REVIEW OF TECHNOLOGIES FOR ACTIVE SUPPRESSION FOR FUEL TANK EXPLOSIONS

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BACKGROUND

Historically, fuel fire and explosion is a major cause of aircraft losses in combat. Data from Southeast Asia showed that over half of the aircraft combat losses involved fuel fire and explosions. To increase survivability, various techniques have been implemented to reduce the vulnerability of the aircraft's fuel system. Ullage (the vapor space above the fuel level in a fuel tank) in aircraft fuel tanks can have a potentially explosive fuel-air mixture. Fuel tank explosions are a result of ullage deflagrations where the combustion overpressure generated exceeds the structural strength of the tank. Initially, large-scale use of passive protection systems was first developed based on reticulated foams. These systems imposed penalties on the fuel systems, since they displaced and retained fuel and sometimes had a finite limit on installed service life. To eliminate such penalties, the use of active systems was pursued, notably Halon 1301 inerting of the F-16 fuel tanks and nitrogen inerting in the ***C-5.*** However, these systems also had their own set of penalties. As a result, reactive systems were investigated.

Several alternative systems for reactive suppression for fuel tank explosions, developed by the Navy and Air Force in the 1980s, showed potential in full-scale tests. Among these are the Linear Fire Extinguisher (LFE), Parker Hannifin Reactive Explosion Suppression System (PRESS), Scored-Canister System (SCS), and Nitrogen Inflated Ballistic Bladder (NIBB). Further development to bring these new technologies to maturity was discontinued mainly due to limitations in research funding. This funding may have also been abandoned due to unresolved operational questions.

Protecting aircraft fuel systems from fuel fire and explosions is not a new concept or requirement for the aviation community. Special design attention is required, and many techniques and devices have been developed to protect the fuel system. Each has its own advantages and disadvantages [1].

For the purposes of this paper, reactive systems will be defined as systems that react to the initiation of an explosion and discharge a substance intended to suppress the explosion by either physical or chemical means. These amount to a "last ditch" effort to prevent an explosion from causing damage. Research indicates that in order to prevent damage, the deflagration must be suppressed in the first few milliseconds. Research into such systems dates back to the 1950s, but only recently have technological advances in detection/discrimination systems and the associated electronics made it possible to design systems that can react quickly enough [2].

Active systems are also called pre-protection systems. Presently, available methods for protecting military aircraft from **fuel** tank ullage explosion are based on providing pre-protection, that is. providing a protection environment in the ullage in advance of ignition. This requires maintaining a protection environment. Since the probability of fuel tank ignition at any moment during service life of the aircraft fleet is extremely low, costs and operational penalties of providing protection when not needed accumulate over time to become enormous. Pre-protection systems have continued to be used in spite of their penalties because, with the increasing efficiency of modern projectiles, it has been assumed there is insufficient time after ignition to limit pressure rise reliably. However, there have been fundamental technological advancements in explosion detection, fiber optics, solid-state electronics, microprocessor control. and electro-propellant actuation systems [3].

SCOPE/OBJECTIVE

The scope of this effort called for an evaluation of active techniques. However. the technologies specifically previously mentioned (LFE, PRESS, SCS, and NIBB) are considered reactive systems. Although both reactive systems and active (pre-protection) systems were investigated, only reactive systems will be discussed in this paper. The objective of this project was to assess the current status of previously developed alternative systems for consideration as possible alternates to present aircraft fuel tank inerting systems and locate state-of-the-art information on existing technologies.

APPROACH

The systems mentioned previously were reanalyzed along with recently developed systems (utilization of gas generator technology, halon alternatives, etc.). This provided the background and understanding of these technologies to decide which ones require additional research and development. A follow-on project (as a part of the Next-Generation Fire Suppression Technology Program (NGP)) will be utilized, if needed, to perform additional research in association with pertinent system manufacturers. Real-scale explosion testing will take place at existing test facilities. The manufacturers will, at their discretion and expense, develop the systems to be able to withstand the aircraft fuel tank environment. minimize maintenance impact as well as initial system support costs.

