Aviation Rulemaking Advisory Committee

Explosion Suppression

Task Group 2

EXPLOSION SUPPRESSION

ARAC Fuel Tank Harmonization Working Group, Task Group 2

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1. Abstract:

HARMONIZATION TERMS OF REFERENCE

TITLE OF INITIATIVE: PREVENTION OF FUEL TANK EXPLOSIONS

Background: The cause of TWA800 747 accident has been attributed to a fuel tank explosion within the center wing fuel tank (CWT). The source of ignition of the explosion is believed to be within the fuel tank, however no conclusive ignition source has been found by accident investigators. The National Transportation Safety Board has concluded from the accident investigation that an explosive mixture of fuel-air vapors existed in the empty CWT of TWA800. The presence of explosive mixtures in the tank is exacerbated by heating of the residual fuel in the tank due to the location of the air conditioning equipment below the CWT.

The FAA has identified 10 transport airplane hull loss events since 1959 which were attributed to fuel tank explosions. The investigation of TWA800 and the number of fuel tank explosions which have occurred in service have led the FAA to question the adequacy of transport airplane certification requirements relative to fuel tank design, specifically with respect to environmental considerations and the adequacy of steps to minimize the hazard due to potential of ignition sources, both in initial design and over the life of the airplanes.

Based on its preliminary study, the FAA believes several approaches to improve fuel tank explosion safety have potential for implementation in the commercial airplane fleet and, therefore, warrant further detailed study. The first is minimization of hazard due to explosive fuel system conditions by mandating certain design and maintenance practices. The second is prevention of the occurrence of a flammable fuel/air mixture in the tanks through some means of inerting, or modified fuel properties such as JP-5. The third means includes mitigation of the hazards of a fuel tank explosion through installation of polyurethane foam or fire suppression systems. The FAA published a notice on April 3, 1997, requesting public comment on the proposed NTSB recommendations. Cost benefit data provided by commenters was inconsistent and in many cases no justification for the data was provided. A significant amount of data has been collected and must be evaluated. The FAA has determined that amendment to the Federal Aviation Regulations concerning fuel tank flammability may be necessary.

The following task should provide the basis for the FAA and JAA to determine what regulatory action should be taken to increase the level of safety of the existing fleet, current production airplanes, and new type designs to address the fuel tank explosion threat.

SPECIFIC TASK:

Prepare a report to the FAA/JAA that provides specific recommendations and proposed regulatory text, that will eliminate or significantly reduce the hazards associated with explosive vapors in transport category airplane fuel tanks. Proposed regulatory text should ensure that new type designs, in-production airplanes and the existing fleet of transport airplanes are designed and operated so that during normal operation (up to maximum certified operating temperatures) the presence of explosive fuel air vapors in all fuel tanks is eliminated, significantly reduced or controlled to the extent that there could not be a catastrophic event. (This task addresses means of reducing explosion hazards by eliminating or controlling explosive vapors. The FAA is also engaged in a separate activity to evaluate whether additional actions should be taken to ensure that ignition sources are not present within the fuel tanks. Therefore, control of ignition sources are not within the scope of this task.) In developing recommendations to the authorities, a report should be generated that includes the following:

1) An analysis of the threat of fuel tank explosion due to internal and external tank ignition sources for the major fuel system designs making up the transport fleet, including transport airplanes with heat sources adjacent to or within the fuel tanks. The SAFER data presented to the FAA in 1978, which includes evaluation of fuel tank safety in both operational and post crash conditions, should be used as a starting point for determining the level of safety.

2) An analysis of various means of reducing or eliminating exposure to operation of transport airplane fuel tanks with explosive fuel air mixtures (e.g., inerting, cooling of lower center tank surfaces,

combination of cooling and modified fuel properties, etc.) or eliminating the resultant hazard if ignition does occur (installation of selective/voided/full tank reticulating foam, explosion suppression systems). Technical discussion of the feasibility, including cost/benefit analysis, of implementing each of the options on a fleet retrofit, current production, and new type design airplanes should be provided.

3) An analysis of the cost/benefit of modified fuel properties that reduce exposure to explosive vapors within fuel tanks. The FAA has asked industry through the American Petroleum Institute to provide pertinent information on fuel properties. The degree of modification to fuel properties necessary to eliminate or significantly reduce exposure to explosive fuel tank ullage spaces in fleet operation must be determined by the group. Factors that may enhance the benefits of modified fuels, such as cooling provisions incorporated to reduce fuel tank temperatures should be considered. Cost information for the various options should be developed, such as engine air/ground starting at low temperatures, maintenance impact, emissions and fuel freeze point, should be analyzed by the group and be provided.

4) Review comments to the April 3, 1997, Federal Register Notice and any additional information such that validated cost benefit data of a certifiable system is provided for the various options proposed by commenters. This information will be used in preparing regulatory action.

   Note: In many cases specific cost data provided in the comments to the notice was competition sensitive, therefore the ARAC group should contact commenters directly and request participation in the group.

5) Recommend objective regulatory actions that will eliminate, significantly reduce or control the hazards associated with explosive fuel air mixtures in all transport airplane fuel tanks to the extent that there could not be a catastrophic event.

In addition to the above tasks, support the FAA in evaluation of application of the proposed regulation to the various types of transport airplanes (turbo-propeller, business jets, large transports, and other turbine-powered aircraft types which may be affected by a change in fuel properties/availability) and any impact on small businesses.

This activity will be tasked for a 6 month time limit to complete the tasks defined above. The FAA will consider the recommendations produced by ARAC and initiate future FAA regulatory action. However, if the group is unable to provide the FAA with proposed regulatory language within this time period the FAA will initiate rulemaking independently. **Participants of the ARAC should be prepared to participate on a full time basis for a 6 month period if necessary.**

PROPOSED HWG ASSIGNMENT: We recommend that this project be managed by a new Fuel Tank Harmonization Working Group (FTHWG), that would report directly to the ARAC Executive Committee.

2. Table of Contents:

3. Introduction:

The assigned efforts of the ARAC Fuel Tank Harmonization Working Group were divided into eight separate tasks, each then assigned to individual Task Groups to conduct the associated investigations and analyses. Each Task Group is staffed by individuals from the various industry, business and professional interests. These assignments are:

Task Group 1:	Service History/Fuel Tank Safety Level Assessment
Task Group 2:	Explosion Suppression
Task Group 3:	Fuel Tank Inerting
Task Group 4:	Fuel Tank Selective/Voided/Full Tank Reticulating Foams
Task Group 5:	Tank cooling/Ullage sweeping
Task Group 6:	Fuel Properties and Its Effect on Aircraft and Its Operation
Task Group 7:	Fuel Properties and Its Effect on Infrastructure
Task Group 8:	Evaluation Standards and Proposed Regulatory Action Advisory Group

For the purposes of identifying the spectrum of aircraft being considered and the characteristics of these aircraft relative to size, operations and environment, a matrix of Standard Aircraft was prepared by Task Group 8 . This matrix is designed to ‘bracket’ the fleet of existing aircraft, with the exception of the smaller transport aircraft, like those at the lower end of the bizjet group, and provide generic representatives upon which the task groups would conduct their analyses. In addition, Task Group 1’s review of the service and incident history, supported by the temperature studies conducted by Task Group 5, identified the environmental differences between wing tanks and center wing tanks (CWT), especially CWTs with external heat sources. It was then proposed and accepted that the specific case of the 747 CWT be included as an additional configuration in each group’s analyses. The Standard Aircraft Matrix is included in Section **10., Other Supporting Data**.

This report documents the activities and findings of Task Group 2, which has the assignment of researching the industry for existing technologies and systems specifically designed to actively monitor, detect, react to and suppress an explosion event before the event can produce catastrophic results, by such means as temperature, structural over-pressure, etc. For the purposes of the Fuel Tank Harmonization Working Group and the assigned reporting, this form of suppression is specifically and distinctly different than fuel tank inerting systems or passive void filling foam systems.

