ASSESSMENT OF DESIGN AND RELIABILITY OF SOLID PROPELLANT GAS GENERATORS FOR F-22 ENGINE-NACELLE FIRE SUPPRESSION

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ABSTRACT

Based on data from comprehensive tests in a realistic, but well-defined and controlled facility, solid-propellant gas generators (SPGG) have been demonstrated to effectively suppress simulated engine-nacelle fires and their reignition. By effective it is meant that on an agent-mass basis, SPGGs were superior to a currently used agent, Halon 1301, and its most-promising alternative, HFC-125, in extinguishing engine-nacelle fires and suppressing their subsequent reignition. The program to evaluate SPGGs as fire-suppression systems for engine-nacelle fires should, therefore, he continued, so that issues related to its deployment are resolved. Technical issues to he addressed concern the formulation of design equations that could reduce the number of test fires needed to scale a SPGG system, quantification of the weight of possible SPGG delivery systems, and determination of the potential corrosive/ erosive effects caused by SPGG use. One practical issue that needs to be addressed soon is the development of a standard test to qualify emerging SPGG technologies for deployment. Although details for such a test are still open-ended, data from this program suggest that a nonfire test would be sufficient to obtain appropriate results, and that if a flame-based test were to he used, the flame should be a turbulent-spray flame of JP-8, or other liquid military fuel. This program was supported through USAF Contract No. F09603-95-D-0180/DO-RZ01 with Capt. Mark A. Gillespie, Aerospace Survivability Flight 46th Test Wing, Wright-Patterson Air Force Base, acting as Contract Technical Officer for the Battelle-based project.

INTRODUCTION

Halogenated hydrocarbons, or halons, have recently been implicated in the apparent depletion of stratospheric ozone over populated areas [1]. If this global perturbation were to continue, there could be a significant adverse impact on human health, climate, and environmental systems. Because of this dire implication, the production of ozone-depleting chemicals was discontinued on 1 January 1994, in accordance with international legislation, the Montreal Protocol [1]. Halons are strategic chemicals because they have been used for decades as fire extinguishing agents in the engine nacelles of most military and civilian aircraft [2]. After years of operational experience, "(Halon) H-1301" (bromotrifluoromethane, CF_3Br) had emerged as the favored agent; however, environmental concerns have caused the ozone-depletion detriment of H-1301 to be given precedence over its firefighting attribute, resulting in its use only in critical applications.

In 1992, the US Air Force began searching for a "non-ozone-depleting solution" for on-board aircraft-fire extinguishment [1, 2]. This timing was dictated, in part, by the production schedule for an advanced aircraft, the F-22, which was to pioneer an H-1301 alternative. The program for evaluating alternative extinguishing agents, which would be commercially available for the F-22, was directed by the USAF Wright Laboratory [1]. This program, "The Halon Replacement Program for Aviation," was subsequently expanded in scope to include the requirements of all US military and commercial aircraft-engine-nacelle applications, and was cosponsored by the USAF, Navy (USN), Army (USA), and Federal Aviation Administration (FAA). One primary objective was to find a near-term "drop-in" replacement agent for H-1301.

The Halon Replacement Program for Aviation consisted of three phases. Phase I was the Operational Parameters Study; Phase II, the Operational Comparison of Selected Agents; and Phase III, the Establishment of Design Criteria Methodologies. As the result of a decision made at the end of Phase II, "HFC-125" (pentafluoroethane, C_2HF_5) was selected as the most promising replacement agent with which to proceed.

There are multiple considerations when replacing an agent in an aircraft fire protection system. The most important among these is the weight and volume of the agent and delivery equipment. Unfortunately. HFC-125 was not as effective as H-1301 at suppressing most fires. Therefore, compared to H-1301, larger on-board weights and volumes of HFC-125 were required. Because aircraft have stringent weight and space limitations, their fire-suppression capabilities would require a downgrading to meet these limitations, possibly compromising aircraft/pilot survivability. Equivalent performance to H-1301 is paramount.

While research on gaseous alternatives continued, attention extended to other fire-suppression technologies. notably the Solid Propellant Gas Generator (SPGG), a concept that showed early promise [3]. The initial SPGG concept used technologies designed for the inflation of automobile airbags, relying on the controlled burning of solid reactants to produce large volumes of inert gases, namely water (H_2O), carbon dioxide (CO_2), and nitrogen (N_2). After initial demonstration. the Naval Air Systems Command (NAVAIR) conducted tests to evaluate SPGG applicability to fire suppression in engine nacelles and dry bays [3]. As a result, NAVAIR explored implementing SPGG on its V-22 and F/A-18 E/F aircraft, as well as on other advanced prototypes.

