TRANSIENT APPLICATION, RECIRCULATING POOL FIRE, AGENT EFFECTIVENESS SCREEN: FINAL REPORT

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ABSTRACT

A three year research effort has been conducted as part of the Next Generation Program (NGP) to develop a laboratory screening device suitable for predicting the behavior of halon alternatives in full-scale fire suppression experiments. Most of the work has focused on the transient delivery of gaseous agents and interactions with an obstacle-stabilized propane pool fire. The final report of this effort was recently issued as a NIST report (NISTIR 6733). Motivation for the study and significant findings are summarized in this paper.

INTRODUCTION

The amount of a gaseous agent required to extinguish fires in full-scale engine nacelles varies greatly with the geometry of the test fixture and the manner in which the flame is stabilized. It has been observed that if the test is designed to allow fuel to collect behind obstacles in the vicinity of a hot surface, a significantly higher mass of agent is necessary for sustained suppression [1]. The superior performance of chemically acting agents such as CF_3Br and CF_3I relative to a hydrofluorocarbon alternative like HFC-125 is also accentuated in some of these tests. Full-scale testing carried out by the Navy using two different fixtures, each meant to simulate fires in the F/A-18 engine nacelle, led to different conclusions regarding the amount and relative performance of both HFC-125 and solid propellant gas generator (SPGG) fire suppressants [2].

The complexity and unpredictability of full-scale tests can be traced to two factors: flame stabilization, and agent mixing. Flame stability is governed by local geometry, surface temperature, and fuel and air flow patterns. Flame extinction will occur if the agent is entrained into the flame zone in sufficient concentration, if the fuel and air flows are disrupted enough by the agent discharge process, or by a combination of the two effects. Entrainment and localized flame stretch are, in turn, controlled by the way the fire suppression system is designed and by the location of the fire relative to the discharge nozzle.

Figure 1 shows a full-scale mock-up of an F-22 engine nacelle built by the Air Force Research Laboratory at Wright-Patterson AFB, which was used to test the suppression effectiveness of HFC-125 and SPGG suppressants, as compared to halon 1301 [3]. When the engine mock-up is slid in on its rails, an annular region is formed about the core where flammable vapors can build and leaking fuel can accumulate. Air is brought in through a scoop at the lower right of the structure, it mixes with fuel vapor and/or a spray from a simulated leaking hydraulic, fuel or lubricating oil line, and is ignited by a spark or hot surface such as the bleed-air line. A fire can be stabilized anywhere when the fuel and air mixture is within its flammable limits and the local velocity is below the flame speed. The many obstructions in the flow formed by the nacelle frame, fuel lines, and miscellaneous equipment in the nacelle and on the engine core act as flame holders. The fire extinguishing agent is released into the nacelle near the air

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inlet. Depending upon the amount of agent released, the rate of agent addition, the presence of hot surfaces or electric arcs, and the location of the fire relative to the injection point, the fire may or may not be fully extinguished. An engine nacelle simulator such as the one in Fig. 1 is useful for demonstrating that a particular agent or system can successfully control full-scale fires, but it is not suited for screening the suppression effectiveness of new compounds, for ranking alternative technologies, or for gaining understanding of fire suppression physics.

Agent suppression effectiveness for liquid fuel fires such as those described in NFPA 2001 is determined in a laminar diffusion flame using a cup burner [4]. Measurements of suppression effectiveness using a counter-flow burner are preferred for revealing the detailed chemical pathways in the process [5]. In either of these burners the minimum concentration for suppression is found by increasing the agent flow slowly until a critical mole fraction is achieved in the oxidizer stream and flame extinction is observed. In practice, however, agents designed to replace CF_3Br are discharged rapidly, not quasi-statically. Solid propellant gas generators, for example, typically discharge in 10 ms to 500 ms. A robust and repeatable means to evaluate the effectiveness of different formulations and application rates requires a non-conventional screening device.