The members of Task Group 2 have performed a search for reference material and documents concerning systems that have been specifically designed to suppress or extinguish an explosion within a fuel tank. This search began with the questions to the Department of Transportation and the Department of Defense, and then to vendors known to be involved with such systems. Through this search and questions of the committee’s membership at large, it was quickly discovered that a great amount of research had been accomplished in this arena concerning military operations and the need to protect combat aircraft from external threats where fuel ignition could result, such as ballistic impacts of High Energy Incendiary (HEI) and Armor Piercing Incendiary (API) projectiles.

From actual live-firing tests and system performance bench tests conducted at the Naval Weapons Center at China Lake, California, and the Flight Dynamics Laboratory at Wright-Patterson Air Force Base, Dayton, Ohio, a number of systems have been identified as having demonstrated positive results in providing fuel tank and dry bay protection from fuel vapor explosions. The applicable technologies center around four separate methods of dispersing the suppressant

- ✦ Inert Gas Generators
- ✦ Gas Generator driven Agent Dispersal
- ✦ Explosive Expulsion of Low Pressure Agent
- ✦ Explosive Release of High Pressure Agent

Research and test information was received from the Joint Technical Coordinating Group on Aircraft Survivability (JTCG/AS), Air Force Wright Aeronautical Laboratories, Survivability/Vulnerability Information Analysis Center (SURVIAC), and the National Institute of Standards and Technology (NIST). A bibliography of these documents are listed in Section **5., References**.

From these contacts, a list of companies involved in this technology was generated. All of the companies identified were contacted and were provided a questionnaire and invitation for face-to-face discussion meetings with Task Group 2. From those contacts, detailed technical information was received from

- ✦ Kidde Aerospace and Defense (including Graviner and Fenwal Safety Systems),
- ✦ Meggitt Electronics (formerly ARMTEC, Detection Systems) ,
- ✦ Pacific Scientific / HTL,
- ✦ Primex Aerospace Company (including the former Olin Aerospace Co.), and
- ✦ Whittaker Safety Systems.

Of these five, each company with the exception of Meggitt, met with task group members to discuss their particular systems and capabilities.

4. Summary:

4.1. Discussion:

The Kidde Aerospace systems have operational roots in the military. Originally produced by Graviner, the system provided in tank, wet-bay protection using an IR optical sensor, a low vapor pressure suppressant, Pentane, and a small explosive charge to rupture the storage container and throw the suppressant out into the space surrounding the container. This system was placed in service on a number of British military aircraft and has been documented as functioning satisfactorily and 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 1970’s and early 1980’s, and the suppression systems along with them.

In developing this system, a number of suppressants were evaluated and 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, the post-crash considerations and the likelihood of a fuel tank being ruptured during the crash, leave Pentane as a very undesirable and questionable suppressant.

Pacific Scientific / HTL produce a line of fire extinguishing products, specifically for dry-bays and classically defined fire zones, and a line of explosion 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 explosion 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.

For the F22 dry-bay protection scheme, Pacific Scientific designed stand-alone sensor-bottle combinations that can react more quickly than their standard extinguishing technology. This system incorporates multiple ‘bottles’, using Halon 1301, to provide appropriate coverage.

None of the Pacific Scientific components or systems have been tested in a wet-bay, and knowingly need a significant amount of additional development and testing to provide adequate protection in this environment. For a complex aircraft fuel system, additional development for alternate, more suitable suppressants, and microprocessor controllers to deal with multiple bottle arrays and variations in ullage volume must be conducted (to minimize any over-pressure hazard).

Primex Aerospace developed a line of solid propellant gas generators, based in the automotive air bag industry, and extending into dry-bay explosion suppression. These systems produce gaseous carbon dioxide, nitrogen and water, which can be used directly as a suppressant, or can

The latter of these systems, as with the others, was developed around the military needs 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 an explosion. Though emersed 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. Development testing is still necessary to characterize a gas generator system that is compatible with today's aircraft and their requirements.

Whittaker Safety Systems produce a line of fire safety equipment and gas analyzers. In the mid 1980's, they developed, against a military RFP, a dry-bay explosion suppression system based on their fire extinguishing technology, but specifically aimed at the wide area dispersal and quick response needed. Later development of this system utilizes Halon 1301 in a long tube and released by a shaped charge attached to the tube wall axially, and dubbed the linear fire extinguisher, LFE®. A dual-spectrum optical sensor detects fuel ignition and the controller reacts by triggering is a small explosive initiator, mounted outside the fuel bay, which ignites the shaped charge attached to the storage tube.

Testing was successful against the normal range of external threats and was the first system to demonstrate any protection against the 30mm high energy incendiary (HEI) threat.

This system was bid, against Kidde's proposal, for the military P-7A program, as a wet-bay, ullage protection system. Testing has shown this technology to be very effective, with the shortest reaction times of any investigated, but further development is necessary to define a system that is adequately compatible with the closed fuel tank and variations in ullage volume.

4.2. Conclusions:

From the review of the technologies produced by the companies listed above, it is evident that the technology exists and is effective in suppressing the pressure effects of an explosion before those effects can become hazardous to the tank enclosure / structure.

a) Optical sensors have been developed to discriminate between the actual ignition of the hydrocarbon fuel and an extensive number of common and potential light sources.

b) Microprocessor controls have been developed to a level that reliable and explicit decisions can be made within the requisite times. A dedicated controller logic will still be necessary for each specific aircraft installation.

c) Dispersal systems are adequate to provide rapid distribution and suitable concentrations of suppressants.

d) Installations on new aircraft as well as retrofit of existing aircraft appear to be within the capabilities of the technology investigated.

It is evident that this technology is not yet fully mature and a significant amount of development is still required to refine the details to the specific requirements of fuel tank wet-bay protection.

a) Some technologies are out-dated and need to be revisited in light of the current state-of-the-art.

b) Specific design philosophy is needed in each system to adequately address the resulting tank pressures due to the discharge of the suppressant with various liquid levels and ullage volumes (i.e., submerged discharges, excess suppressant release {pressure} and insufficient suppressant release {concentration}).

c) Addition of redundancy, multiple discharges, is needed to meet the potential of recurring ignition.

d) Minimization of in-tank wiring and introduction of potential ignition sources.

e) Alternate suppressants necessary to reduce reliance on Halon 1301.

  1) Alternate suppressants must be compatible with the temperature, altitude and contamination requirements of fuel systems in general.

  2) Alternate suppressants must be compatible with engine components and subsystems.

f) Mature system designs are required to establish

  1) Comparable installation cost and weight estimates.

  2) Appropriate maintenance procedures and intervals.

g) Reliable operation.

  1) Inspections for pressurized containers must be defined and evaluated.

  2) Reliability to perform when commanded must be proven.

  3) Reliability against uncommanded discharges must also be proven.

  4) In depth evaluation of failure modes and hazard assessments.

h) Appropriate ground safety systems and procedures must be developed to protect ground and maintenance personnel during open tank maintenance.

5. References:

5.1. Documentation Received:
The following documents (in alphabetical order) have been received and reviewed:

5.1.1. AFWAL-TR-07-3032, (AFWAL/FIES, WPAFB, OH 45433-6553) Aircraft Dry Bay Test Evaluation, by H.F. Robiadek, Boeing Military Airplane Company, Seattle, WA 98124-2207 for Flight Dynamics Laboratory, Air Force Wright Aeronautics Laboratories, Air force Systems Command, Wright-Patterson AFB 45433-6553, Excerpts.

5.1.2. Graviner Explosion Protection System Installation and Maintenance Manual, excerpts of.

5.1.3. Graviner Report Number 32-001-04, Suppression of Fuel Tank Explosions - An Assessment of Efficacy for McAir, P.E. Moore, N.S. Allen, 18 November 1986.

5.1.4. IMECHE Conference Presentation, on Oct 27-30, 1987, Fire Protection and Survivability, D.N. Ball, Graviner

5.1.5. JTCG/AS-87-T-004, Critical Review of Ullage Code, Dr. N. Albert Moussa, September 1989.

5.1.6. JTCG/AS-87-006, Compartmentalization Aircraft Wing Tank Active Ullage Explosion suppression Tests, Final Report, J. Hardy Tyson, July, 1988.