PROGRAM SCOPE

The platform selected For the SPGG evaluation was representative of the F-22. This decision was made because the F-22 configuration was similar to the USN F/A-18, and because the F-22 had a defined requirement for a nonozone-depleting fire suppressant. The effort reported here was an R & D test program, not a competition for a commercial SPGG product for the F-22, or any other aircraft.

In the future, other aircraft, such as the F-15, C-17, and KC-135, may also need H-1301 free agents for engine-nacelle fire suppression. To facilitate the transition of SPGG technology to these aircraft. with minimal additional testing, the scope included an effort that focussed on developing an understanding of the extinguishment mechanism(s) by which SPGGs operate. Specifically, efforts were directed toward investigating issues regarding hot-surface reignition, ventilated-pool fires, cold-temperature performance, and possible modes of suppression (inerting, straining, cooling, and/or chemical interference).

In assessing SPGG technology, performance was evaluated in terms of the mass and concentration of agent required to extinguish a fire at various simulated-flight conditions. Both inert and possibly chemically active SPGGs were tested, and their performance measured relative to the performance of H-1301 and HFC-125. These data were then analyzed with the intent of providing guidance regarding the application of SPGGs for generic engine-nacelle fire protection, as well as for qualifying and certifying future SPGG-based systems.

PROGRAM OBJECTIVES / FACILITIES

The specific objectives of this research and developmental testing program were to (1) evaluate the feasibility of SPGG technology for suppressing engine-nacelle fires; (2) assess inert and chemically active SPGG as H-1301/HFC-125 replacements: and (3) provide guidance for qualifying SPGG-based systems based on suppression science.

The Aircraft Engine-Nacelle Fire-Test Simulator (AENFTS), operated by the Flight Dynamics Directorate (FIVS), Wright Laboratory (Wright-Patterson AFB, OH) is a ground-test facility designed to simulate the fires that exist in the annular compartments around aircraft engines. This facility has been used extensively to test the effectiveness of different agents for engine-nacelle fire prevention, detection, and extinguishment [2, 3]. For this program, an engine-nacelle simulator was fabricated to represent the geometry and operation **of** the F-22 engine, the F-I 19. Systems Research Laboratory, the local support contractor, designed the simulator, while the Developmental Modification and Manufacturing Facility at WP AFB performed the fabrication. Simulator design was based on data from Boeing, Pratt & Whitney, and the F-22 System Program Office. The simulator was intended to be as realistic as possible in terms of clutter, engine/airframe components, geometry, temperatures, and air flow, while providing sufficient access for instrumentation and maintenance. The robust, high-fidelity simulator, capable of multiple tests, was constructed of 321 stainless steel, which is not an F-22 material. **A** schematic external view of the overall test fixture used is shown in Figure 1.

Upon fabrication, the F-22 simulator was integrated into the test section of the existing AENFTS. The new test section retained most of the features of the pre-existing facility, but was upgraded with a system capable of heating the entire engine-core surface to temperatures up to 1000 °F. Also, a heated bleed-air duct was included as an F-22 specific hot surface to simulate reignition. The temperature of this bleed-air duct was controllable up to about 1500 °F.

Extinguishing agents were delivered to the nacelle fire from a cylindrically shaped, high-pressure bottle (halons), or from high-pressure manifolds (SPGG). The bottles could be chilled via a dry-ice jacket to evaluate their performance at cold temperatures, while the SPGGs were cold-soaked to determine if low temperatures affected performance. Output of the halon cylinder was controlled by a floating piston, using ring spacers to vary position. The vertically mounted cylinder, which accommodated up to –25 lbs of agent, was pressurized with N_2. Output from SPGG manifolds was regulated by mounting various numbers and sizes of propellant charges. The diameter, wall thickness, length, and material of the agent-delivery line for the AENFTS were similar to those for the H-1301-based F-22 system.

