FLUID DISPENSING AND DISPERSION

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INTRODUCTION

This paper is a condensed version of a chapter in the forthcoming Next Generation Program (NGP) final report edited by the authors. It summarizes the research conducted during the NGP program on fluid dispensing and dispersion within aircraft engine nacelles by various principal investigators, including the authors.

Fire-suppression systems for protecting aircraft engines typically consist of a suppressant storage bottle(s), a piping system connecting the bottle(s) to the discharge port(s), and the discharge nozzle(s). In some cases, nozzles are not used; the fluid simply discharges from the pipe-end.

Fluid dispensing addresses the multi-component, two-phase flow of the fire suppressant through the piping before it is discharged. Fluid dispensing includes the initial conditions for agent discharge that affect the subsequent dispersion of the suppressant. The fluid dispensing aspects will be discussed in the *Fluid Storage* and *Fluid Transport through Piping* sections. The aspects of fluid storage are related to the determination of the thermodynamic state of the fluid in the bottle and the sizing of the bottle required to accommodate sufficient agent required for fire suppression without compromising the bottle's structural integrity. The discussion of fluid transport through piping describes the flow of fire suppressant through various piping configurations (straight pipes, bends, tees, etc.). The two-phase computer code was derived from a code widely used in the nuclear industries. This program was benchmarked against transient experimental data available in the literature as well as experiments conducted in the NGP.

Bench-scale and full-scale experiments and computer modeling were used to determine fluid dispersion. If the suppressant is a gas, then dispersion may not be an issue because the gas usually will be dispersed easily throughout the protected space. If a superheated liquid agent is released, flashing will occur which also facilitates dispersion. Halon 1301 is such an example. Because of its flashing characteristics and rapid evaporation, the dispersion of halon 1301 in an enclosure, even cluttered with obstacles, usually poses no difficulties. If the suppressant has a high normal boiling point, or it is released at temperatures below its normal boiling point, liquid droplets will be atomized at the discharge nozzle. The actual droplet size-distribution delivered to the fire will be different from the initial distribution at the nozzle. After liquid droplets form, depending on their number density and ballistics (even before they arrive at the fire zone), droplet-droplet and droplet-surface interaction often occurs in the highly-cluttered environment of the nacelle. These processes may alter the initial droplet size and velocity distributions significantly. The presence of high-speed airflow can also affect the droplet size and velocity. If the dispersing spray impacts a solid obstacle, pooling, dripping, splitting, splashing, or shattering of the droplets will result. Dripping and pooling retain the liquid on the nacelle's bottom surface; cutting or splitting of the impacting droplet at the edge of the surface may result in smaller droplets, as can splashing and shattering. The surface temperature also plays a role in the droplet-surface interaction.

Serious fires in aircraft engine nacelles, sufficient to terminate a mission, usually involve liquid fuel – either jet fuel or hydraulic fluid supplied by a leak in its supply system. There are two primary types of fire: spray or pool. Fuel sprays occur when a pressurized line develops a relatively small orifice, caused by battle or other damage, which results in a misting or atomized discharge of droplets. Fuel from larger openings in pressurized lines may flow over the hot surfaces and ignite there, or end up in pools below the engine contained by aircraft structure or other clutter. The typical sources of ignition are: electrical sparking or hot surfaces. Because aircraft engines produce and reject large amount of heat, many large hot surfaces exist on the outside of the engine. The air required to maintain combustion is furnished by flow from the atmosphere for which the original purpose is to cool the engine.

The most likely region for fires in engine nacelles is the long, narrow, annular space between the engine core and the outer aerodynamic skin. A large number of components are located within this region resulting in a complex, cluttered geometry. The nacelle design typically includes ventilation, either via an external scoop or other source, to both cool the engine and avoid the build-up of flammable mixtures. In general, this engineered airflow has sufficient momentum to dominate the buoyancy produced by burning, and the dynamics of a fire within a typical nacelle are dominated by the designed airflow.