The first task ofthis effort assessed the fuel tank operating environment of several aircraft. This included a brief survey of the fuel tank operating environments (temperature, pressure, maximum allowable overpressure, design threat. fuel type, fuel tank configuration, etc.) of various aircraft to determine the operating conditions that must be satisfied by the existing technologies. Next, a literature search of previous efforts was performed. which included a search of the Survivability/ Vulnerability Information Analysis Center (SURVIAC) and Defense Technical Information Center (DTIC) databases, a review of recent Federal Aviation Administration **(FAA)** reports (generated as a result ofthe TWA-800 incident), a review of the Bureau of Mines information, and a review of information from the Gas Research Institute. **A** survey of US Air Force, US Navy, other Department of Defense points of contact, and current manufacturers of these technologies assisted in the determination of their development status—if more advanced technologies have been developed, if any technological breakthroughs have occurred recently, and if these systems are recommended for specific types of aircraft (fighter/attack, bomber, cargo/ transport). Information such as military service, date of development, technology developed, suppression mechanisms, ability to withstand the fuel tank operating environment, maintenance impact, logistics concerns, technological challenges, system initial and support costs, retrofit impact, requirements impact, suppressant/technology utilized, expulsion method, effectiveness, restart funding required, and testing performed assisted in the assessment of the potential viability of future investments in a particular alternative technology.

FINDINGS

Due to the space limitations, only reactive systems will be discussed in this paper. The reactive systems discussed include LFE, PRESS, SCS, solid propellant gas generator (SPGG), NIBBS, and technologies developed by Pacific Scientific.

LINEAR FIRE EXTINGUISHER (LFE)

Projectile-induced ullage explosions are usually generated by a specific sequence of events. The elapsed time from threat impact to a fully developed explosion occurs within milliseconds. The LFE system, initiated by projectile function or fragment impact flash, operates within the same millisecond time frame and is expected to create a "protected" ullage space before damaging overpressures are developed from the ensuing explosion. The parallel explosion-development/ LFE system-activation sequence is as follows:

- Projectile penetration causes an incendiary flash and the subsequent detonation disperses incandescent particles and fragments within the threatened fuel tank, beginning the process of explosion development.
- Optical sensors respond to the incendiary flash, triggering a detonator to activate the extinguisher(s).
- The extinguisher(s) discharges an explosion inhibitor that suppresses the explosion, thus negating development of damaging overpressures.

The LFE system consists of an optical sensor (either discriminating or non-discriminating), a hollow thin-wall stainless steel tube for extinguishant storage, and a combination detonator and flexible linear shaped charge (FLSC) for extinguishant discharge initiation [4]. Figure 1 shows the LFE system.

