of conditions resulting in "real" nacelles.

However, the influence of the mixing time, as indicated by the value τ, on the recirculation zone extinguishing concentration as proposed in the previous mixing model discussion, can be evaluated further with respect to local obstacles or clutter. Prior studies [7, 8] proposed a simple expression for the mixing coefficient τ, that being proportional to the ratio of the bluff body rib height L to the free stream velocity U (it has also been proposed that a proportionality coefficient of 22.79 has been used for this geometry and orientation in some cases). This relationship assumes a rib perpendicular to the flow axis in both height and width, being of constant width, and featuring a two-dimensional flow field of steady flow velocity. The calculation of τ can also be performed using actual concentration data measured over the top of the bluff bodies stabilizing the flame and within the flame recirculation zone region, and Equation (3). This approach can accommodate a variety of clutter geometries and flow directions, as long as the measurement point is representative of the flow direction entering the recirculation zone (if multiple directions of significant flow are known or suspected, then measurements can be made from multiple directions, and using an averaged flow profile based upon pro-rated flow data).

Table 5 compares the values of τ for both approaches, for all the test run conditions. Since the velocity and rib height approach does not define a proportionality constant, the runs are rank ordered in terms of their value of τ, from lowest to highest (if the proportionality constant of 22.79 is used, then taus of 0.13 to 0.71 are observed, which is consistent with prior literature.

Table 5. Rank Order of τ Values in All Test Run Conditions For Both Mixing Models.

1" Clutter (Runs 1-8)				3" Clutter (Runs 9-12)			
Pool Fires		Spray Fires		Pool Fires		Spray Fires	
Calculated	Curve	Calculated	Curve	Calculated	Curve	Calculated	Curve
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

It can be seen that both the “Calculated” (using the L/U correlation and AENTF nacelle velocity measurements of David and Disimile [10]) and “Curve” (using Halonyzer “curves” and Equation (3)) data do not correlate with each other very well, in terms of the rank order of the τ values calculated using the conditions of each fire test run. It can be seen that the data was segregated by the rib height and fire type, since it came apparent upon review of the values determined from the Halonyzer traces that the values were largely influenced by these two parameters when they varied in the conditions of each test run. It is hypothesized that the calculated values using only the free stream, steady state velocity and fixed rib height may deviate from that using actual concentration data for the at least two reasons. First, the local velocity is greatly perturbed and changes in a transient manner during the extinguisher discharge period, due to the entrainment and mixing of a high mass flow rate, high momentum flow of extinguishant upstream into the free stream airflow, which mixes into the air stream in an unsteady and turbulent manner. This phenomenon impacts local velocities everywhere in the nacelle during discharge, including near the fire region. This observation has been noted by other investigators in the literature, although in some cases special provisions have been made in some of the laboratory scale tests to artificially adjust the air velocity to accommodate and dampen this perturbance, which is not practical under full scale conditions. Secondly, the velocity-and-rib height approach does not take into account the type of fire that is generated, either in this case a pool fire or spray fire, which creates different thermally-influenced dimensions of the recirculation zone (and hence the mixing and concentration dilution rates as well as local velocity changes), as well as requiring larger agent mass discharges that impose secondary effects on the mixing rate (as discussed later). Therefore, it should not be surprising to find that such a simple correlation, when applied to the complex flow fields associated with “real” engine nacelle geometries and conditions, should not provide satisfactory prediction of the indicated test results. The veracity of the approach of using actual Halonyzer concentration curves and Equation (3) will be supported further with additional analysis discussed later in this paper.

It was then of interest to determine what impact the various physical parameters of the nacelle have on the calculated values of the mixing coefficient tau, as determined from the actual fire test data, using the ANOVA data analysis technique. It was found from this analysis that the calculated values of tau using experimental data increased by 80% when the 3 inch all rib height was used, versus the 1 inch rib height, as seen in Figure 9. This reveals that the theoretical increase in tau with rib height (the “L” of L/U) is justified by calculations derived by the theoretical data, although the fact that a full three-fold increase in tau values with the larger rib height was not accounted for is likely due to the influence of other factors such a fire type that make the relationship more complex.