5.1.7. JTCG/AS-89-T-006, Evaluation of the Linear Fire Extinguisher (LFE); Volume 1: Explosion Suppression and Dry Bay Fire Suppression Ballistic Test Program. John F. Barnes, Sept '89 Prepared for the Joint Logistics Commanders Joint Technical Coordinating Group on Aircraft Survivability

5.1.8. JTCG/AS-90-T-003, Fire/Explosion Protection Characterization and Optimization: Phase ii Alternative Dry Bay Fire Suppression Agent Screening Everett W. Heinonen, Ted A. Moore, Jonathan S. Nimitz, Stephanie R. Skaggs, and Harold D. Beeson; New Mexico Engineering Research Institute, The University of New Mexico, Albuquerque, NM. October 1990.

5.1.9. JTCG/AS-91-VR-002, Evaluation of the Linear Fire Extinguisher (LFE) Volume ii, Water-Based Explosion Suppression Agents Ballistic Test Program, John F. Barnes and James R. Duzan, Sept 1991.

5.1.10. Kidde Graviner Report Number 32-009-01, Results of Active Ullage Explosion Suppression Trials, NAWC - China Lake, 1-12 May 1995, A.J. Randle, 25 May, 1995.

5.1.11. Kidde Presentation material, Wichita, KS 16 April 1998.

5.1.12. NAWCWPNS TM 8006, Testing of Active Ullage Suppression Systems with Agents Alternate to Halon 1301, Executive summary (Report not completed), A.B. Bernardo, April 1997. Excerpts.

5.1.13. NIST SP 861: Evaluation of Alternative In-Flight Suppressants for Full-Scale Testing in Aircraft Engine Nacelles and Dry Bays. William L. Grosshandler, Richard G. Gann and William M. Pitts, Editors, April 1994.

5.1.14. NIST SP 890: Fire Suppression System Performance of Alternative Agents in Aircraft Engine and Dry Bay Laboratory Simulations, Volumes 1 and 2, Richard G. Gann, Editor, November 1995.

5.1.15. Pacific Scientific - Electro Kinetics Presentation material, Duarte, CA, 1 May 1998.

5.1.16. Primex Aerospace Presentation materials, Wichita, KS, 16 April 1998.

5.1.17. SD90-007: Response to Request for Information, Lockheed Letter 5261 LMK/129/001 P-7A Ullage Protection system, January, 1990.

5.1.18. SURVIAC-TR-89-021 Gas Explosion Suppression Agent Investigation, Final Report, July 1989, Survivability/Vulnerability Information Analysis Center (SURVIAC) Booz - Allen & Hamilton Inc, 4141 Colonel Glenn Highway, Suite 131, Beavercreek, Ohio 45431

5.1.19. Walter Kidde Aerospace, Proposal Number 7300-700: Ullage Protection System for P-7A Aircraft

5.1.20. Whittaker Safety Systems Presentation materials, Simi Valley, CA, 1 May 1998.

5.1.21. WL-TR-91-3008, Fire/Explosion Protection Characterization and Optimization Phase I - Data Analysis and Documentation Ullage Protection via Various Venting and Inertant Combinations - Final Report, N. Albert Moussa, John J. Murphy, Jr., May 1991.

5.2. Interviews conducted:

5.2.1. The following companies, facilities and individuals (in alphabetical order) were contacted:

5.2.1.1. Kidde Aerospace and Defense: Including Fenwal, Kidde Graviner, Santa Barbara Dual Spectrum, L'Hotellier & Walter Kidde Aerospace:
Tom Hillman, 919-237-7004

5.2.1.2. National Institute of Standards and Technology (NIST):
Dr. Richard G. Gann, 301-975-6866

5.2.1.3. Naval Weapons Center, China Lake, CA:
Hardy Tyson, 760-939-3681

5.2.1.4. Pacific Scientific (Electro Kinetics Division):
Bill Meserve, 626-359-9317
Mike Fone, 805-963-2055

5.2.1.5. Primex (formerly Rocket Research of Olin Chemical Co.):
Paul Wierenga, 425-885-5000

5.2.1.6. Whittaker - Safety Systems Division (formerly Systron Donner):
Frank Bosworth, 805-584-4100

5.2.1.7. Wright-Patterson Air Force Base, Survivability Group:
Jim Tucker, 937-255-6052
Martin Lentz, 937-255-6302

5.2.2. The following companies (in alphabetical order) and individuals prepared and conducted presentations on systems, equipment and/or technologies which range from fully developed to a demonstrated promise for development into a usable product:

5.2.2.1. Kidde Aerospace and Defense, with representation from Fenwal: April 16, 1998 in Wichita, KS; Tom Hillman, John J. O'Neill, and Erdem A. Ural, PhD (Fenwal)

5.2.2.2. Pacific Scientific: May 1, 1998 in Duarte, CA; Mike Fone and Bill Meserve

5.2.2.3. Primex Aerospace: April 16, 1998 in Wichita, KS; Paul Wierenga

5.2.2.4. Whittaker Safety Systems: May 1, 1998 in Simi Valley, CA; Frank Bosworth

6. Background:

6.1. Active Explosion Suppression:

Systems have been developed to suppress explosions occurring in enclosed fuel tank spaces and dry bay spaces. This is achieved by very quickly sensing the actual explosion and then very rapidly discharging a suitable suppression agent (suppressant). These systems have successfully demonstrated their ability to extinguish explosions, to prevent damage due to explosive over-pressure, and to prevent sustained fires in extensively documented military research and testing.

Similar explosion protection systems have been used in various industrial applications, in military aircraft in the fuel tank ullage and dry bay applications, and in commercial aircraft in vent box applications.

Typical systems designed for the most recent use on military aircraft in dry-bay protection systems, consist of optical detector systems, control unit/power supply systems, and suppressor systems.

6.1.1. Detector System:

The detector system provides an output to the control unit/power supply system, identifying that a hydrocarbon fire is present and, by the nature of the detector installation design, where the fire is located. Due to the extremely rapid response time required, optical detection is necessary.

6.1.2. Control Unit / Power Supply System:

The control unit / power supply system receives the electrical output from the detectors, and any other necessary input (such as fuel level information in the case of fuel tank ullage protection case), and commands the discharge of the suppressant system. Current technology allows a wide range of design configurations, from numerous small, simple systems, monitoring neighboring portions of the area to be protected, each capable of discharging suppressant within their specific area of influence, to large integrated systems which monitor the entire area to be protected, adjusting for changes in ullage volume, and capable of controlling the discharge of suppressant throughout the entire area or partial areas.

6.1.3. Suppressor System:

The suppressor system consists of the suppressant (suppression agent), the suppressant storage container, the suppressant release mechanism (solenoid valves, squibs and rupture disks, etc.) and the distribution network (ports or tubing if appropriate). The signal from the control unit / power supply system is used to activate the suppressant release system.

Current technology offers a number of different types of suppressant dispersal systems. Solid propellant gas generators produce inert gaseous exhaust (N_2, CO_2 and H_2O) which can be used directly to purge a volume of combustible vapors or air (principally O_2), or can be used to drive a quantity of suppressant from the associated canister and into the volume being protected, low vapor pressure suppressants (such as Pentane, water or water/AFFF mix) can be thrown from a scored container by the shock action of a small explosive within the canister, or a high vapor pressure or pressurized suppressant (such as Halons or pressurized water, AFFF mix) can be released by the explosive rupture of the pressurized storage container or associated rupture disks. These technologies have been demonstrated in numerous ground tests and shown to have significant merit.

6.2. Why the Military uses this technology:

During the Viet Nam War, a significant percentage of the aircraft losses were directly attributed to the US aircraft being highly vulnerable and minimally survivable when hit by small -to-medium arms fire. As a result of this assessment, the Armed Services formed joint services task groups dedicated to identifying combat aircraft vulnerability and improving their inherent survivability. One such task group is the Joint Technical Coordinating Group on Aircraft Survivability (JTCG/AS) based at Wright-Patterson AFB, Ohio. In roughly the same time frame, the UK began development of fuel tank ullage protection systems.