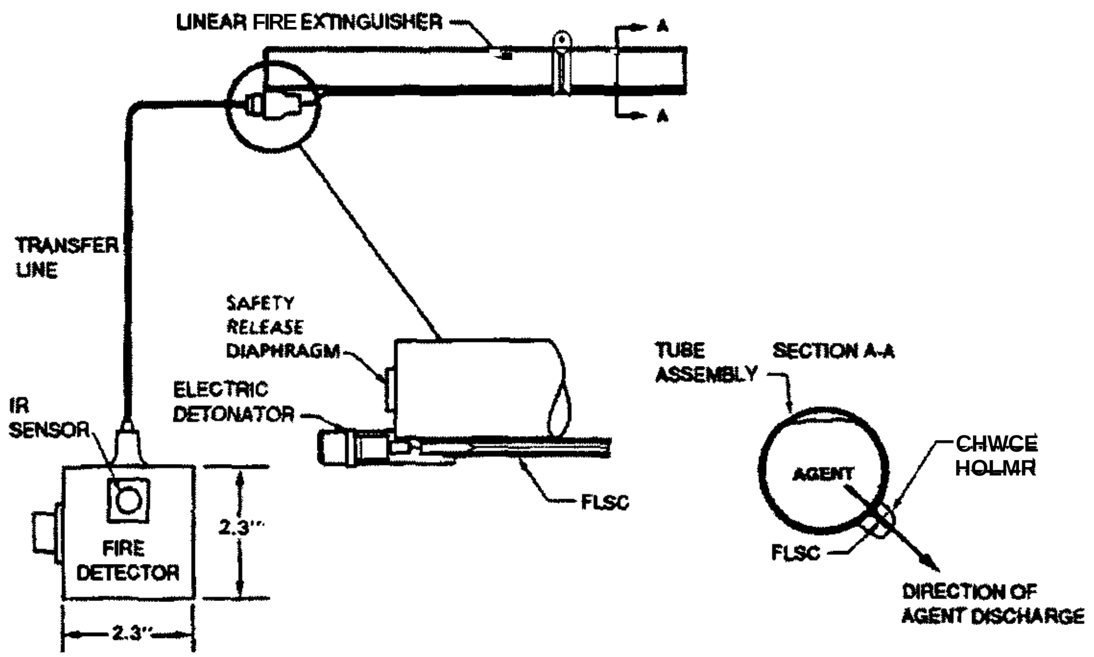

Figure 1. LFE System.

An active explosion suppression system is feasible, hut dependent on the suppression agent used [4]. Some of the extinguishing agents tested include the following [5, 6]:

- distilled water
- aqueous film-forming foam (AFFF) and water solution
- water, AFFF, and Halon 1301
- water and monoammonium phosphate powder
- 30% calcium chloride and water solution
- 50% ethylene glycol and water solution
- 70% ethyl alcohol and water solution
- Halon 1301 and water mixture
- propane
- monoammonium phosphate powder mixed with Halon 1301
- FC-218
- HFC-227ea
- HFC-125
- Pentane

Some advantages and disadvantages of the LFE system include (1) speed (response within 5 ms), (2) suppressant speed – 1000 ft/sec, (3) detectors, (4) 1 channel IR fiber optic, (5) efficient distribution, and (6) low weight (mostly suppressant), while the disadvantages include (1) power consumption, (2) detector technology lags, (3) ullage overpressure with halon, and (4) reaction forces from tube [7].

The following items must be addressed [8]:

- Compatibility of the suppressant with the environment and the fuels requiring protection, especially considering alternative suppressants.
- Reactive loads that are imposed on the aircraft structure when the LFE is discharged.
- Complete installation and operation of the finalized system.
- Concerns of overpressures must he conducted. Pyrotechnic devices in aircraft fuel tanks present a potential risk to the aircraft.
- Effects of discharging the LFE is when it is completely submerged in fuel, and the ability of dispersing the agent successfully into the fueled areas.

Discussions with Government personnel indicate that a LFE test program is scheduled to be performed the summer of 2000 at Wright-Patterson AFB. OH. The upcoming test program will not only address the LFE, but will also attempt to quantify the previously described reactive loads, if possible. In later studies, methods to mitigate these loads will he explored."

PARKER REACTIVE EXPLOSION SUPPRESSION SYSTEM (PRESS)

The Parker Reactive Explosion Suppression System (PRESS) is designed to be installed in aircraft fuel tanks and react to and suppress fuel tank explosions. It consists of an optical detector, transmission lines and a suppression tube(s) containing a water/brine solution. This system is designed to respond within a few milliseconds to engage the flame front and reduce

"Jim Tucker, Applied Research Associates, personal conimunicstion, March 2000.

pressures below damage causing levels. After detection, the transmission lines transmit a signal to the suppression tube, which initiates an exploding bridgewire circuit. This, in turn, initiates a detonating cord and propellant internal tube, creating a high pressure expulsion force to expel the adjacent bladder filled with water. The water exits through orifice holes, is transmitted through radial channels in the external nozzles and released as 5-micron thick sheets. These sheets break up into IO-micron droplets, which absorb thermal energy released by the explosion. This process occurs in its entirety within a few milliseconds [3].

Some advantages of the PRESS system include (1) fastest responding system – allows less suppressant, lighter weight, (2) system designed for liyuids like water – greater potential, **(3)** tank overpressure problem not evident, and (4) nozzles allow directed flow of suppressant, while the disadvantages include (1) requirement of large scale proof-of-concept testing, (2) a more complex system – chance for malfunction despite high reliability components, and (3) possible expense in manufacture [7].

“Ball park” cost estimates were perfonned and showed that the system would be fairly expensive.* The following items must be addressed [4]:*

- Use of explosives and chemical propellants inside fuel tanks to suppress a fuel explosion.
- Introduction of water into a fuel system.
- Introduction of a chloride brine into a fuel system.
- Ultra-fast suppressant dispersion raises concerns about mounting bracket reaction loads.
- Resistance to battle damage.
- Discharge of suppressant when the dispersion tube is submerged in fuel (potential of producing a hydraulic ram effect) [3].
- Installation of the PRESS system in small compartments. The installation would be difficult and costly. Also detection would be difficult since the detectors were line of sight.