Presently, suppression system-proving tests are performed on the ground using airflows which replicate flight conditions. Test fixtures, such as the Aircraft Engine Nacelle Fire Test Simulator (AEN) at Wright-Patterson AFB (WPAFB) in Dayton Ohio and the Ground Test Nacelle Simulator at Patuxent River NAS (Naval Air Station), have been constructed to represent full-scale geometries typical of aircraft nacelles. Extensive sets of experiments and live-fire tests with varying degrees of complex internal geometry have been conducted to evaluate the performance of suppression systems and new agents. These tests and experiments have provided significant insight into the essential features of successful systems and serve as the bases for present acceptance tests. However, the results from these tests, particularly when fire extinguishment (as opposed to merely the concentration of agent) is the criterion, are often difficult to understand given the lack of a detailed, well-characterized flow field.

Adding to the difficulty in extinguishing fires in nacelles, especially in flight, is their cluttered interiors, as shown in Figure 1. These bluff bodies create many "flame-holders" and recirculating zones into which the suppressive agents have difficulty penetrating. In the case of fires in flammable liquid in the bottom of the nacelle, the pool fire is often temporarily suppressed by an agent, but rapidly flares up again after the agent is exhausted. The re-ignition of the liquid pool is probably caused by continuing vaporization from the pool near adjacent hot surfaces having temperature above the ignition point in spite of the suppression.

In addition, a phenomenon, termed *accelerated burning*, was witnessed in this test program which resulted from too-slow injection of insufficient agent to suppress the fires. It is believed that the injection transient served to facilitate mixing of fuel vapor and air leading to a more intense fire than if nothing had been done.

Figure 1. Typical aircraft engine nacelle clutter.

FLUID STORAGE

When the suppressant is a fluid, it is stored in a pressure vessel. In most applications, the release or discharge of its contents depends on the initial and transient pressure within the ullage. For a pure fluid, the ullage will be at the vapor pressure of the fluid at the prevailing temperature. If the applications are limited to room temperature or above, fluids with high vapor pressures at room temperature may be released at an adequate rate. However, such a discharge becomes problematic at very low temperatures such as those typical of the upper atmosphere. The conventional way to alleviate this problem is to use a suppressant gas (*e.g.*, nitrogen) to raise the pressure above the vapor pressure of the fluid. Alternatively, the so-called hybrid system, which uses a solid propellant gas generator (SPGG), upon activation provides the pressure to drive the fluid out of the bottle. The hybrid system will not be discussed here; the focus of this section is on pure fluid pressurized with a suppressant gas.

The thermodynamic state of the fluid in the bottle not only determines the initial conditions for discharge in case of a fire, but it also provides data for the structural design of size and strength of the bottle at elevated temperatures.

The bottle pressure is a complex function of ambient temperature because of the temperature-dependence of the fluid's vapor pressure, the partial pressure of the added nitrogen in the ullage, and its solubility in the fluid. For halon 1301, the pressure-to-temperature relationship and the solubility of nitrogen have been characterized well. Unfortunately, for many potential replacement fluids, such relationships and solubility data do not exist.

The thermodynamic state of the storage container can be determined by an appropriate equation of state applicable to mixtures (fluid and pressurized gas) with empirically determined binary interaction coefficients [1]. Other thermodynamic frameworks have also been used [2]. In the following, the development of a computer code, named PROFISSY (acronym for PRoperties Of FIre Suppression SYstems) [3], to calculate the thermodynamic state in the bottle will be discussed.

PROFISSY was developed to help bottle designers or users to estimate temperature-pressure characteristics of their contents. The program also predicts whether a liquid-full condition would occur at elevated temperatures for a given initial fill, defined as the amount of liquid divided by the vessel volume. When thermal expansion of the initial liquid fills the vessel completely as the vessel is heated, the internal pressure of the vessel will rise sharply at elevated temperatures [2].

The current PROFISSY code, running on a PC, supports thermodynamic state calculations for halon 1301, FC218, CF_3I, HFC125, and HFC227ea. Experimental data have been obtained to compare to the code's predictions for these fluids [4]. In general, the predictions were found to be within $\pm$10 % or less of the measurements. The code can be extended to include other fluids with added nitrogen.