6.3. Military Service Experience and History with this technology:

In the UK, Graviner, LTD designed and fielded a fuel tank ullage protection system which utilized an Infrared (IR) optical sensor, a controller and a series of canisters filled with liquid Pentane, strategically positioned within the fuel tank. 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. Some of these aircraft were still in operation in the early 1990’s, and as far as this writer knows, the ullage protection systems also remained operational.

This is the only ‘operational’ fuel tank ullage protection system uncovered in this technology investigation and as such, provides limited confirmation of the technology’s overall success. In practice, the Graviner system has been credited with a number of ‘saves’ (suppression of actual fuel ignition), but has also been credited with a number of ‘false alarms’ (uncommanded discharges).

7. Design Alternatives:

No alternative designs were investigated.

8. Design and Installation Requirements:

This section identifies the considerations that need to be addressed in the design and installation of possible systems developed around the explosion suppression technologies described within this report.

8.1. Optical Detector Systems:

8.1.1. Design:

The number and placement of detectors required to protect a fuel tank ullage space or a dry bay is dependent upon the volume of the tank or space, the area affected, and the internal physical geometry, including physical obstructions such as spars, ribs, bulkheads, baffles, stringers, fluid lines and quantity indication probes, which obstruct the clear visual fields of the detector.

Hydrocarbon fuel fires produce radiant energy in the spectral range of 0.10 to 100 micron wavelengths, with most of the radiant energy emitted in the infrared region between 0.7 and 10 microns and a strong emission band at 4.4 microns due to the carbon dioxide molecule excitation. It should be noted that commonly used aviation fuels, including Avgas, exhibit almost identical spectral characteristics.

Optical detectors are of two general types, thermal and photon.

8.1.1.1. Thermal Detectors:

Thermal detectors produce an electrical output in response to absorbed, radiant energy and the subsequent heating of a sensing element. These detectors have a response time dependent on the amount of energy received per unit time by the sensing element and the temperature change rate per unit of time of the sensing element.

8.1.1.2. Photon Detectors:

Photon detectors produce an electrical output in response to absorbed photons. Appropriate filtering lenses are utilized to ‘focus’ each photoelectric sensor on the desired wavelength and color temperature, thereby tailoring the sensor to respond to a specific input. Since heating of a sensing element is not required, photon detectors have much sorter response times and can detect smaller energy sources reliably over a greater range of distances.

Discriminating detectors have an ability to distinguish between anticipated extraneous light sources such as electrical sparks, welding arcs, lightning, maintenance lighting, sunlight, etc., and the actual ignition event. Current technology sensors may contain multiple photoelectric sensors within a detector, each filtered to a different, specific wavelength and utilization logic. These detectors can greatly reduce or eliminate the potential for false alarms.

8.1.2. Installation:

The current technology in detectors allow a range of installations from completely within the fuel tanks and ullage spaces, to remote mounting outside the fuel tank and ullage space, using optical cables and appropriate penetrations or windows to monitor the volume within.

A significant number of sensors are required due to the sensor’s limited field of view and the internal tank obstructions. In a new aircraft design, such concerns can be optimized to provide the best coverage with the fewest number of sensors.

8.2. Control Unit / Power Supply Systems:

8.2.1. Design:

The number of control / power supply units are dependent on the ‘zone’ definition used in the overall protection scheme being implemented. Each unit is designed to electrically receive signals from a number of sensors and to electrically trigger the appropriate number of suppression systems in response. Additionally, some technologies reviewed can require the input of liquid levels within the tank to minimize the pressure rise effects from the discharge of the suppressors. If the installation of such a system is to be made in an aircraft which has an MMEL item for inoperative fuel quantity indication systems, an independent means of determining the fuel level (or ullage volume) will be necessary.

If a single unit is expected to provide protection for an entire tank or tank system, then all sensors report to the single control / power supply unit (a single ‘zone’ system). Similarly, multiple ‘zones’ might be defined to protect an extended tank system.

Due to the importance of systems such as these, functional status from either power-up BIT checks or continuous BIT checks must be reported to the cockpit, in the preferred format for the particular aircraft type or design.

8.2.2. Installation:

The control / power supply is designed to be installed in a dry environment, and electrically connected to the sensor systems and the suppressor systems. Inputs from the aircraft fuel quantity indicating system or a dedicated liquid level indication system may be required.

8.3. Suppressor Systems:

8.3.1. Design:

The number and placement of suppressors required to protect a fuel tank ullage space or a dry bay is dependent upon the volume of the tank or space, the area affected, and the internal physical geometry, including physical obstructions such as spars, ribs, bulkheads, baffles, stringers, fluid lines and quantity indication probes, which impede the dispersal of the suppressant.

The systems design must provide protection for the worst case situations, i.e., turbulent, hot, high aromatic fuel. The basic requirements to be addressed in the design are:

a) Rapid dispersal time: Dispersal of the suppressant must occur in 10 to 25 msec.

b) Adequate Suppressant Concentration:

c) Ability to discharge the agent without creating unacceptable loads in the mounting and adjacent structure.

d) Ability to adjust the amount of suppressant discharged to account for varying ullage volume.

e) The initiating system and its attendant electrical power source and supply system must not add an explosion hazard to the fuel tank environment.

f) Suitable safeguards and maintenance procedures must be in place to ensure inadvertent suppressant discharge does not occur with personnel in the tanks.

g) Suitable power-up or continuous BIT capability must be provided.

8.3.1.1. Suppressant:

The suppressant used or chosen-

a) Must fully transform at the lowest predicted in-service temperature

b) Must have satisfactory fire suppression characteristics.

c) Must be environmentally acceptable and governmentally approved.

d) Must not present a substance health hazard to maintenance personnel.

e) Must not have any adverse effects on the fuel usability following agent discharge into a tank.

f) Must not have an adverse effect on the tank structure or other tank mounted equipment through corrosion or other deterioration.

8.3.1.2. Suppression System Container:

The container types developed thus far have the following shapes: tubular, cylindrical, hemispherical, and conventional fire bottle design. The means of initiating the agent discharge is electrical operation of solenoid valves, fire extinguishing agent squibs, and other pyrotechnic initiators.

The suppression system used must possess the following qualities:

a) At discharge, the tank over-pressure created must be acceptable.

b) At discharge, the thrust loads imposed on support structure must be acceptable.

c) Must provide long life of the assembly including the contents and the initiating system.

8.3.2. Installation:

A typical system requirement is for sufficient electrical system capacity to provide the combined current draw for simultaneous initiation of multiple suppressors. While this current draw is high, it is of brief duration. If an existing aircraft electrical system were unable to meet this requirement, means are available to provide it.

Special structural provisions may be required to handle the high thrust loads created by the tubular linear fire extinguisher system (LFE®) manufactured by Whittaker. Lesser addition thrust loads may also be exhibited by the Kidde hemispherical suppressors and by the Primex gas generator system. No thrust loads are generated by the Kidde cylindrical suppressor system.

9. Technical Data:

9.1. Kidde Aerospace and Defense

Kidde Aerospace and Defense now includes Fenwal Safety Systems, Kidde Graviner, Santa Barbara Dual Spectrum, L'Hotellier, and Walter Kidde Aerospace.

The research conducted on the original Graviner system dates prior to 1951. In 1954, a British patent was granted to Graviner Manufacturing Ltd. (Now Kidde-Graviner)

Graviner suppression systems utilizing IR optical sensors and pentane suppressant were fitted to the following British military aircraft: AVRO Vulcan, Handley Page Victor, Vickers Valiant, and Hawker Hunter. It is reported that "saves" have occurred with these systems. False initiations also were experienced.

A lot of IR sensor development has occurred since the original systems were installed. The status of present day IR sensor technology as used in Kidde dry bay suppression systems being flown on the F-18, F-22, EH-101, and V-22 aircraft allows for the successful recognition of and response to hydrocarbon fires and the exclusion of response to specific anticipated false light sources. Present sensors weigh 0.25 pounds and utilize 28 VDC power at 5 mA. The response time is 2 to 3 milliseconds and can be made quicker. Sensors would be located outside the tank, with optical viewing ports through the tank walls or flange mounted on the inside tank wall with wires passing directly through the wall. The number of sensors will vary with the size of the tank. The controller / power supply unit would be provided to satisfy the various system requirements when established, including BITE and flight deck annunciation. Sequential firing can be provided should the simultaneous firing current exceed the instantaneous current capacity of the aircraft electrical system.