The air-delivery system allowed for in-flight simulation at slightly super-atmospheric pressure. The inlet air supply originated from a blower, with a capacity of 8780 scfm, or 11.2 lbs/s, and a high-pressure blow-down system, with a capacity of 8800 lbs of air at 2000 psig. A flow-control vent bypass system was used to regulate air flow to the engine nacelle. The air flow system consisted of a differential pressure and current transmitter, controller, current transducer, and a 24-in butterfly valve, with pneumatic actuator/positioner. The air-exhaust subsystem consisted of components downstream of the nacelle transition, including 24-in piping from the nacelle outlet, a IO-in butterfly valve at the ejector inlet, a 24-in atmospheric throttling butterfly valve, an ejector, adaptive piping, a water quencher/sump section, a 48-in exhaust stack, a scrubber bypass valve, a scrubber with recirculating-water pump, scrubber-to-fan ducting (42-in), and a centrifugal exhaust fan with outlet ducting.

Instruments were included to measure temperature (5–10 thermocouples at 2 fire zones; near fuel nozzle); pressure (near agent release point; inside agent bottle; downstream AENFTS); velocity

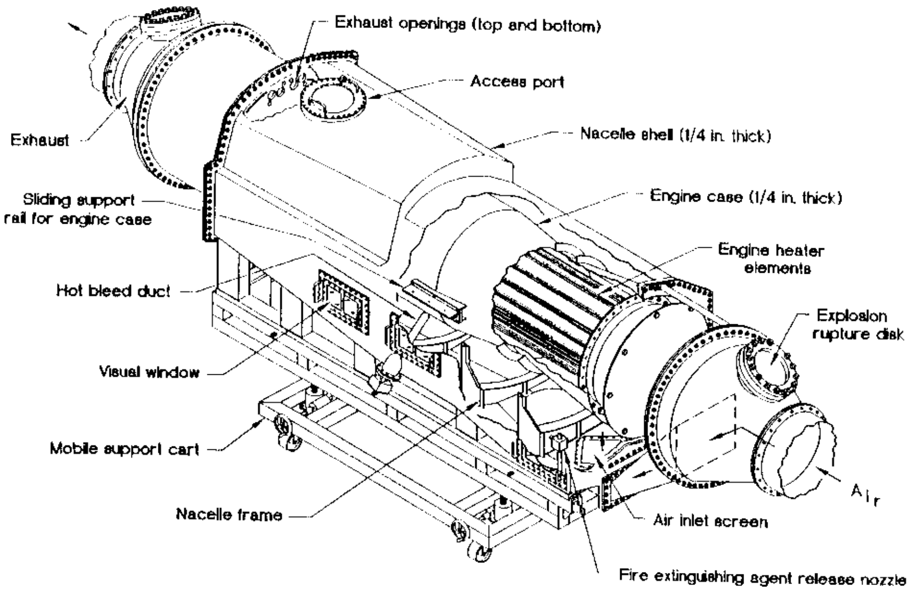

Figure I. External view of the F-22 engine-nacelle fire-test simulator.

(at, upstream, downstream of fire zones); and concentration (Statham Halonizer for H-1301, HFC-125; proprietary O_2/CO_2 analyzer for SPGG). Fire Zone 1 was in the vicinity of the hot-air bleed duct. Fire Zone 2 was in the vicinity of the main fuel line. These zones are shown in Figure 2, an internal view of the AENFTS. Tolerances for these mcasured parameters were as follows:

Engine-surface, bleed-air duct temperature: ±10 °F
Internal air flow: k0.02 lb/s
Engine-air temperature: ±2 °F
Air back-pressure: k0.02 psig
Agent quantity: ±0.01 lb

Agent temperature: ±2.0 °F
Agent bottle pressure: ±5.0 psig
Fuel temperature: k2.0 °F
Flame preburn time: f0.02 s
Post-dump fuel flow time: k0.02 s

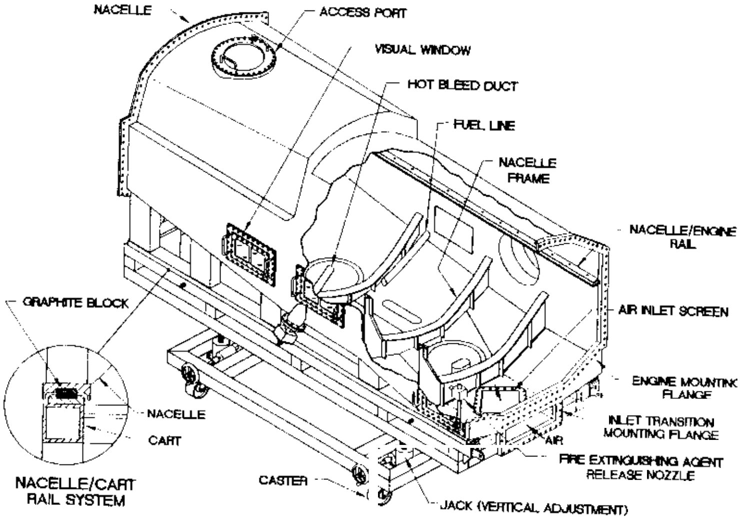

Figure 2. Internal view of the F-22 engine-nacelle fire-test simulator.