FLUID TRANSPORT THROUGH PIPING

A key technical approach in the present program was utilization of advancements made in other applications that deal with multi-phase flows. In particular, the highly sophisticated computer codes that have been developed for thermal-hydraulic analyses of nuclear power systems have all the characteristics required for fire-suppressant systems. These include models that account for relative slip between liquid and vapor phases, thermodynamic nonequilibrium between the phases, changes in two-phase flow regimes, choked flows, and transport of noncondensable gases. Such codes are also structured for numerical analysis of fast transients, well capable of the transients anticipated for suppressant systems.

As stated above, the current halon-delivery systems generally consist of a pressurized vessel connected to the delivery locations by a piping manifold. The suppressant fluid is maintained in a liquid state by the pressurization of the system, usually up to several MPa. The system is activated by a quick-opening valve in response to either an automatic or manual trigger which then expels the suppressant through the piping. This system must deliver all the fluid to the discharge locations very quickly, generally within 0.1 s to 10 s.

Since halon and its potential replacement fluids are in a vapor state at standard pressure and temperature, at the discharge location the fluid will be a two-phase mixture of superheated liquid and vapor in thermal nonequilibria. Also, because of the large pressure difference between the source and the downstream exit, continuous flashing is anticipated as the fluid travels through the piping, and two-phase choked flow may occur at various locations inside the manifold.

Hence, to predict the performance of the delivery system accurately, a computer code must be a transient, nonequilibrium, two-phase code. The short delivery times require fairly high flows, which tend to promote homogeneous two-phase flow, *i.e.*, little slip. However, in imbalanced piping networks, with side tees and other fittings, some separated flow may occur (stratified flows, slug/plug flow, *etc*.). Hence the code should be able to predict slip between phases and the corresponding effect on pressure losses, which can be important when separated flow encounters a directional change, such as at a side tee. The ability to predict the transport of noncondensable gas is also important. The fluid, pressurized with a gas, is initially saturated with the gas. During the delivery and as the system depressurizes, the added gas comes out of solution and expands, and this evolution must be included. One additional requirement is that the code should be useful for estimating the transient hydrodynamic loads on the piping. Thus the momentum equations need to be sufficiently detailed to estimate the unbalanced force in piping sections between elbows and other fittings.

The code is based on a one-dimensional, two-fluid model of two-phase flow. In this model, separate conservation equations are written for the liquid and gas phases for mass, momentum and energy. Constitutive relationships are specified for interphase transport of mass, momentum and energy. Heat transfer between the fluid and passive structures such as pipe walls are modeled. The program also contains built-in models for wall friction and two-phase critical flow. The transport of noncondensable gas in the system, namely the nitrogen gas, as well as the nitrogen released from solution during the agent's discharge, is modeled via separate mass conservation equations, with constitutive relations to specify the rate of gas release. The conservation equations are solved using a semi-implicit numerical method, with user-supplied boundary and initial conditions.

The program was deliberately made flexible in terms of types of fluids and piping layout. The current version of the program allows the user to select any one of five fluids – water, halon 1301, CO_2, HFC-227ea or HFC-125. Modules are available in the program with which the user can model a delivery system, including one or more supply tanks and a combination of piping networks. The user can also model valves in the system, with specified valve opening times if needed.

The code-development effort included an experimental task to obtain data needed to assess the code. The experimental program utilized a discharge loop using several suppressants. Major flow parameters which have not been measured heretofore were measured successfully. These include measurements of instantaneous discharge rates, fluid temperatures, and void fractions at various locations along a discharge pipe [5].

Such a discharge is a highly transient process, generally lasting from less than a second to a few seconds. The program was benchmarked against transient experimental data available in the literature, as well as experiments conducted as a part of this project, on the discharge of HFC-227 and HFC-125 in a specially prepared discharge loop. The present experiments lasted from 1.5 s to 6 s. In addition to transient pressures at various points, these experiments also measured parameters such as the transient mass discharge, fluid temperatures, and the void fraction near the exit. These are the first dynamic measurements of mass flows, fluid temperatures, and void fractions using suppressants. These new data allowed a more comprehensive assessment of the computer program than was possible with previous experimental data. The results of the assessment showed that the program is capable of predicting the performance of various delivery systems with several fluids.