Discussions with Government personnel indicate that limitations in research funding prohibited demonstrating the effectiveness of PRESS for suppressions of fuel vapor explosions ignited by live fire incendiary rounds in a 100-gallon test tank at the Wright-Patterson AFB, Aircraft Survivability Research Facility (ASRF) gun range. These discussions also indicated that the **PRESS** nozzle design was too complex and required very tight tolerances (which prohibited a low cost manufacture). To alleviate this problem, conventional nozzles were used in a radial fashion to generate the same effect.’

Parker Hannifin representatives stated that the PRESS technology has been shelved due to technical and funding issues. The technical issues included the nozzle technology development. Several different approaches were attempted. In their opinion, nozzle technology has not advanced to a state that would allow the PRESS technology to be further pursued by Parker Hannifin. The funding issues, as previously stated, prohibited the investigation of this system at the WPAFB ASRF.*

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* Chuck Clark, Parker Aerospace, personal communication, March 2000.

† J. Michael Bennett, 46th TW/OGM/OL-AC, personal communication, January 2000.

SCORED CANISTER SYSTEM (SCS)

The pentane filled scored-canister system (SCS) is designed to achieve suppression by creating a fuel-rich atmosphere in the ullage while avoiding fuel contamination resulting from use of a nonpressurized container. Figure 2 displays this device.

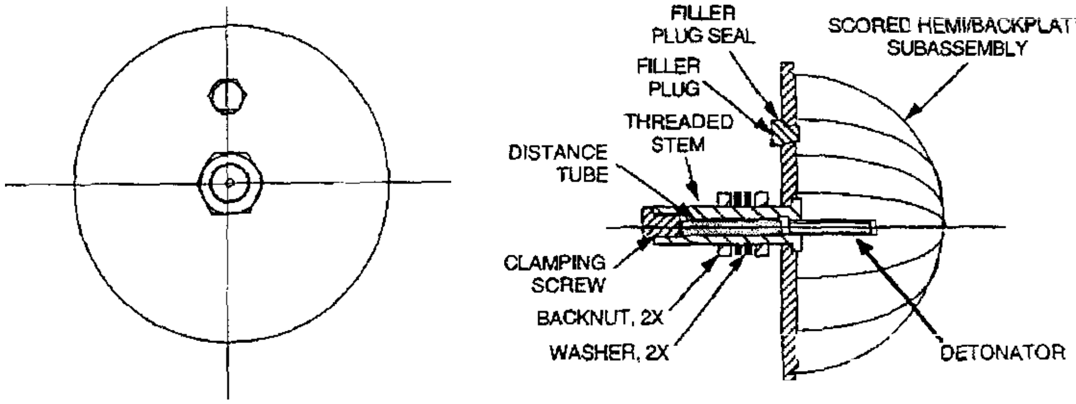

Figure 2. Kidde-Graviner SCS.

Each SCS suppressor is composed of a scored, frangible hemisphere filled with a liquid-phase suppressant. The suppressor units are not pressurized and are suitable for operating under negative-pressure excursions within temperatures ranging from –35 to +60 ºC. The explosive device is carried at one end of a hollow stem that protrudes through the center of the unit's back plate. The explosive "blast" in the center of the liquid suppressant hydraulically couples to the scored frangible wall of the hemisphere, which fails along the score lines. **The** suppressor walls open within approximately 2.0 ms of activation, and the explosive energy expels the suppressant as a cloud of spray, made up of fine droplets, which expands into the fuel-tank ullage [6].

This system was placed in service on a number of British military aircraft and has been documented as functioning satisfactorily, and is being credited with a number of "saves" (suppressant discharges associated with actual ignition threats), though plagued with a large number of false alarms. These aircraft were phased out of service in the late 1970s and early 1980s along with the suppression systems.