9.1.1. Kidde Technical Data

9.1.1.1. Weight

The system weights were provided and are shown on Figure 9.1.

If the threat area within a tank can be considered localized, the system can be tailored to the localized area and all impacts would be greatly reduced, accordingly. Such a concept, if feasible, would be highly desirable.

9.1.1.2. Size (cargo/passengers/fuel displaced)

No size estimates were performed.

9.1.1.3. Range Impact

No range impacts were performed.

9.1.2. Certifiability status

While this technology has been used on military aircraft, it has not been used on commercial aircraft in fuel tank ullage explosion suppression. Use on commercial aircraft would require design, structural and electrical load analysis, and testing of effectiveness of a specific system, a reliability analysis, operational impact determination, and approval of a suitable suppressant.

9.1.2.1. Similarity to previous tests or flight experience

The Graviner system has received substantial laboratory testing and has been used on the following British aircraft in fuel tank ullage protection: AVRO Vulcan, Handley Page Victor, Vickers Valiant, and Hawker Hunter. Very similar dry bay protection systems have been used in the following US aircraft: F-18, F-22, EH-101, and V-22.

9.1.2.2. Additional Testing or Analysis

A test program for a proposed commercial aircraft design would need to be accomplished, as discussed in 9.1.2. Later technology sensors would need to be verified to not cause inadvertent initiation. The final design should be tested at various fuel quantities to verify prevention of over-pressure.

9.1.2.3. Other Effects on the Aircraft

No other effects have been identified.

9.1.3. Safety

Ullage explosion protection systems have been installed in British military aircraft used in service. No safety problems are known.

9.1.3.1. Effectiveness in preventing over-pressure hazard (from the explosion)

Substantial testing has proven that an explosion suppression system of this type can prevent structurally damaging over-pressures, even for threats due to high energy ignition sources resulting from tank penetrations by various types of armaments.

9.1.3.2. Evaluation against Historical Commercial Aircraft Over-pressure events

It is believed that explosions resulting from the lower energy ignition sources, which might occur in commercial aircraft, could be successfully suppressed based on the protection which is currently provided against the much higher energy ignition sources caused by armament penetrations of dry bays on F-18, F-22, EH-101, and V-22 aircraft.

9.1.3.3. Negative Impacts

9.1.3.3.1. Increased Landings due to range reduction (due to the added weight)

Increased landings would occur due to fuel volume reduction only if portions of the suppression system are located below the surface of the fuel. It is anticipated that all the sensors and most or all of the currently available hemispherical type suppressors could be located in the ullage, no fuel volume reduction would occur and no increases in landings would be expected.

Aircraft range reduction due to the added weight of a hemispherical type suppressor system has been calculated to be approximately as follows:

Large Transport:	6.38 nautical miles
Medium Transport:	8.19 nautical miles
Small Transport:	11.88 nautical miles
747 Center Wing Tank only:	2.24 nautical miles

Therefore, the effect of range reduction on landings is considered negligible.

9.1.3.3.2. Increased landings due to extra fuel consumed

Increased landings, due to increased fuel consumption caused by added system weight, would occur. The magnitude of the increase could vary, due to the complexity of the system configuration chosen. The maximum suppression system weights are shown in the data table included in 9.1.4, Cost Impact.

The additional block fuel consumed at constant range due to the added weight of a hemispherical type suppressor system has been calculated to be as follows:

Large Transport:	0.080 % increase
Medium Transport:	0.082 % increase
Small Transport:	0.092 % increase
747 Center Wing Tank only:	0.028 % increase

Therefore, the effect of additional fuel consumption on landings is considered negligible.

If the option was chosen, of protecting only the ignition source threat area in only one tank, the negative impact would be greatly reduced due to a minimum system weight. The weight of this option has not been defined.

9.1.3.3.3. Personnel Hazards

Inadvertent system operation has occurred with early type sensors. This is not expected with the later technology sensors presently being used. The observation of proper in-tank maintenance procedures is necessary with any such systems and must include system disarming prior to tank entry for maintenance.

9.1.3.3.4. Aircraft Hazards or Effects

To avoid any hazard related to tank over-pressure associated with the discharge of the system, it is designed to sense fuel level and discharge the amount of suppressant required by the ullage volume present.

To avoid or minimize the addition of wiring within the tank, the design can provide for sensors mounted against the inside surface of outside tank walls with wiring outside the tank. Tank level information can be provided from level sensors mounted inside the tank, with wiring in conduits where sensors are not mounted on tank outside walls.

For any suppressors which can not be mounted on outside tank walls, wiring for suppressor initiation at a momentary 5 amps per suppressor, must be housed in conduits inside the tank.

9.1.3.3.5. Other Equipment Hazards or Effects

Other equipment hazards have not been identified.

An equipment effect worthy of note is the possibility of the fuel quantity system MEL item being deleted in support of the suppressor system. The suppressant system, in most applications, requires some type of fuel quantity or fuel level input. The fuel quantity system, if used for this purpose, might be removed from the MEL, as one option..

9.1.4. Cost Impact

9.1.4.1. Component Costs and Standard Aircraft Matrix Summary

The system cost and weight are shown in Table 9.1.

9.1.4.2. Retrofit

9.1.4.2.1 Design Costs

These costs have not been calculated due to lack of data.

9.1.4.2.2 Installation Costs

The installation labor cost per aircraft is estimated to be as follows if accomplished during scheduled maintenance while fuel tanks are open and are based on a labor rate of $45 / m-hr:

Large Transport:	$16,650
Medium Transport:	$11,925
Small Transport:	$6,840
747 Center Wing Tank only:	$9,540

9.1.4.2.3 Operational Costs

There are no known system operational costs.

9.1.4.2.3.1 Maintenance Costs

9.1.4.2.3.1.1 Scheduled Maintenance Costs

The scheduled maintenance man-hour requirements are estimated to be as follows:

Note: Check interval varies with aircraft type and operation.

Daily / Weekly: None.
C-checks (@ 18 to 24 mo.): 1 m-hr for BITE check.
D-checks (@ 6 to 8 years): 1 m-hr for BITE check.

9.1.4.2.3.1.2 Periodic Parts Replacement Costs

Detonator replacement is estimated to be required at 10 year intervals and would occur at heavy maintenance; however, the material cost is not available.

9.1.4.2.3.1.3 Unscheduled Maintenance Costs

These costs, comprised of costs of delays, cancellations, out-of-service time, and maintenance man-hours and materials, have not been determined due to lack of reliability data.

9.1.4.3. Current Aircraft (Production Incorporation and Continued Production)

9.1.4.3.1 Design Costs

These costs have not been calculated due to lack of data.

9.1.4.3.2 Installation Costs

These costs have not been calculated due to lack of data.

9.1.4.3.3 Operational Costs

There are no known system operational costs.

9.1.4.3.3.1 Maintenance Costs

9.1.4.3.3.1.1 Scheduled Maintenance Costs

The scheduled maintenance man-hour requirements are estimated to be as follows:

Note: Check interval varies with aircraft type and operation.

Daily / Weekly: None.
C-checks (@ 18 to 24 mo.): 1 m-hr for BITE check.
D-checks (@ 6 to 8 years): 1 m-hr for BITE check.

9.1.4.3.3.1.2 Periodic Parts Replacement Costs

Detonator replacement is estimated to be required at 10 year intervals and would occur at heavy maintenance; however, the material cost is not available.

9.1.4.3.3.1.3 Unscheduled Maintenance Costs

These costs, comprised of costs of delays, cancellations, out-of-service time, and maintenance man-hours and materials, have not been determined due to lack of reliability data.

9.1.4.4. New Aircraft

9.1.4.4.1 Design Costs

These costs have not been calculated due to lack of data.

9.1.4.4.2 Installation Costs

These costs have not been calculated due to lack of data.

9.1.4.4.3 Operational Costs

There are no known system operational costs.

9.1.4.4.3.1 Maintenance Costs

9.1.4.4.3.1.1 Scheduled Maintenance Costs

These costs have not been calculated due to lack of data.