FLUID DISPERSION IN HIGHLY-CLUTTERED NACELLES

The release and transport of an agent into an engine nacelle is sensitive to local geometrical features or “clutter” that are difficult to resolve numerically without using an excessively large CFD (Computational Fluid Dynamics) grid. Examples include wire bundles or hydraulic lines. Capturing these features in a grid will result in extremely small time steps for accurate numerical simulations of the agent’s release and its subsequent suppression or extinguishment of the fire. An alternative is to use a sub-grid scale model to represent the macroscopic effects of these small features using reasonably sized CFD grid-cells. This approach permits faster and more efficient iterative simulations of the nacelle and its fire-suppression design during the aircraft’s conceptual and preliminary design phases—thereby reducing the time and cost of final qualification testing of the system.

The research effort focused on the development of sub-grid scale models for CFD and the experimental validation of these models using data obtained from flow measurements around simulated clutter packages and a simplified quarter-scale nacelle simulator with well-defined boundary conditions and suppressant dispersion and fire test data from a full-scale nacelle simulator. In addition, the dispersion of high-boiling point agents and low-temperature dispersion were also examined.

Quarter-Scale Nacelle Simulations and Tests

Quarter-scale experiments (to allow access of appropriate diagnostics guided by pretest calculations) were performed at WPAFB [6]. Flow conditions were scaled to match the Reynolds numbers in the extensive set of experiments performed in the AEN facility as part of the Halon Alternatives Program. Calculations were performed using both the CFD-ACE code (a commercial computational fluid dynamics model with a body-fitted coordinate grid) and the VULCAN code (which is a CFD fire-field model using a Cartesian grid and for which sub-grid scale models were developed) and then were compared with experimental data at multiple cross-sections within the flow field.

Transport around Clutter and Recirculation Zones

Experiments were conducted to quantify velocity, turbulent intensity, and drag on various bluff-body shapes in a low-speed, highly turbulent wind tunnel. The experimental data were obtained using thermal anemometry and were intended to validate CFD codes. Circular cylinders (single and in tandem), spheres (single and tandem), a simulated wire bundle, a structural rib, and a cubic arrangement of spheres with cylindrical connectors were tested from 1 m/s to 10 m/s in a free-stream turbulence intensity of approximately 10 %. A circular cylinder was also tested in laminar flow at a turbulence intensity of 0.6 % for comparison with published data. Drag measurements were estimated using a momentum-deficit approach. The results show higher turbulence behind the bluff body when compared to the same configuration in a laminar flow field. Also, the drag coefficients were lower than the same configurations in laminar flow.

The flow in an aircraft engine bay is low speed and highly turbulent. The data from these tests were used to develop a sub-grid-scale model to account for the effects of small objects in the engine bay that are difficult to resolve using a CFD mesh. The data were collected using a single thermal anemometry probe traversed upstream and downstream of sixteen configurations. The data were analyzed to obtain mean velocity, turbulent intensity, and drag coefficient. In addition, the data history was analyzed to gage the Strouhal number of the bluff-body wake.

Full-Scale Nacelle Modeling and Testing

The NAVAIR's full-scale 'Iron Bird' nacelle at NAS Patuxent River, Maryland, which generates conditions typical of an advanced tactical aircraft, was used for this effort. Figure 2 shows the fire test simulator. The nacelle is roughly 3.18 m long. The width and height vary significantly along the length, but are contained within a region 1.45 m high and 1.15 m wide. The simulator is designed for testing at one flight condition, traveling at 0.55 Mach number at sea level.