More importantly, it was found that calculated tau values were increased 262% when considering pool fire scenarios versus spray fires, as shown in Figure 10. This is logical, given that pool fires create larger recirculation zones than spray fires that will change in concentration more slowly for a given input flow from the free stream, although the apparent increase might be more than anticipated. However, the perplexing dilemma (at least initially) with this data is that the Halonyzer concentration traces evaluated with this technique collected their data under <u>no fire</u> conditions, since the instrument is not intended to be used under actual fire conditions. The question then becomes whether the Halonyzer data somehow retains some relic of the influence of fire type in its “no fire” data, to justify the otherwise logical correlation with fire type, or if some other explanation is justified. The only acknowledged "relic" that distinguishes the test runs between those with pool fires versus spray fires in the "no fire" Halonyzer test reenactments was that larger extinguishing agent masses were required to extinguish the pool fire tests (due to a larger flame region, more stable flame and other factors), with the same amounts being used in the "Halonyzer" tests. As stated previously, once the threshold mass required for extinguishing for the conditions of a given run was determined, the test was "reinacted" using the same mass discharged but with no fire, with the Halonyzer concentration measuring device installed in and near the fire region, to determine (as best as possible) local concentration measurements during fire conditions when the threshold quantities of agent mass are applied to accomplish extinguishment. However, this increase in total agent mass discharged may also affect to some degree another parameter – the rate of mass discharged – since actual discharge tests using the nacelle mass flow meter with larger total masses discharged were observed to also increase to a limited extent the instantaneous mass flow rate using these extinguishers under realistic conditions. This increase in mass flow rate increases the rate of rise of free stream concentration X(t) over time t, which is a type of "relic" of pool fire tests versus spray fires, when replicating Halonyzer "no fire" tests using the same agent masses as that required to extinguish these respective fires. If the increase in rate of rise of the concentration profile in the recirculation zone does not increase proportionally with the free stream concentration profile, then the numerator of Equation (3) may increase to a greater extent than the denominator, resulting in an increase in tau as the rate of free stream concentration change increases. However, if the value of tau is solely a function of the local geometry and velocity (presumably in the direction perpendicular to the main axis of the flame holders), then the proportionality in the traces will likely stand, and such a proposed explanation may not be valid. Other potential candidate explanations also exist. The high flow rate of a high momentum jet of extinguishing agent, discharged and oriented perpendicular to the direction of flow of the nacelle air flow, may considerably alter the direction of flow in the region near the flame, with the vector component normal to the axis of the flameholder obstruction therefore reduced and hence increasing the value of tau. Additionally, if the increased total mass of extinguishant has a modest increase in flow rate but discharges over a longer sustained period, and the nacelle region upstream of the flame region is not completely mixed but has a larger uniform concentration of extinguishing agent due to a longer discharge period, then it may result hypothetically in a reduced flow velocity into the flame region. This is possible since mass flow is conserved through the region, and with a larger mixture concentration of agent being a much higher density (over four times or more the vapor density of air), resulting in a much higher bulk gas density that may result in a lower velocity to maintain constant mass flow rates (this hypothetical conjecture has not been verified). The actual rationale for this influence of fire type on "no fire" Halonyzer experiments should be verified with additional experiments focused on resolving this issue.

Figure 11 shows that impact of air and agent temperature on the value of tau. It reveals larger values of tau for colder air and agent temperatures, which may be due to increased agent and air density and constant mass flow rates, which could decrease the velocity as a result as well as volumetric flow, and possibly a portion of the agent may remain in liquid state, which reduces the agent's contribution to the velocity and flow rate, in comparison to hotter conditions.