TECHNICAL APPROACH

Details on the metric, or standard of measurement, for the test program, as well as the parameters at which these essential data were acquired, are provided below.

PERFORMANCE METRIC

The performance metric was the minimum weight of agent (halon or SPGG) required to extinguish a fire and prevent subsequent reignition. Because of the one-time discharge nature of agent deployment, this quantification required multiple tests. To better the trial-and-error method, a procedure was devised that used iteration to “bracket” the minimum weight of agent required. The procedure used required the completion of 5 successful extinguishments at a weight of agent to establish an “upper limit” of performance. After 5 successive tests at a given weight resulted in extinguishment, the procedure required the next weight tested to be half the difference between this “upper limit” and the highest unsuccessful weight. When the calculated next weight was within 10% of the last weight tested, convergence was reached, and the minimum test weight bracketed.

TEST PARAMETERS

These parameters are known to influence the extinguishment of engine-nacelle fires [1, 2]:

Engine-surface temperature *(variable)*
Internal-air temperature *(variable)*
Fuel temperature *(variable)*
Fuel type *(fixed:* JP-8)
Cross-sectional area *(fixed:* area = *7.7* ft^2; volume = 85 ft^3)
Fuel prebum time *(fixed:* 20 s)
Air-flow rate *(variahle)*
Configuration/clutter *(fixed:* simulated F-22 engine: F119)
Agent-distribution/discharge location *(fixed:* upstream of hot-air bleed duct)
Fire location *(variahle: vicinity of hot-air bleed duct; vicinity of main fuel feed line* ***leak)***
Agent temperature *(variable)*
Fuel post-dump time *(fixed:* 8 s)

Because of time and budget restraints, not all these parameters were varied in this program. Based on previous test results, it was decided that some parameters would be held constant (fixed), while others were varied over a limited, but significant range [1, 2]. Values for each parameter were established based on representative operational environments encountered by the F-22 in a typical mission profile.

TEST PLAN

A 3-phase Test Plan was developed and executed for this program, as follows: I: Simulator-Fire Validation; II: Baseline-Fire Definition; III: SPGC Testing. The objective of Phase I was to assess tires generated in the F-22-like engine-nacelle test fixture, and then determine which **fuel** nozzle, flow rate, and spray direction to use in the subsequent phases. The propensity for reignition within the AENFTS was also assessed. An attempt was also made to define a test condition that could be used to evaluate the consistency and repeatability of the simulator in generating a “standard” fire for “calibration purposes.”

To select a working fuel nozzle, fuel-flow rate, and fuel-spray direction, fires were generated at the two zones within the AENFTS. Different nozzles, flow rates. and spray directions were tried in various combinations. These parameters were empirically varied to produce the most robust fire based on visual information (ease of ignition; absence of soot), and temperature (the highest average clutter temperatures).

At the outset, it was not known whether reignition would occur in the AENFTS during any test. Reignition would result in more agent being required for "success." Reignition was thought possible because of the F-22s hot-air bleed duct (Figure 2), whose maximum temperature (–1130 "F) is near the hot-surface ignition temperature of JP-8 at similar conditions (~1150 °F) [4, 5]. Because reignition was possible. its role in defining the performance metric was included *a priori*. Hence, after extinguishing a fire with an agent, a reignition, for whatever reason, classified that test as a "failure." If the fire was extinguished and reignition did not occur. the test was a "success." These criteria were also used in NAVAIR tests [3]. Given these definitions for success and failure, an assessment was made of the conditions at which reignition could be made to occur repeatedly. Fires were created at the same conditions used for selection of the fuel nozzle, flow rate, and direction tests. Preburn times and air-flow rates were varied to create the highest air temperatures within the AENFTS.

The procedure was to ignite a fire under a trial set of conditions, and let the fire exist for a specified "preburn" time. After the preburn time expired, fuel flow was stopped until the fire extinguished. Following that, fuel was reapplied for 8 s. Times were determined for fire extinguishment and reapplication fuel flow until reignition based on engineering judgment. Combinations of preburn time and air flow rate were repeated 5 times, and the number of re-ignitions recorded. Conducting this procedure increased the confidence that (re)ignitions created in the AENFTS were reproducible.