In developing this system, a number of suppressants were evaluated. Pentane and Halon 1101 were the two found to be superior suppressants. Halon was rejected due to its high vapor pressure and need for a pressurized container. leaving Pentane as the suppressant of choice for suppression of explosions within an enclosed fuel tank. On the other hand, post-crash considerations and the likelihood of a fuel tank being ruptured during the crash, leave Pentane as a very undesirable and questionable suppressant

Field experience has been accumulated on the AVRO Vulcan, the Handley Page Victor, the Vicker Valiant and the Hawker Hunter. but the general data available does not provide a complete service history. This is the only "operational" reactive fuel rank ullage protection system uncovered in this technology investigation and as such. provides limited confirmation of the technology's overall success [8].

The following items must be addressed:

- Inadvertent system operation has occurred with early type sensors.
- Tank overpressure associated with the discharge of the system.

NITROGEN-INFLATED BALLISTIC BLADDER SYSTEM (NIBBS)

The Nitrogen-Inflated Ballistic Bladder System (NIBBS) is a device for achieving a number of fuel system vulnerability improvements with one system. It is, in the developers' words, "a single system capable of eliminating all of the fuel problems currently requiring multiple mitigation systems. The NIBB inherently self-seals instantly (eliminating dry bay fires in adjacent spaces and stopping fuel depletion), attenuates hydrodynamic ram pressures. eliminates ullage explosions, prevents dry bay fires, and eliminates engine air-intake fuel ingestion."

The McDonnell Douglas Corporation originally conceived NIBBS as a hydraulic ram attenuation device. It was tested by NAWC, China Lake, CA, with considerable success. Subsequently, the Boeing Company, Seattle, **WA,** modified the design for ullage protection. The system consists of self-sealing inflatable bladders on the fuel tank walls. As the fuel is used, the bladders inflate with nitrogen, thus, eliminating the ullage space and producing a protective, inerted air gap between the fuel and the adjacent dry bay. The bladders are semi-permeable, so as they reach the limit of their distension, the nitrogen flows into the growing ullage space, providing inerting to prevent an explosion [2].

SOLID PROPELLANT GAS GENERATORS (SPGG)

Primex produces various fire suppression and explosion protection technologies, which are installed on various military aircraft. Primex Aerospace has developed a line of solid propellant gas generators, based on the automotive air bag industry and extending into dry-bay explosion suppression. These systems produce gaseous carbon dioxide, nitrogen, and water, and they can be used directly as a suppressant. This generates a large volume of gas in milliseconds from an electrically initiated, exothermic reaction releasing carbon dioxide, nitrogen, water, and trace compounds. Recent versions of these systems were developed around the military's need for aircraft protection against the external, incendiary projectile threat.

Company and military tests at China Lake have shown successful ullage protection with response times quick enough to suppress a ullage explosion. Though immersed applications still need to be evaluated and qualified, the technology appears to have a lower sensitivity to variations in ullage volume than a typical halon suppressant release.

The advantages to gas generation technology for ullage protection are (1) quickly disperses non-corrosive inerting agents without pressurized containers, (2) long shelf life (20 years), **(3)** low maintenance, (4) no freezing point depression issues, ***(5)*** canisters are not powered except for activation, ***(6)***canisters can be installed in tank where required, (7) can be selectively discharged by a remote controller, and (8) gas is radially discharged resulting in good suppressant dispersion and creates no reaction loads on the aircraft structure.

The disadvantages of gas generation technology for ullage protection are (1) high temperatures of discharge gases, (2) controller must know ullage volume and fuel level (FQIS) to ensure tank is not over-pressurized from variable ullage volumes and to ensure canister is not activated under the fuel level (hydraulic ram effect may rupture tank), **(3)** canister wiring must be routed in tank,

(4) volumes larger than 120 ft' have not been tested, and *(5)* single shot canisters require tank entry after discharge and containers are not re-usable.

Another configuration that Primex has developed is a hybrid system wherein a liquid suppressant is discharged by the gas generator. The expanding gases from the gas generator expel a liquid suppression agent. This has been successfully tested in live fire testing, hut has not been demonstrated for fuel tank explosions. The advantages are (1) long shelf life, (2) low maintenance, (3) usable with any low pressure suppressant, (4) no high pressure discharge into ullage, *(5)* low propellant weigh requirement, ***(6)*** ullage volume (FQIS) input to controller desired but not required, (7) canisters are not powered except for activation, (8) can be BITE checked, (9) controllers can selectively discharge canisters, and (10) faster discharge rates than nitrogen charged systems.