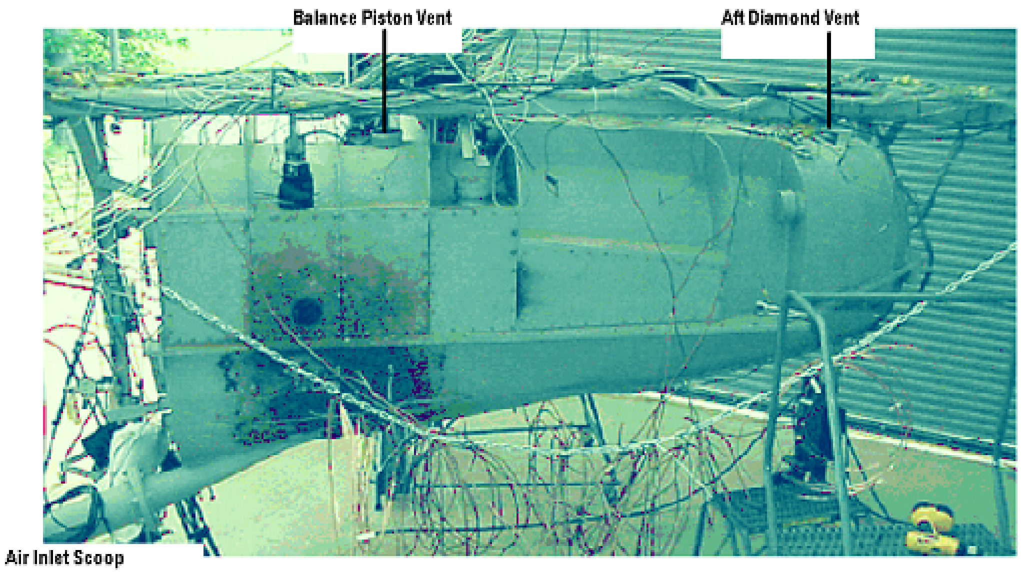

Figure 2. Ground Test Nacelle 'Iron Bird' Simulator.

The VULCAN code was used to perform full-scale nacelle modeling. The fire-suppression model for VULCAN is based on a critical Damköhler number (the ratio of the mixing or flow time to the chemical time) for extinction. For Damköhler numbers smaller than a critical value, the flame will be extinguished. Chemical time-scales for suppression were obtained using perfectly-stirred reactor (PSR) calculations with detailed chemistry to determine the PSR mixing time that corresponds to extinction. Combustion in VULCAN is modeled using the eddy-dissipation concept (EDC) – a distribution of PSRs that relate the fuel-consumption rate to the fluid-mixing rate, the latter obtained from turbulent time-scales. Radiative thermal losses and losses to the walls, while included in VULCAN, are neglected in the suppression model because the magnitude of these losses is dependent on the heat flux through the wall, which is unknown. Estimates indicate that heat losses to obstructions are significant here and tend to increase the chemical time-scale.

The ground simulator was outfitted with a set of four suppressant nozzles that were found to be sufficient to suppress a fire when 3.2 kg of suppressant was discharged. Numerical simulations have been conducted for suppressant injection through these nozzles into the nacelle (in the absence of a fire) to obtain information on the distribution through the nacelle [7]. The suppressant was assumed to enter the nacelle in the vapor phase or to vaporize very rapidly relative to other time-scales. The suppressant's mass flux for each nozzle was assumed to be proportional to the nozzle area.

As a measure of sufficient distribution in the nacelle, the portion of the nacelle volume for which the suppressant's mass-fraction exceeds 30 % has been used for characterization. Even with low-intensity mixing, this amount generally is sufficient for extinction and represents a conservative estimate of suppressibility. The failure to fill the nacelle completely does not indicate that suppression will not occur, but rather reduces the confidence in suppression. If the turbulent mixing in the nacelle were sufficient to create homogeneity, the mass fraction throughout the nacelle would exceed 0.3 for all of the scenarios simulated. Clearly, inhomogeneities arising from imperfect mixing are significant.

Simulations were also conducted to ascertain the effect of removing a single suppressant nozzle, while keeping the overall mass of injected suppressant constant at 3.2 kg injected uniformly over 3 s. For these conditions, the nacelle volume in which the fraction exceeds 0.3 was evaluated. These results were compared to those shown for all four nozzles functioning; the nacelle was completely filled, according to this criterion, for the range of flows considered. The simulation results indicate that depending on nozzle location, the removal of one nozzle results in no, little, or significant effect on suppressant distribution throughout the nacelle.

Pool fires stabilized behind obstructions have been identified as among the most challenging fires to suppress [8, 9]. Obstructions such as structural ribs provide a region of recirculating flow that suppressant is relatively slow to penetrate where hot products help stabilize the flame. In certain scenarios, such as those described in [7, 10, 11] the concentration must be maintained at an elevated level in the flow past the stabilization region for a substantial period to ensure that adequate suppressant penetrates the stabilized region.