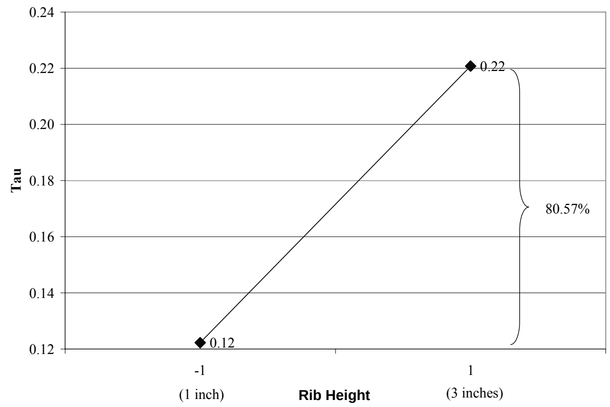

Figure 9. Influence of Flame Stabilizing Rib Height on Value of Tau.

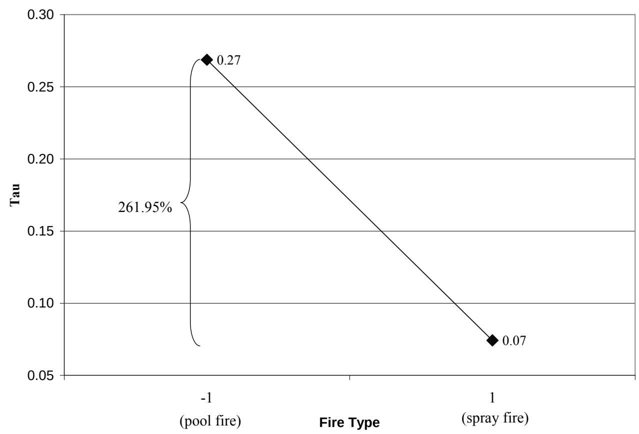

Figure 10. Influence of Fire Type on Value of Tau.

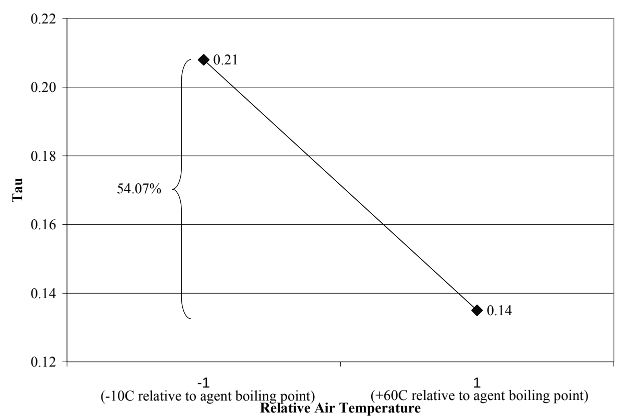

Figure 11. Influence of Agent and Air Temperature on Value of Tau.

PRINCIPLE: "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 6 is summary of the peak concentration data (peak because reaction rate time scales are considered so much shorter than residence time scales that the quenching process is estimated to be immediate, without the need to "hold" the concentration for a set time) for all of the experimental runs and their sets of conditions. These experiments were performed using the minimum threshold total mass required to be discharged to extinguish the fires for each set of the sixteen run conditions, and repeating the fire experiments under identical operational conditions and with the same total mass discharged relevant to each run, in a "no fire" condition with the Halonyzer measuring probes installed above the rib stabilizing the flame in the region, and within the flame's recirculation zone (when the flame exists). This provides an estimate of the concentration profiles and peak concentration near and in the fire region required for extinguishment (although it is acknowledged that the presence of a flame will change the flow dynamics and, to some extent, local agent concentrations). It can be seen from the table that, although there is a spread of required concentrations for both agents depending upon the run conditions, the average concentrations required for both the spray and pool fires correlated to each agent's published cup burner and flammability limit required extinguishment concentrations, respectively. This result is consistent with the results of Hamins et al [2], who observed and documented a similar relationship. In general, HFC-227ea required concentrations were slightly higher than these laboratory standards, while CF_3I was slightly lower; the rationale for why full-scale conditions should be slightly more beneficial (compared to bench-scale screening tools) for a chemically-active agent like CF_3I over the non-chemically active HFC-227ea is an area worthy of additional exploration; the previously cited ability of chemically active agents to prevent re-ignition (or possibly inhibit the ability of a heated surface to sustain a weakened flame), or differences in the mixing behavior between the agents of varying physical properties are possible suspect influences, amongst others.