9.1.4.4.3.1.2 Periodic Parts Replacement Costs

Detonator replacement is estimated to be required at 10 year intervals and would occur at heavy maintenance; however, the material cost is not available.

9.1.4.4.3.1.3 Unscheduled Maintenance Costs

These costs, comprised of costs of delays, cancellations, out-of-service time, and maintenance man-hours and materials, have not been determined due to lack of reliability data.

Table 9.1. Estimated Explosively Discharged Suppressant Systems Weight and Procurement Costs

Kidde - Explosion Suppression System

Estimates are for Pentane-based Suppressant

	Tank Vol. (US Gal)	Sensors qty/wt (#/lb)	Suppressor qty/wt (#/lb)	Controller weight (lb)	Misc weight (lb)	Total System weight (lb)	Est Costs ($) *
Large Transport							
+ Canister Suppressor	25000	50/20.0	400/280.0	4	20	324	$303,000
Hemi Suppressor		50/20.0	125/312.5	4	62.5	399	$150,500
Medium Transport							
+ Canister Suppressor	10000	35/14.0	250/175.0	4	15	208	$196,500
Hemi Suppressor		35/14.0	85/212.5	4	42.5	273	$106,000
Small Transport							
+ Canister Suppressor	2000	20/8.0	100/70.0	4	10	92	$90,000
Hemi Suppressor		20/8.0	40/100.0	4	20	132	$58,000

747 CWT							
+ Canister Suppressor	17000	40/16.0	378/264.6	4	18	302.6	$278,800
Hemi Suppressor		40/16.0	40/100.0	4	20	140	$76,000

+ Canister is an out-of-production design

* Ball-park costs based on units identified in study and current production costs.
No estimates made for installation on new acft or as a retrofit on existing acft.

9.2. Pacific Scientific / HTL

Pacific Scientific is a major supplier of cargo compartment fire extinguishing systems and components, pneumatic products for missiles, automatic fire suppressions systems for military ground vehicles. The technology applicable to explosion suppression are optical sensors, Halon-discharge bottles, and a near "drop in" Halon replacement agent called Triodide.

9.2.1. Pacific Scientific / HTL Technical Data

The military ground vehicle explosion suppressions systems must suppress a fire/explosion in occupied vehicles such as tanks and armored personnel carriers. The over-pressures, heat, oxygen concentration, hydrocarbon combustion by-products, and the toxicity of the agent must be survivable and meet military specifications. The sensor is a discriminating, three-frequency optical sensor which 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. The F-22 dry bay protection system has multiple bottles with sensors on each bottle, and BITE check capability.

Pacific Scientific / HTL does not manufacture and have not tested explosion suppression systems for fuel tanks, only for applications in dry bay and occupied areas. Significant development would be required to adapt their current technologies to fuel tank applications. It is not known how much signal attenuation and signature shift would occur with a fuel film over the sensors and how their discharge bottles would react in a submerged environment. Further development would be required to account for variable ullage and discharge pressure by using microprocessor controls and multiple bottle arrays.

9.2.1.1. Weight

No weight estimates were developed since the applicability of this technology is not known for explosion suppression in fuel tanks. No detailed design was performed and no weight data was submitted

9.2.1.2. Size (cargo/passengers/fuel displaced)

No sizing estimates were developed.

9.2.1.3. Range Impact

No range impact estimates were developed.

9.2.2. Certifiability status

Pacific Scientific explosion suppression systems have not flown on commercial airplane and have not been previously certified. This technology has been qualified in military applications, but not on commercial aircraft. Consequently, an extensive and rigorous analyses and testing programs would be required to prove the effectiveness of the technology and design, the safety of the aircraft, and the system reliability.

9.2.2.1. Similarity to previous tests or flight experience

No previous ground or flight testing have been done for this technology on commercial aircraft.

9.2.2.2. Additional Testing or Analysis

A complete testing program will have to be performed to demonstrate proof of concept and design, before any certification testing can be performed. Prevention of tank over-pressures in a variable ullage volume and the effects of discharging the agent under the fuel would have to be demonstrated.

9.2.2.3. Other Effects on the Aircraft

No other effects on the aircraft have been identified.

9.2.3. Safety

The effectiveness of this technology for explosion suppression in fuel tanks has not been demonstrated or determined. If this could be demonstrated, then the safety of discharging into a variable ullage volume and possible discharges under the fuel would have to be demonstrated. Possible wing over-pressurization could result if the system designed for an empty tank discharges into a full tank. Also, the hydraulic ram effect of discharging the agent under the fuel could cause the tank to rupture.

9.2.3.1. Effectiveness in preventing over-pressure hazard (from the explosion)

The effectiveness of this technology has not been demonstrated in preventing over-pressures in fuel tanks, only in military aircraft dry-bays.

9.2.3.2. Evaluation against Historical Commercial Aircraft Over-pressure events

No evaluation was performed since the capabilities of the technology has not been demonstrated for explosion suppression in fuel tanks.

9.2.3.3. Negative Impacts

9.2.3.3.1. Increased Landings due to range reduction (due to the added weight)

No evaluation was made.

9.2.3.3.2. Increased landings due to extra fuel consumed

No evaluation was made.

9.2.3.3.3. Personnel Hazards

Since the inadvertent firing of the agent when personnel are in the tank is a potential threat, the system would be de-energized before entering the tank.

9.2.3.3.4. Aircraft Hazards or Effects

Possible tank over-pressures could result from the discharge of agent sized for an empty tank when the tank is full. Also the hydraulic ram effect if the agent is discharged under the fuel could rupture the tank. System designs would need to avoid these conditions.

9.2.3.3.5. Other Equipment Hazards or Effects

None has been identified.

9.2.4. Cost Impact

Since the technology has not been demonstrated to protect against explosions in fuel tanks and an system design was not developed, an exhausting cost benefit was not performed. Only the ROM costs below was provided by Pacific Scientific / HTL:

DESCRIPTION	QTY	$ EACH	$ TOTAL
Optical Sensor	8	900.00	7,200.00
Amplifier	1	5,000.00	5,000.00
Extinguisher	8	1,600.00	12,800.00
Control Unit	1	5,000.00	5,000.00
Cable Harness	1 set	15,000.00	15,000.00
Brackets/Misc. fixing devices	1 set	10,000.00	10,000.00
		TOTAL	$45K.

9.2.4.1. Component Costs and Standard Aircraft Matrix Summary

No data available.

9.2.4.2. Retrofit

No data available.

9.2.4.3. Current Aircraft (Production Incorporation and Continued Production)

No data available.

9.2.4.4. New Aircraft

No data available.

9.3. **Primex Aerospace Company** (Including the former Olin Aerospace Company)

9.3.1. Primex Technical Data

Primex produces various fire suppression and explosion protection technologies which are installed on various military aircraft. The technology applicable to explosion protection are chemical gas generator systems, similar to the gas-air-bag technology in automobiles. This generates a large volume of gas in milliseconds from an electrically initiated, exothermic reaction releasing carbon dioxide, nitrogen, water and trace compounds. The gas generation technology has been successfully demonstrated in live fire testing to protect a fuel tank from catastrophic over-pressure for armor piercing incendiary threats (API), but was to slow to protect a fuel tank against a 23mm high energy incendiary (HEI). However, the initiation of the gas generators was triggered by the test apparatus or personnel and was not initiated by a reactive sensing devise which would be required for explosion suppression systems on aircraft. There is sensing technology available which could trigger the gas generation technology fast enough to suppress an explosion, but this has not been demonstrated. Sensor initiated gas generation systems have demonstrated compliance for aircraft dry bay fire/explosion protection on the V-22 and F-18E/F aircraft.