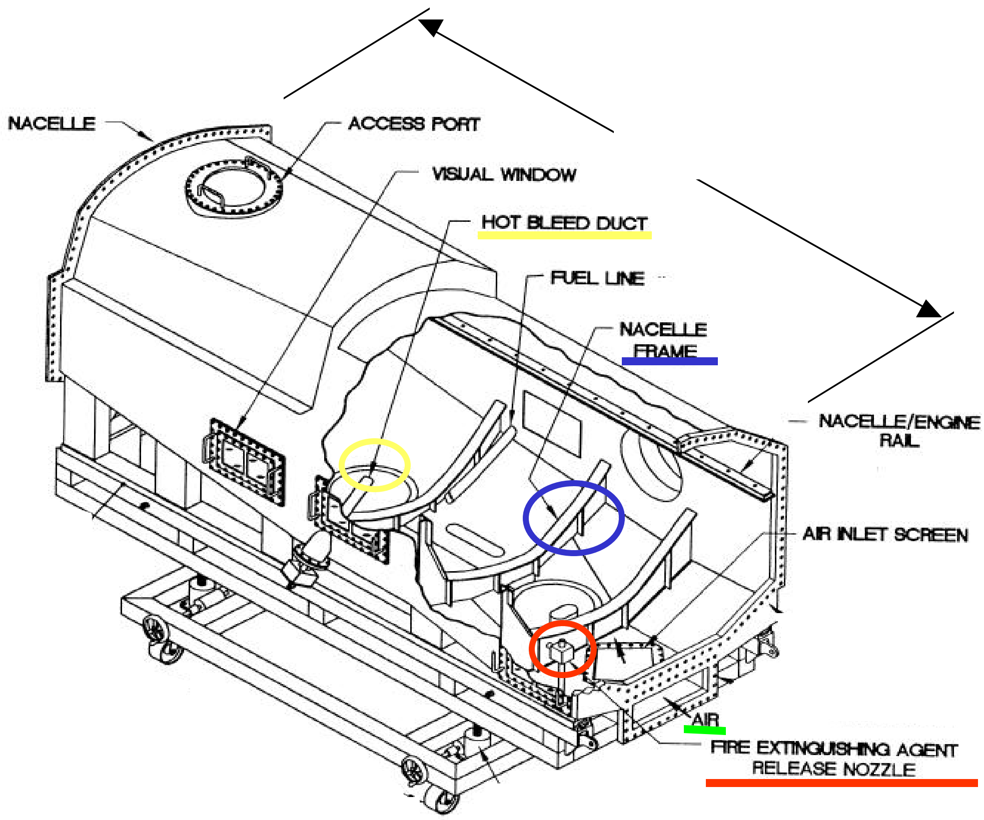

Figure 1. Full-scale F-22 Engine Nacelle Simulator at WPAFB [3]

Hirst and Sutton [6] developed a wind tunnel to explore the impact of step height, air flow, and pressure on the blow-out of a jet fuel pool fire stabilized behind a backward facing step. Hirst et al. [7] studied the suppression of these types of fires using various halons, and concluded that a liquid pool burning in a flow behind an obstacle is the most difficult fire to extinguish. This was born out in full-scale tests done later [8].

Experiments by Hamins et al. [9], in cooperation with Walter-Kidde Aerospace, were conducted in a wind tunnel scaled down from the earlier work by Hirst to examine the performance of HFC-125 and HFC-227ea. Investigations at the Air Force Research Laboratory [10] as part of the Next Generation Program (NGP) sought to determine the detailed structure during suppression of a non-premixed methane/air flame stabilized behind a step. The changing character of the flame with step height and air velocity was examined, along with the amount of halon 1301 required to suppress the flame as a function of the flow parameters and injection interval.

A turbulent spray burner was designed in earlier work at NIST [11] to simulate an engine nacelle spray fire resulting from a ruptured fuel or hydraulic fluid line. In this apparatus, the agent release and mixing processes were well controlled and the air flow was maintained constant with a sonic orifice. This arrangement allowed the agent to be discharged without disrupting the incoming air. The turbulent spray burner was used with both gaseous and powdered agents. Hamins et al. [9] redesigned the burner to include a heated disk in the center of the flow downstream of the fuel nozzle. They showed that the concentration of nitrogen necessary to extinguish a turbulent propane flame increased substantially with surface temperature. The same trend, but to a lesser degree, was observed with hydrofluorocarbons.

Previous studies have demonstrated the effectiveness of SPGGs and their hybrids in full-scale fire suppression experiments [12, 3]. Solid propellant gas generators undergo rapid solid-phase reactions producing inert gases, principally carbon dioxide, water vapor, and nitrogen, as well as particulates composed of inorganic salts. Each component individually behaves as a fire suppressant. For many applications, particulate use is unacceptable and the SPGG hardware is typically designed to filter particulate mass during deployment. Hybrid generators are particularly attractive for some special situations such as inhabited spaces or cold temperature applications [13]. The hybrids use the hot inert SPGG exhaust to vaporize and expel a secondary suppressant, typically a liquid, such as water or a low boiling point halocarbon, through a nozzle [12].