Several pool-fire configurations and locations within the nacelle were used in the simulations. The calculated results indicate that pool fires at certain locations are difficult to stabilize because of the peculiar circulation. The surface areas of the largest possible pools in each section were measured in the ground-test simulator. Similar pool areas have been used in the simulations. The pools were assumed to be filled with JP-8, and the evaporation rate was based on heat feedback to the pool. In general, it is difficult to predict the thermal feedback to a pool from a fire, because these fires are partially advected beyond the pools by the convective flows in the nacelle. It is particularly difficult to determine the evaporation rates without measurements. The uncertainty of the evaporation rate may be as high as 50 %. Suppression was predicted for all pool fires in the nacelle using a specified four-nozzle configuration and 3.2 kg of suppressant when this mass was injected over three or four seconds.

To examine the effect of varying the mass of suppressant injected and the rate of injection, a series of additional simulations for fires in a specified pool configuration were conducted. It is noteworthy that the mass of suppressant injected plays little role in determining the occurrence of suppression here. There will be a lower bound in terms of suppressant mass injected over a short period, although this has not been identified here. More significant in practice is the duration over which suppressant will act to inhibit reignition and allow cooling of heated surfaces. Thus the requirements are likely to be dictated by a combination of the rate required to flood the compartment with a high enough concentration and the mass required to maintain that concentration to inhibit potential reignition sources.

Suppression is sensitive to heat flux from the fire to the pool. If the heat flux and, hence, the fuel evaporation are reduced by 50 %, suppression is substantially easier for the cases considered. Similar results are expected if the fuel is cold or if there are substantial heat losses through the nacelle under the pool. While relatively high engine temperatures are expected during operations, temperatures during ground tests may be such that reduced evaporation is experienced.

The capping of various nozzles caused large-scale inhomogeneities that left certain regions with little suppressant. A series of simulations was conducted where one nozzle was assumed to remain capped. To examine the effects of these inhomgeneities for the majority of these simulations, the flow from each of the other nozzles was maintained at previous values when all nozzles were open, giving a reduced rate for the sum of the three remaining nozzles and an increased duration of injection. For fires in the extreme forward and aft pools, the removal of various nozzles did not alter the predicted suppression.

As the rate of injection was reduced to a third or more, many volumetric regions of the nacelle did not have sufficient suppressant for all fires. This was caused by inhomogeneities in the concentration, since the average concentrations in the nacelle were sufficient to suppress all fires. Suppression also failed as the rate of injection was reduced to one third or more. Sensitivity studies in these simulations disclosed that the pool vaporization is very sensitive to temperature, heat losses, details of the geometry, and the momentum associated with injection.

The model-validation experiments described above and others for studying fire-suppression of obstruction-stabilized flames were conducted in roughly square wind tunnels. In aircraft engine nacelles, the width-to-height aspect ratio tends to be large. The characteristic dimensions identified are obstructions on the order of 5 cm in height in wide channels on the order of 10 cm to 30 cm. In each of these simulations, the inlet velocity was 5 m/s, the turbulent intensity was 10 %, and the turbulent length-scale was 0.025 m. Pool sizes were narrow relative to the channel width. Simulations indicate that dilatation from a pool fire behind a rib induces secondary recirculation sweeping the fire outward and along the ribs transverse to the flow. Observation of these flow-fields indicates that they may reduce the suppressant penetration into certain portions of the flame-stabilized region. However, within aircraft, structural supports and clutter are observed to be oriented in both transverse and longitudinal directions. The consequences of longerons (streamwise obstructions) were examined by adding longerons just outside of the pool. It was observed that the longerons do not prevent spread of the fire beyond the ribs. Mass-fraction profiles in the recirculation zone indicate, however, that longerons do affect the flow, because rate of transport of agent is greater with ribs than without. Further, the time to suppress the fire is reduced. If longerons reduce the time required to suppress a fire, a series of experiments in high-aspect-ratio wind tunnels could be conducted. If the experiments were consistent with the simulations, then both the potential of reduced suppressibility caused by dilatation and the possibility that longitudinal clutter ameliorates it become considerations in design.