Table 6. Results of Fire Tests

Agent	Max Conc	Min Conc	Avg Conc	Avg Spray	Avg Pool	Cup Burner	Flam. Limit
227ea	**14.8**	**6.3**	**10.82**	**8.78**	**12.85**	**6.2**	**11**
CF3I	**7.7**	**2.43**	**3.74**	**2.36**	**5.12**	**3.2**	**6.8**

The aforementioned acknowledgement that conditions present (including concentration profiles) near the flame region while a fire is present are to varying degrees different than under "no fire" conditions, in which concentration data is actually collected, suggests that a means to estimate the actual concentration profiles present under fire conditions, using the "no fire" data available, would prove beneficial. The following is a proposed protocol to grossly estimate the approximate concentration profiles under "fire" conditions from such data:

1. Assume a general "No Fire" concentration profile for the numerical data collected in the fire zone. The mathematical structure

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

where $X_{nf}(t)$ is the concentration in the "no fire" region at time t, $X_{\infty nf}$ is the peak concentration observed 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 concentration rise at t=0), is a potential curve fit approach, and was used in this analysis. Although this expression can be made to generally fit the profile of actual typical Halonyzer traces (at least up to the peak, which is the only concentration segment of interest), it deviates slightly in its initial conditions (having small, non-zero initial conditions for it and its derivative), although it is a workable tool. The exponent is raised to the second power in this case, although it would be preferable to leave it variable; however, the limited number of independent boundary conditions limits its variability. Using an extra intermediate data point prior to the peak on the concentration trace, a_{nf} can be calculated, since $X_{\infty nf}$ and $t_{p_{nf}}$ are already known. If multiple repeated experiments are performed (as in this case), then averages of each repeat can be made for each variable.

2. Assume that the tau of "fire condition" is twice that of "no fire" conditions. This observation that the mixing coefficient tau is roughly twice as large for combusting conditions as with non-combusting conditions was noted by Winterfeld [6], which was also cited by Hamins [2], who also published the raw data from which such an assumption could be drawn. Since the free stream concentration X_f would be expected to be roughly the same whether a fire existed or not, Equation (2) can be used to express it as a function of either X_{nf} or X_{fire}. Therefore, expressions of X_f using both X_{nf} or X_{fire} are set equal to each other, while using the previously calculated value of tau (τ) for the conditions of interest, and using (2 x τ) to replace τ in the expression using X_{fire}, and with the values of X_{nf}, X_{fire} and X_f all noted to be equal at the time t = 0, permitting one to solve for the fire condition coefficient

$$a_{fire} = (a_{nf} \text{ x } t_{p_{nf}})/(2 \text{ x } t_{p\,fire}) \quad (5)$$

3. Solve the expression $X_{nf}(0) = X_{fire}(0)$, since the former term can be calculated directly, permitting one to calculate $X_{\infty fire}$ as an expression of only $t_{p\,fire}$ (since Equation (5) can permit such further simplification).
4. The preceding derivations can be inserted into 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), as an expression of only $t_{p\,fire}$, permitting a solution of the equation for $t_{p\,fire}$ using iterative techniques. This also permits the finite calculation of $X_{\infty fire}$, a_{fire} and $X_{fire}(t)$ (of the form of Equation (4)), to propose 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 airflow rates, and with widely varying tau values, as examples to test the "robustness" of this proposed approach. The calculated peak concentrations expected under fire conditions and threshold agent mass requirements is shown in Table 7. One can see that that the peak concentrations (far right column) is uncannily similar to the cup burner concentration for each agent of question (3.02 vs. 3.2 for CF_3I, and 5.78 vs. 6.2 for HFC-227ea), regardless of the fire type, tau value or other differences, even with all of the cascading approximations and assumptions used in this analysis. This limited data suggests that cup burner values may have more universal application as accurate peak values in the fire zone itself during a fire can be estimated, and that the preceding estimation protocol may indeed may be of some utility (or some variant thereof) in estimating threshold concentrations that are required in a fire locally by using only "no fire" Halonyzer data, but much more data and theoretical analysis needs to evaluated using such an approach to affirm that such a tool or derivative can be a reliable indicator.