PROGRAM OBJECTIVES

The research summarized here was conducted over a three year period and is reported fully in the final report [14]. The specific objectives put forth in the original proposal were to provide a well-characterized test fixture for screening the effectiveness of agents to suppress and prevent re-ignition of a turbulent, obstructed flame; to allow evaluation of the impact of transient agent delivery on flame extinguishment; and to provide a means to screen the effects of new and currently available agents on solid and liquid fuel surfaces.

Full funding for the three year period was to deliver the following products:

- a well-characterized bench-scale suppression screen for comparing the performance of gaseous agents and dispersed fluid mists in suppressing and preventing re-ignition of a turbulent, obstructed flame burning either gaseous or condensed fuels;
- documentation on the screen apparatus including detailed design information and experimental procedures, with round-robin testing among interested partners to insure utility of the documentation;
- an evaluation of the impact of transient agent delivery on flame extinguishment; and
- development of a means to screen the effects of new agents on condensed (solid and liquid) fuel

surfaces.

The focus of the research deviated a bit from what was originally proposed, in some instances due to budget reductions and in others due to discovery.

- Solid fuels were not examined because there was no evidence that they posed a greater threat than propane in this scenario.
- A formal round-robin was not established, but work conducted during the same period at the University of Maryland [15] and the Air Force Research Laboratory [10] helped to support the conclusions drawn in the current study.
- The design for the liquid mist agent delivery system was not finalized due to the complexity of the process, although the general direction for such a system and its likely capabilities were revealed.
- More emphasis was placed on the deployment of an SPGG suppression effectiveness screen.

SUMMARY OF IMPORTANT FINDINGS

The transient application, recirculating pool fire (TARPF) agent effectiveness screen developed in this research project features a propane fire stabilized behind an obstruction. The character of the flame and the impact of the air flow, fuel flow, obstruction geometry, and rate of agent addition on the amount of material needed for suppression were evaluated for N_2, CF_3Br, and a solid propellant gas generator. The importance of the injection process on the flow field and the transport of the agent downstream was examined, and a simple mixing model was used to explain the observed trend of decreasing suppressant mole fraction with increasing injection duration, even for agents as different as CF_3Br and N_2. Direct numerical simulation of the suppression event was shown to successfully predict the quantity and rate of N_2 required to extinguish the flame, based upon a published global reaction rate for premixed propane/air flame propagation.

The final report [14] describes a comprehensive study utilizing experimentation, advanced numerical modeling, and analysis to develop and characterize a well-controlled fire suppression facility. Sample experimental results demonstrate the utility of the facility. Fabrication drawings and the operational procedures are detailed in the report. The facility provides the capability to test solid-propellant gas generators, allowing direct comparison of compressed and solid-propellant generated gases for the first time. The capability to test SPGGs under well-controlled laboratory conditions allows evaluation among different propellant formulations, particulate yields, and burning rates for various SPGG designs. Results showed that the effectiveness of the hybrid SPGG exceeded that of CF_3Br and that its effectiveness is significantly greater than expected from the model prediction. Further research could lead to significant improvement of the SPGG, as well as traditional agents, through enhanced suppressant system design.

Key findings can be summarized as the following:

- The minimum mole fraction of agent for suppression, normalized by the cup burner value, correlates with $[1 - \exp(-\Delta t/\tau)]^{-1}$, where Δt is the injection time interval and τ characterizes the mixing time behind the obstacle in the flow.
- The general character of the flame and its extinction by a thermal gaseous agent is captured by a direct numerical simulation of the flow based upon single-step chemistry, and numerical experiments have corroborated the simple correlation of the experimental data for N_2.
- The measured difference between the decrease in agent storage bottle pressure and the arrival of the agent at the fire highlight the importance of determining the agent concentration locally and the difficulty in relating changes in bottle pressure to actual mixing conditions.

- For the first time, both compressed and solid-propellant generated gases can be compared side by side, and the effect on performance of different formulations, particle loadings and burning rates for various SPGG designs can be unambiguously discriminated.
- When the temperature of a hot surface downstream of the pool is above 800 ^oC, the flame, following suppression, will reignite and stabilize on the hot surface. At a temperature below 800 ^oC, the number of reignitions approaches zero. This result is in contrast to when the hot surface is located between the stabilizing step and the fuel pool, in which a delayed reignition can be observed at temperatures as low as 400 ^oC [15].
- The effectiveness of suppression with a liquid agent is dependent upon how well the droplets are entrained into the flame zone downstream of the stabilizing obstacle.

Several other research areas require further investigation. These include the effect of the air flow on the steady-state extinction mole fraction of agent, the relationship between agent injection and its concentration history at the flame, and especially the observed differences in the normalized mole fractions of CF_3Br, N_2, and the SPGG for very short injection time intervals.

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