VULCAN was used to predict the results of the fire tests. Table 1 shows a condensation of all tests for which simulations were available. The primary observations therein include whether or not the fire was extinguished, the model's predictions, the period of injection of the agent, and an estimate of the observed times-to-extinguish versus the predictions. These latter comparisons required a bit of interpretive judgment unique to each simulation to decide when extinction was complete. Similarly, while the injection period for the actual fire-test data was acquired, the link between the recording video and the data-acquisition system had failed, unbeknownst to the test engineers. Consequently, the synchronization of the visual data to the agent-injection transient was not available during post-processing. The time of extinction was clearly observable with an uncertainty of ± 0.1 s, but the initiation of mixing the agent could be observed only by a sudden increase in the intensity of the fire. The uncertainty of this observation is estimated to be ± 2 s.

Table 1. Comparison of Fire Test Results and Pretest Simulations.

Test	**Fire Test**	**Fire Test**	**VULCAN**
Test number	Time to extinguish (s)	Agent injection, Rise time (s)	Time to extinguish (s)
2	Out in 1.3 s	6.8	1.1 (estimated)
3 & 12	Accelerated Burning	10.0	Marginal out
5	Out in 5.2 s	7.0	1.9 (estimated)
6	Out, no data	No data	1.9 (estimated)
7	Out in 4.4 s	9.5	Out
8	Out >6.3 s	4.4	1.9 (estimated)
9	Out in 4.85 s	5.0	n/av
10 & 11	Out in 2.3 s	9.6	n/av
13	Out in 11.2 s	6.5	Not out
14	Not out	10.4	Not out
15	Out in 28.9 s	7.2	3.4 (estimated)
16	Not out	9.3	Not Out
17	Not out	10.8	Not out
18	Out in 6.0 s	5.6	1.5 (estimated)
23	Not out	13.8	N/A
24	Out in 3.9 s	3.8	N/A
25	Out in 1.8 s	2.4	N/A

Dispersion of Agents with High Boiling Points

As part of a halon replacement research program, new high-boiling-point chemical suppressants have been identified. These agents would discharge in a liquid state, breaking into liquid droplets, and then be entrained within the flow passing through the nacelle, impinging on various objects prior to reaching the fire. The goal of this research was to enhance the fundamental knowledge of interactions of sprays with clutter. To this end, this program focused on the ability of water sprays to pass through a series of cylindrical obstacles, representing generic clutter, while moving in a turbulent co-flow. Results indicated that the amount of suppressant captured by the clutter was directly related to the stream-wise spacing of the clutter and co-flow air speed at the clutter location. A low-speed flow facility with the test section's air speed ranging from 0 m/s to 12.0 m/s was modified for the current program. The major components of this facility include an inlet contraction, a turbulence generator, a test section, a clutter section, and the return and separation plenum. The results of this work provide valuable insight into the transport of liquid agents through nacelles and provide essential data to develop sub-models to aid in the design of fire-suppression systems for aircraft [12].

Low Temperature Agent Discharge

To assure that there is no substantial deterioration in dispersion or performance of agents at temperatures below their normal boiling points, tests in a simulated aircraft engine nacelle were conducted. CF_3I (with normal boiling point of −22 ºC) was used as a surrogate for the study. These discharge tests were performed at –40 ºC. The experimental apparatus, (called Extremely Low-temperature Environment For Aircraft Nacelle Testing, ELEFANT) consisted of a simulated engine nacelle with baffles, an agent release port, four observation windows, and two measurement ports. To achieve an operating temperature of –40 °C, the entire facility was placed inside an environmental test chamber, and the cold experiments were conducted inside the chamber. Discharge tests at room temperature were also conducted inside the chamber with the refrigeration unit turned off to establish baselines for comparisons.

The results from the two measurement locations in the nacelle have shown that the dispersion of CF_3I under the cold condition with the equipment and the discharge nozzle used is not very effective, and there is substantial reduction in the agent's vapor concentration. The situation worsens at the location furthest away from the agent-injection port. If the extinguishing concentration for the nacelle is designed based on room-temperature test data, the measurements indicate that dispersion and performance are likely to deteriorate when the agent is used at a temperature lower than its normal boiling point.

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