The disadvantages of the gas generator-hybi-id system are (1) suitable low pressure suppressant needed, (2) water has been demonstrated effective but has freezing point issues, (3) canister triggering wiring and squibs-initiators must be located in tank, (4) single shot canisters, and *(5)* requires tank entry to replace after discharge.

The following items must be addressed:

- Putting pyrotechnic devices (squib or pyrotechnic initiators) into the tank may present a risk to the aircraft.
- Development testing is still necessary to characterize a gas generator system that is compatible with today's aircraft and their requirements.
- Putting additional wiring and squib initiators in the fuel **tanks** presents a new set of safety concerns which need to be addressed.
- This system could require testing for material compatibility. fuel solubility, gas generator inerting capacity, and toxicity; servicing: safety; fire and explosion detection: analysis of impacts on engine components and operation: flight certification: manufacturing: handling: logistics: and redesign of an entire system [8].

PACIFIC SCIENTIFIC

Pacific Scientific produces a line of fire extinguishing products, specifically for dry bays and classically defined fire zones, and a line of fire suppressors specifically designed to protect the occupied compartments of military armored ground vehicles against an external projectile threat and secondary. internal explosions. The occupied compartment fire suppression system utilizes a three-frequency optical sensor. a non-microprocessor controller and solenoid opened suppressant bottles, specifically tailored to maintain a survivable atmosphere after discharge. The military ground vehicle fire suppressions systems must suppress a fire/explosion in occupied vehicles such as tanks and armored personnel carriers. The overpressure heat, oxygen concentration, hydrocarbon combustion byproducts, and the toxicity of the agent must be survivable and meet military specifications. The sensor is a discriminating. three-frequency optical sensor that has good false alarm immunity and will not fire the suppressant for a long list of false light sources. The halon bottles are solenoid activated, not squib activated.

Pacific Scientific does not manufacture and has not tested explosion suppression system for fuel tanks. Other Pacific Scientific fire suppression systems have been qualified in military applications. However, the effectiveness of this technology for fire suppression in fuel tanks has not been demonstrated or determined. A significant amount of additional development and testing to provide adequate protection in this environment is needed. A complete testing program will have to he performed to demonstrate proof of concept and design before any certification testing can be performed [8].

The following items must be addressed:

- Inadvertent firing of the agent when personnel are in the tank.
- Possible tank overpressure could result from the discharge of agent sized for an empty tank when the tank is full.
- The hydraulic ram effect if the agent is discharged under the fuel could rupture the tank.

SUMMARY

Providing a recommendation as to which technology should he pursued further by the NGP has been difficult since each technology has its own distinct advantages and disadvantages. The following will briefly summarize their status.

- The upcoming LFE test program (summer of 2000) will not only address the LFE, but will also attempt to quantify the previously described reactive loads, if possible.
- The PRESS technology was shelved due to technical and funding issues. The technical issues included the nozzle technology development. Several different approaches were attempted. In their opinion, nozzle technology has not advanced to a state that would allow the PRESS technology to be further pursued by Parker Hannifin. The funding issues, as previously stated, prohibited the investigation of this system at the WPAFB ASRF.
- Insufficient information was located regarding the SCS and NIBBS systems to make a clear recommendation for their pursuit.
- Newer technologies, such as the gas generator technology developed by Primex and the Pacific Scientific technologies, also have merit; however, they require further testing to ensure they will not he detrimental to an aircraft fuel tank.

ACKNOWLEDGMENTS

This research is part of the Department of Defense Next-Generation Fire Suppression Technology Program, funded by the DoD Strategic Environmental Research and Development Program under DSS-W contract number SP0700-96-D-4000. The COTR for this effort is Mr. Martin L. Lentz (46''TW/OGM/OL-AC). The author would like to acknowledge the following organizations for their assistance with this project: 46th Test Wing, Aerospace Survivability Flight, AFP Associates, British Petroleum, DuPont, E. Raymond Lake Company, Kidde-Fenwal, Meggitt Safety Systems, Naval Air Warfare Center Weapons Division, New Mexico Engineering Research Institute, Parker Aerospace - Air and Fuels Division, Primex Aerospace Company, and The Boeing Company.

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