Table 7. Calculated Peak Concentrations Under Fire Conditions (Examples).

Example Run Conditions	Tau	$X_{\infty nf}$	$X_{\infty fire}$
Run 13: CF_3I, Pool Fire, Hi Rib ht., Low Air	0.54	6.3	3.02
Run 11: HFC-227ea, Spray Fire, Hi Rib Ht, Hi Air	0.17	11.2	5.78

Although this analysis suggests the viability of a near "universal" critical concentration value to be considered for all engine nacelle conditions for each agent, it is of interest to investigate what parameters of the engine nacelle extinguishing process contribute significantly to any variability that is seen in required threshold concentrations (at least considering Halonyzer data under "no fire" conditions) observed to be necessary for extinguishment for varying operational conditions in an engine nacelle. Therefore, an ANOVA analysis was performed using the nacelle extinguishing and resultant Halonyzer concentration data collected in this project, using the peak concentration found to be reached in the fire zone at the threshold extinguishing mass for each set of run conditions in the experimental series as the response variable.

It was found as a result of the ANOVA analysis, in addition to the significant affect of agent type and fire type on the required threshold concentrations necessary (as discussed previously), that increased agent flow rates (resulting from increased extinguisher storage pressures) reduced the required threshold agent concentration by about 31%, as shown in Figure 12. It may be that the same physical forces previously discussed that may possibly reduce the value of tau due to increased agent mass flow rates may result in lower peak concentrations under "no fire" conditions, since smaller taus "shrink" the differences in free stream, "no fire" fire zone and "fire" fire zone peak values, resulting in less "overshoot" in peak concentration required and observed in the "no fire" Halonyzer data evaluated here. Figure 13 shows from the ANOVA analysis that taller rib heights (from 1 to 3 inches in this case) increase the required critical fire zone concentration by 22 percent. Alternatively to the prior example, the larger ribs result in higher values of tau, which in turn require higher values of the "no fire" peak concentration in the fire zone (as used in this analysis) to reach a given concentration under "fire" conditions, which may explain this observed increase in peak concentrations under "no fire" conditions with the taller ribs. No other parameters (or "factors") were shown to be statistically insignificant.

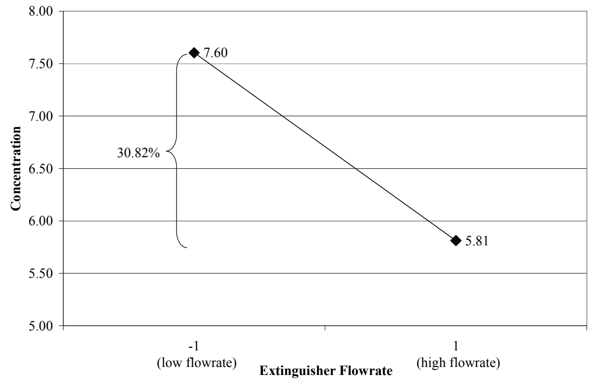

Figure 12. Variability in Peak Concentration Required Due To Extinguisher Flow Rate.

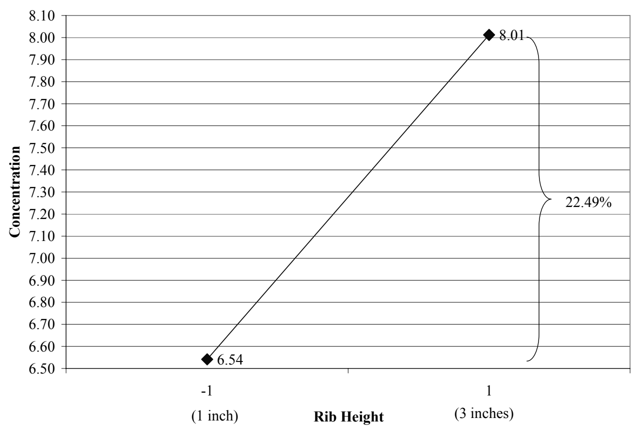

Figure 13. Variability in Peak Concentration Required Due To Rib Height.