SPGG TEST RESULTS

Atlantic Research Corporation teamed with Walter Kidde Aerospace to develop, demonstrate, and field gas generator fire suppression systems as an approach to meet the needs for the next generation of fire suppressants for both military and commercial applications. WKA is the world leader in fire suppression technology, while ARC is the free world leader in tactical rocket propulsion and a producer of commercial and military gas generators. Under contract through a Technology Reinvestment Program funded by DARPA (Contract No. N660001-96-3-8900), the ARC/WKA team had developed and successfully tested two types of gas generator concepts: a Chemically Active Solid Propellant Gas Generator (CSPGG) and a Pyrotechnically Augmented Liquid Agent System (PALAS). The CSPGG produces inert gas and chemically active agents that prohibit reignition. Whereas, the PALAS device employed a gas generator to heat and expel a halon substitute (Halon 1301 vaporizes easily across a wide temperature range whereas many of the replacement compounds do not vaporize easily at low temperatures). The CSPGG technology was selected for demonstration in the F-22 Engine Nacelle. Basic propellant data are provided in Table 1; FS-59 was selected for testing on this platform [6, 7]. Other SPGG approaches are also currently under development [8–11].

TABLE 1. CSPGG PROPELLANT SUMMARY.

Formulation	**FS-55**	FS-59
T_c, K	2187	2056
T_{ex}, K	1058	1144
Moles of Gas	4.2	3.9
% Solids in Exhaust	3.4	12.2
n (>2000 psi)	0.72	0.30

SPGG were extremely effective, exceeding the efficiency of competing systems, including Halon 1301 and HFC-125. In F-22 engine-nacelle testing, the SPGG using FS-59 outperformed, on a weight basis, all current candidates to replace halon. The results are tabulated in Table 2. The three cases tested in the engine nacelle were as follows: (1) Zone 1, where fire was in the line-of-sight of the suppressant flow, and a reignition threat (JP8) was posed; (2) Zone 2, where clutter was involved (non line-of-sight), with no reignition threat; and **(3)** Zone 2, but under "Cold" conditions (temperature of –40 °F). FS-59 CSPGG generators performed extremely well in all situations, requiring much less agent by weight than either HFC-125 or Halon 1301. Successful tests were repeated five times to increase the confidence in these findings.

TABLE 2. F-22 ENGINE NACELLE RESULTS: POUNDS REQUIRED FOR EXTINGUISHMENT.

System	Halon 1301	HFC-I25	CSPGG
Fire Zone 1 (ambient)	14	14	0.5
Fire Zone **2** (ambient)	2.3	4	**1**
Fire Zone 2 (cold)	—	3.5	1.5

SUMMARY AND ANALYSIS

A maximum weight of –1.5 Ibs of SPGG suppressed *all* the fires in the AENFTS, whereas a minimum weight of **–14** Ibs of HFC-I25 or H-1301 was required for the same. Effectiveness appeared to be the direct result of the achieving a specific elevated concentration of some constituent by some ultra-fast time, and sustaining it for a sufficiently prolonged duration.

Fire suppressants are classified as either "chemically active" or "chemically inert," depending upon the relative weight and/or concentration of agent needed [5, 12–13]. If the amount required is "relatively high," agents are thought to act primarily in a physical mode when extinguishing tire (cooling, inerting, and/or straining the flame). Agents (e.g., N_2 and CO_2) are considered "physical" agents. If the amount required is "relatively low," agents are thought to act primarily in a chemical mode when extinguishing fire (disrupting branching reactions keeping flame chemistry self sustaining). Initially, many halons, especially Halon 1301, and many "dry-chemicals," (e.g., the alkali-metdl nitrates, carbonates, and oxides) were thought to act primarily as "chemical agents."

The mechanism by which dry chemicals suppress hot-surface reignition has also been investigated [14,151. Dry-chemical powders are thought to suppress reignition by effectively coating, inerting, or insulating the hot surface, all physical effects. Given the similarity in test results between H-1301 and HFC-125, the effort to understand the mechanism(s) by which the SPGGs tested here in engine-nacelle fires was somewhat handicapped. The data acquired during this effort do, however, support general theories. For further consideration, consult the analysis of this fire suppression test program published by NIST [16].

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