The advantages to gas generation technology are as follows:

- a) Quickly disperses non-corrosive inerting agents without pressurized containers
- b) Long shelf life (20 years)
- c) Low maintenance
- d) No freezing point depression issues
- e) Canisters are not powered except to trigger
- f) Canisters can be installed in tank where required
- g) Can be selectively discharged by a remote controller
- h) Gas is radially discharged resulting in good suppressant dispersion and creates no reaction loads on the aircraft structure

The disadvantages of gas generation technology are as follows

- a) High temperatures of discharge gases
- b) 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)
- c) Canister wiring must be routed in tank
- d) Have not tested volumes larger than 120 cubic feet
- e) Single shot canisters
    - 1) Require tank entry after discharge
    - 2) Containers are not re-usable

Another configuration that Primex has developed is a hybrid system where 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 but the has not been demonstrated for fuel tank explosions. The advantages are as follows:

- a) Long shelf life
- b) Low maintenance
- c) Usable with any low pressure suppressant
- d) No high pressure discharge into ullage
- e) Low propellant weigh requirement
- f) Ullage volume (FQIS) input to controller desired but not required
- g) Canisters are not powered except to trigger

h) Can be BITE checked

i) Controllers can selectively discharge canisters

j) Faster discharge rates than nitrogen charged systems

The disadvantages of the gas generator-hybrid system are:

a) Suitable low pressure suppressant needed

b) Water has been demonstrated effective but has freezing point issues

c) Canister triggering wiring and squibs-initiators must be located in tank

d) Single shot canisters

e) Requires tank entry to replace after discharge

9.3.1.1. Weight

The weight estimates shown in Table 1 are for the total tank volume, mains and CWT. The bizjet tank volume is shown as 2000 gallons, but the standard volume is 1200 gallons. The weights are quite low for all models compared to other methods such as foam and nitrogen inerting. Any airplane structural changes are not shown but would be minor.

9.3.1.2. Size (cargo/passengers/fuel displaced)

The canisters are 1-2” in diameter and up to 1’ long and would occupy a minimal tank volume. The controller located outside of the tank would occupy a small volume and would require no modifications to the airplane to install.

9.3.1.3. Range Impact

The only range impact would be carrying the additional weight shown in Table 9.3.

9.3.2. Certifiability status

9.3.2.1. Similarity to previous tests or flight experience

The Fenwal system on the Boeing 707 and 747-100 airplanes had an old technology Halon fire extinguishing system, installed in the surge tanks to prevent ground fires entering the wing. This system was only for fire protection and not intended to be fast enough for explosion suppression. Although this system was qualified and certified, there is little similarity to an explosion suppression system in the tanks, other than the similar technology used. Putting additional wiring and squib initiators in the fuel tanks presents a new set of safety concerns which need to be addressed. A complete new certification program would be required from proof of concept and design, considering failure modes and effects analysis, full scale testing and flight testing would be required for certification.

9.3.2.2. Additional Testing or Analysis

A complete new certification program is required from proof of concept and design, failure modes and effects analysis, full scale testing and flight testing would be required for certification.

9.3.2.3. Other Effects on the Aircraft

The FQIS would need to be functional for the controller to determine ullage volume, this could not be MEL dispatchable as it is today. Accessing the data bus would be required.

An alternative is to provide a dedicated fuel quantity measuring system to provide an input to the suppression system, thereby eliminating the effect on the aircraft FQIS and any MMEL alleviation provided.

9.3.3. Safety

9.3.3.1. Effectiveness in preventing over-pressure hazard (from the explosion)

The gas generator technology has demonstrated effective in suppressing fuel tank explosions for military threats up to API rounds. This is in excess to any threats internal to the tanks. However, the gas generation technology was not tested with a reactive sensor and has not been demonstrated system effectiveness as would be installed on the airplane. There are extremely fast sensors which have demonstrated effectiveness with other explosion suppression technology in fuel tanks. Therefore it is likely that the gas generation technology could be effective in suppressing fuel tank explosions. The gas generation-hybrid technology has shown effective in dry bay applications but not in fuel tank applications.

9.3.3.2. Evaluation against Historical Commercial Aircraft Over-pressure events

This technology was not evaluated against the historical events because the total system (sensors and gas generators) has not demonstrated effectiveness for fuel tank explosion protection.

9.3.3.3. Negative Impacts

9.3.3.3.1. Increased Landings due to range reduction (due to the added weight)

No evaluation was made.

9.3.3.3.2. Increased landings due to extra fuel consumed

No evaluation was made.

9.3.3.3.3. Personnel Hazards

Certainly if the system was activated with personnel in the tanks this could result in serious injury. The system would have to be de-activated prior to any entry into the fuel tank.

9.3.3.3.4. Aircraft Hazards or Effects

Putting pyrotechnic devices (squib or pyrotechnic initiators) into the tank may present a risk to the aircraft. A full safety analysis would be required to determine the resulting level of safety for the system. Presumably the fact that explosion suppressant would be released if the squib was activated would ensure any ensuing explosion would be suppressed.

9.3.3.3.5. Other Equipment Hazards or Effects

None have been identified.

9.3.4. Cost Impact

Only cost of procurement, shown in Table 9.3., have been evaluated. Since the complete system (sensor and gas generators) have not been demonstrated effective in suppressing fuel tank explosion, a complete costs analysis was not performed.

9.3.4.1. Component Costs and Standard Aircraft Matrix Summary

Refer to Table 9.3.

9.3.4.2. Retrofit

No data available.

9.3.4.3. Current Aircraft (Production Incorporation and Continued Production)

No data available.

9.3.4.4. New Aircraft

No data available.

Table 9.3. Estimated Gas Generation and Hybrid Systems Weight and Procurement Costs

Primex - Solid Propellant Gas Generator Systems

Insert Gas produced by solid propellant

	Tank Vol (US Gal)	Sensors qty/wt (#/lb)	Suppressors qty/wt (#/lb)	Controller weight (#)	Misc Weight (lb)	Tot System Wt (lb)	Est. Tot System Cost ($)*
Large Transport							
Active	54,000	30 / 15.0	58 / 290	12.0	40.0	360	$163,500
Hybrid		30 / 15.0	29 / 145	8.0	30.0	200	$141,750
Medium Transport							
Active	24,000	15 / 7.5	26 / 130	8.0	15.0	160	$92,000
Hybrid		15 / 7.5	13 / 65	5.5	10.0	90	$82,250
Business Jet							
Active	2,000	4 / 2.0	4 / 10	3.0	1.0	20	$29,000
Hybrid		4 / 2.0	4 / 10	3.0	1.0	15	$29,000

* Cost estimates based on units identified in study and current production costs.
No estimates made for installation on new aircraft or as a retrofit on existing aircraft.

Based on:
Suppressor unit weight = 5.0 lbs each (1000 gram agent)
Sensor weight = 0.5 lb each
Wiring weight = 0.012 lb/ft
Large Transport = 35 ft per component
Medium Transport = 25 ft per component
Business Jet = 10 ft per component

9.4. Whittaker Safety Systems

Whittaker Safety Systems (previously known as the John E. Lindberg Company and as Systron Donner) is a major supplier of fire, smoke and bleed air leak detection and suppression and detection control systems equipment for military and commercial aviation aircraft.

Whittaker designed the Linear Fire Extinguisher (LFE®) explosion suppression system in response to a military RFP in 1985 for dry-bay protection against API and HEI threat. Original requirements were for aluminum oxide powder as the suppressant, but testing showed this to be a poor requirement and Whittaker Safety Systems moved to develop a Halon system using a similar tubular container design.

9.4.1. Whittaker Technical Data

9.4.1.1. Weight

A comparison of weights, provided by Whittaker, of the Tubular Storage systems to other protection systems (rigid foam, N_2 Inerting, Halon Inerting, Scott Foam, etc.) show the Tubular Storage system to be the lightest system per unit volume protected. Specific weights are dependent on the detailed requirements and the configuration of the installation being evaluated.

9.4.1.2. Size (cargo/passengers/fuel displaced)

Since the concept of the LFE® allows any physical length of tubing to be used, it is not limited in length sizing. However, it is necessary that the container be sized in diameter according to the amount of suppressant needed to protect the volume of the tank being considered; the greater the container diameter, the greater the resulting volume of suppressant to be released.

Due to the pressurized nature of the container, the volume of fuel displaced by the suppressant storage system is minimized.

9.4.1.3. Range Impact

The only range impact would be carrying the additional weight of the system.