OTHER PRINCIPLES NOT EVALUATED

Additional principles were noted in the "Lessons Learned" exercise for which effective verification techniques could not be envisioned by use of full scale testing, or due to other limitations in the scope of the program. They include the following:

1. **PRINCIPLE: "The "quality" or degree of uniformity and effective transport of various extinguishants can be sufficiently predicted using CFD codes upgraded during the research of the NGP program."**

   Rationale for Non-Evaluation: The computer codes developed using customization of the VULCAN fire-based computer code were limited at this time to only two of the sixteen experimental run conditions executed via engine nacelle fire tests, due to the code's limited abilities to simulate cold temperatures, limited fire scenario capabilities, and other limitations. These two potential acceptable fire scenarios were not evaluated to date via use of the computer codes due to the lack of quality mass flow data from the extinguisher system, an essential element to obtain accurate modeling results. A mass flow meter specially sized for use for the flow rates and conditions expected in high rate discharge from the extinguishers in use in the nacelle fire tests was specified, and ordered for assembly. After considerable time and effort over the course of the project, including many trials with various re-designs of the special mass flow meters, it has been found to date that reliable magnitudes of the mass flow rate have been suspect, due to calibration difficulties and the extreme flow rates encountered, amongst other factors. The flow rate profiles, however, may be more accurate, even with the complex bi-modal profiles generated, which may be due to flash boiling or other reasons, but such data is insufficient for the computer modeling task. Efforts continue to re-calibrate and re-adjust the mass flow meter configuration and data transformation, to enable its use in later computer modeling, although it may be limited to low pressure discharges due to limitations in the state of the art in flow meter capacities.

2. **PRINCIPLE: "The effectiveness of bromine in extinguishing flames, at least on a per unit mass basis, is independent of the type of molecule in which it is bound."**

   Rationale for Non-Evaluation: Due to environmental restrictions, military use priorities and lack of current manufacturing, the investigators were unable to obtain sufficient quantities of brominated extinguishing agents with similar physical properties and boiling points to the other agents tested, to minimize secondary variables confounding the comparison between the agents, rather to be based solely upon bromine content. Both Halons 1201 and 1202 were sought but could not be procured in sufficient quantities, due to lack of manufacturing in the former case, and military priority for field use and release restrictions in the latter case.

3. **PRINCIPLE: "Hybrid gas generator fire extinguishers (HFEs) are a more effective way of suppressing fires when using extinguishants with high boiling points."**

   Rationale for Non-Evaluation: The expense of procuring hybrid gas generators, even of only one variety, in sufficient quantities to produce a credible evaluation were not within the financial constraints of the project, while still addressing other high-priority issues desired by the sponsors. Schedule limitations further restrained the potential to evaluate this principle.

TESTING OF SECOND-GENERATION HALON REPLACEMENT 2-BROMO-3,3,3-TRIFLUOROPROPENE

The project was able to perform very limited testing with a "second generation" Halon replacement, 2-bromo-3,3,3-trifluoropropene. This chemical was noted as a promising candidate by researchers in the NGP program; its chemically active component, bromine, avoids potential environmental issues by being packaged in a molecule subject to rapid decomposition in the atmosphere. During the course of the NGP program, the agent was considered further by the fire protection industry, and larger capacities were produced for consideration for various fire protection applications, including aircraft engine nacelle use. Approximately twenty-five pounds of the agent were provided to the NGP investigators by Halotron, Inc., of Las Vegas, NV, for use in a limited number of experiments in this research project.