9.4.2. Certifiability status

9.4.2.1. Similarity to previous tests or flight experience

Whittaker Explosion Suppression System components were designed into the wing structure and first tested on the Bell V-22 Tiltrotor aircraft. Later, similar Whittaker components were tested on equivalent structures of the F/A-18 Naval fighter. These tests were done in controlled testing environments where flight conditions were simulated, but to this date, no system of this sort has flight experience.

9.4.2.2. Additional Testing or Analysis

Further testing is required to determine the compatibility of the suppressant with the environment and the fuels requiring protecting, especially considering alternative suppressants. Testing must address the concerns associated with potential over-pressures, the effects of discharging the LFE® when completely submerged in fuel and the ability of successfully dispersing the agent into the fueled areas.

Further design and development work is necessary to understand and to minimize the reactive loads that are imposed on the aircraft structure when the LFE® is discharged. The testing to date have not shown these loads to be a structural problem, but the nature of high magnitude, impulse loads require a dedicated look at the effects, or potential effects.

A certification program is required to address the complete installation and operation of the finalized system.

9.4.2.3. Other Effects on the Aircraft

The FQIS would need to be functional for the controller to determine ullage volume, this could not be MEL dispatchable as it is today. Accessing the data buss would be required.

An alternative is to provide a dedicated fuel quantity measuring system to provide an input to the suppression system, thereby eliminating the effect on the aircraft FQIS and any MMEL alleviation provided.

9.4.3. Safety

9.4.3.1. Effectiveness in preventing over-pressure hazard (from the explosion)

As described in 9.4.2.2. above, testing to address the concerns of over-pressures must be conducted.

9.4.3.2. Evaluation against Historical Commercial Aircraft Over-pressure events

No evaluation was made.

9.4.3.3. Negative Impacts

9.4.3.3.1. Increased Landings due to range reduction (due to the added weight)

No evaluation was made.

9.4.3.3.2. Increased landings due to extra fuel consumed

No evaluation was made.

9.4.3.3.3. Personnel Hazards

Activation of this system with maintenance personnel in the tank presents a hazard of serious injury. Positive and appropriate deactivation procedures must be incorporated prior to entry into a tank equipped with this suppression system.

9.4.3.3.4. Aircraft Hazards or Effects

Pyrotechnic devices in aircraft fuel tanks presents a risk to the aircraft. A full safety analysis would be required to evaluate the resulting level of safety of the aircraft. In the case of this suppression system, a discharge of the system would release an explosion / fire suppressant into the fuel tank and reduce any threat due to fire or explosion.

9.4.3.3.5. Other Equipment Hazards or Effects

None have been identified.

9.4.4. Cost Impact

9.4.4.1. Component Costs and Standard Aircraft Matrix Summary

Only ROM cost of procurement, shown in Table 9.4., have been evaluated.

DESCRIPTION	$ EACH
Optical Sensors	$1,500
LFE® Units	$800
Controller	TBD
Brackets	TBD

9.4.4.2. Retrofit

No installation data available.

9.4.4.3. Current Aircraft (Production Incorporation and Continued Production)

No installation data available.

9.4.4.4. New Aircraft

No installation data available.

Table 9.4. Estimated Linear Fire Extinguisher System Component Costs

Whittaker Safety Systems - LFE® Suppressant System

FUEL TANK PROTECTION SYSTEMS

Rough Order of Magnitude

SYSTEM COST MATRIX SUMMARY

AIRCRAFT TYPES (MTOGW - MLW)	PROJECTED NUMBER OF TANKS	FUEL VOLUME (US GAL)	PROJECTED NUMBER OF DETECTORS	DETECTOR COSTS	PROJECTED NUMBER OF EXTINGUISHERS	EXTINGUISHER COSTS	TOTAL COSTS
LARGE (800K - 600K)	5	54,000	10	$15,000	30	$24,000	$39,000
MEDIUM (330K - 270K)	5	24,000	10	$15,000	20	$16,000	$31,000
SMALL (160K - 130K)	3	4,000	6	$9,000	12	$9,600	$18,600
REGIONAL T/FAN (76K-69K)	3	3,200	6	$9,000	6	$4,800	$13,800
REGIONAL T/PROP (40K-38K)	2	1,400	4	$6,000	4	$3,200	$9,200
LARGE BIZJET (35K-30K)	3	2,000	4	$9,000	6	$4,800	$13,800

10. Other Supporting Data

10.1 Standard Aircraft Matrix

Proposed Standards for evaluation airplane types

Units:

Weight	pounds	Volume	US gallons
Speed	knots	Pressure	psi
Altitude	feet		

Model	Large	Medium	Small	Regional T/fan	Regional T/prop	Bizjet
General						
Fleet size	2,000	1,400	8,600	1,000	2,000	8,600
MTOGW	800,000	330,000	160,000	78,000	40,000	23,000
MLW	600,000	270,000	130,000	69,000	38,000	20,000
Fuel Volume:						
Total	54,000	24,000	5,000	3200	1400	1200
Center	25,000	10,000	3,000	800	0	0
Wing	26,000	12,000	2,000	2400	1400	800
Tail	3,000	2,000	0	0		
Body	(optional)	(optional)	(optional)	0	0	400
Tank Configurations						
% fleet with Center Tanks	89	97				6
% of Center Tanks with Heat Input						0
% fleet with Tail Tanks	36	25				0
% fleet with Body Tanks	2	0				54
Tank Pressure						
Positive	+1.5	+1.5	+1.5	2	2	+1.5
Negative	-0.5	-0.5	-0.5	-1	-1	-0.5
Bleed flow available after ECS						
Bleed pressure avail after ECS						
Bleed temperature avail after ECS						
Precooler flow avail after ECS						
Precooler max outlet temperature at max flow						
Payload (lbs)	100,000	55,000	40,000	35,000	22,000	1,200
passengers	400	250	150	75	50	6
Short mission						
Range (nm)	2,000	1,000	500			1000
Ground Time (hr)	2.00	1.50	1.25			
Block Time (hr)	4.6	2.3	1.6			
# of flights per day (AOG data)	1,103	1,599	14,682			
# of airplanes in AOG data	757	608	3,552			
# of flights per day	2,914	3,682	35,548			
Medium Mission						
Range (nm)	4,000	2,000	1,000	450	250	3000
Ground Time (hr)	2.00	1.50	1.25	0.33	0.33	
Block Time (hr)	8.6	4.6	2.8	1.4	1.1	
# of flights per day (AOG data)	432	399	4,152			
# of flights per day	1,141	919	10,053	10,000	20,000	
Long mission						
Range (nm)	6,000	4,000	2,000			6500
Ground Time (hr)	2.00	1.50	1.25			
Block Time (hr)	12.7	8.9	5.1			
# of flights per day (AOG data)	206	235	1,060			
# of flights per day	544	541	2,566			
Distribution						
% short missions	63	72	74			54
% medium missions	25	18	21	100	100	27
% long missions	12	11	5			19
Operating environment						
Max. Cruise Alt.	43,000	43,000	37,000	35,000	25,000	41,000
Ground temp max	130 Deg F	130 Deg F	130 Deg F	122 Deg F	122 Deg F	122 Deg F
Ground temp min	-65 Deg F	-65 Deg F	-65 Deg F	-40 Deg F	-40 Deg F	-40 Deg F
Distribution of Ground Temp	-40 to 122 F	-40 to 122 F	-40 to 122 F	-40 to 122 F	-40 to 122 F	-40 to 122 F
Distribution of Cruise Temp	-87 to -22 F	-87 to -22 F	-87 to -22 F	-87 to -22 F	-87 to -22 F	-87 to -22 F
Distribution of Flash Point	100 to 150 F	100 to 150 F	100 to 150 F	100 to 150 F	100 to 150 F	100 to 150 F
Vmo	365	360	340	320	250	360
Mmo	0.92	0.85	0.82	.0.80	0.5	0.83
M cruise	0.85	0.80	0.77	0.75	290T/220E	0.8
Climb rate (Max, Sea Level)	5,000	5,000	4,500	3000	2000	
Descent rate (Normal)	2,000	1,500	2,000	2000	2000	
Descent rate (Max)	3,500	4,000	3,000			