It was originally intended to perform a series of experiments under the identical conditions as those previously tested with HFC-227ea, to compare the results and determine if the agent has potentially improved performance over the currently available "first generation" replacements. Because of the very high boiling point of this agent (95 F), the "cold" temperature tests required conducting experiments at air flow and agent storage temperatures of 75 F, and "hot" tests at 200 F, to maintain the same relative temperature conditions compared to boiling point as with the other agents tested. This notably hotter temperature had an additional effect of significantly increasing 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.

Two condition variations, simulating two prior HFC-227ea run conditions (except at higher temperatures), were conducted with a series of experiments to determine the threshold of extinguishant 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 a lower quantity of repeats was conducted in comparison to the original project test series, based upon engineering judgment. The experimental conditions for the two experiment variations were as follows:

Test Condition 1: 3 lbm/sec airflow, 75 F agent/air temp (10C below boiling point), 750 psi extinguisher pressure, spray fire, with nozzles

Test Condition 2: 1 lbm/sec airflow, 200 F agent/air temp (60 C above boiling point), 750 psi extinguisher pressure, pool fire, with nozzles

The results of the experiments are listed in Table 8. It is apparent from the results that this new "second generation" agent, based only upon very limited data to date, may offer a potential for improvement over currently available Halon substitutes, at least under the conditions tested to date, which warrants further consideration under a wider array of test conditions and applications.

Table 8. Results of Fire Experiments with HFC-227ea and Bromo-3,3,3-TriFluoropropene.

Condition	HFC-227ea	Bromo-3,3,3-Trifluoropropene
1	2.34 lbs (4/5)	2.2 lbs (1/1)
1	2.00 lbs (0/4)	2.0 lbs (3/4)
2	2.73 lbs (0/5)	2.73 lbs (4/4), 2.34 lbs (3/3)

CONCLUSIONS/SUMMARY

A project has been completed, evaluating the principles of extinguishing aircraft engine nacelle fires, the principles having been established by researchers during the decade-long Next Generation Fire Suppression Technology Program (NGP). Full-scale engine fire experiments have been conducted to determine if these principles and their validity can be extended from laboratory-scale experiments to a full-scale fire environment. Based upon the analysis of these experiments, the following observations and conclusions are submitted for consideration:

1. Based upon the experimental data, the less efficient transport of condensed phase (liquid) agent content at cold temperatures to remote fire sites has been demonstrated, in an indirect manner.
2. Some improvement in the homogeneity of extinguishing agent and dispersion efficiency has been demonstrated with the use of multiple discharge sites.
3. Both the nacelle rib (or other physical obstruction) height and fire type (pool or spray fire) were shown to have a significant impact on the minimum concentration required under "no fire" measurement conditions, including increasing the mixing coefficients and the required "overcharge" required under "no fire" conditions to assure sufficient concentration is reached during "fire" conditions.
4. The thermal inhibition of extinguishing agents could not be accurately assessed, due to limitations in the test protocols and measuring techniques in a full-scale environment.
5. The fire region mixing models proposed in the literature have been significantly enhanced as a result of this project, including a means of calculating mixing coefficients with a degree of demonstrated validity.
6. The impact of the initial (pre-agent discharge) free stream velocity on the mixing coefficient appears to be masked by other effects, such as the interruption in flow by the high momentum discharge process itself.
7. It is seen, with physical and mathematical rationale and validity, that the agent concentrations measured under "no fire" conditions (to accommodate Halonyzer and similar measuring probes) are significantly different than that measured under actual "fire" conditions, but a mathematical and physical means has been proposed to relate the two scenarios, and predict concentration profiles based upon profiles measured under "no fire" conditions. This technique may be further refined and validated to provide a potential means to design fire extinguishing systems for aircraft engine nacelles or other ventilated space applications without the need to perform actual full-scale fire experiments, or only a limited set of final verification tests.
8. The new "second generation" Halon replacement 2-bromo-3,3,3-trifluoropropene has demonstrated some promise in terms of improved performance in extinguishing fires over current "first generation" replacements, as judged from the limited set of full-scale experiments conducted to date, warranting additional evaluation for future applications.

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