Fire Safety

Cargo Compartment Fire Detection Certification Project

An FAA technical report was published, "Comparison of Actual and Simulated Smoke for the Certification of Smoke Detectors in Aircraft Cargo Compartments," DOT/FAA/AR-03/34, Suo-Anttila, J., et al., in November 2003. The report documents work conducted by Sandia National Laboratories, under a contract with the FAA, to characterize the differences between smoke particles from flaming fires and particles produced by theatrical smoke generators. Due to safety considerations, theatrical smoke generators are frequently used to show compliance with federal regulations that require a flight test to demonstrate the proper functioning of cargo compartment fire detection systems.

The work included collecting smoke samples on a filter during actual flaming fires and imaging the particles with a transmission electron microscope (figure 1). The size of the primary particles as well as the size and shape of the agglomerated particles could then be directly measured. In addition, the optical properties of the smoke from actual flaming fires and the liquid droplets produced from smoldering fires and theatrical smoke generators were determined by reviewing the existing research literature. The particle sizes from the artificial and smoldering smoke sources were found to be much larger than the particles from the flaming fires. Also, the attenuation of light by smoke from flaming fires was approximately 70% due to absorption and 30% due to scattering, while the attenuation from artificial smoke was 100% due to scattering. This was a significant finding because the detection technology used in the majority of aircraft smoke detectors depends on the scattering of a light beam to produce an alarm. This would imply that current detectors would be much more sensitive to artificial smoke than to smoke from actual flaming fires.

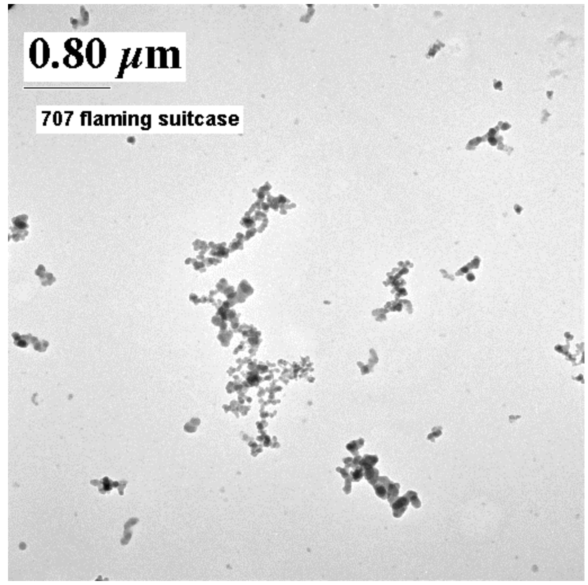


Figure 1. Image of Smoke Particles From a Flaming Fire

The Fire Safety Branch conducted a series of tests in several different aircraft cargo compartments to investigate the validity of this finding. The compartments were instrumented with laser-based smoke meters in a variety of locations. Several models of current smoke detectors were installed and exposed to smoke from flaming fires, smoldering fires, and theatrical smoke generators. In all cases, the detector response time was longer with flaming fires than with either smoldering or artificial smoke sources. The smoke meters readings indicated a significantly greater quantity of smoke at the time of detector alarm for the flaming fires compared to the smoldering or artificial smoke sources.

Dave Blake, ATO-P, (609) 485-4525

Evaluation of Halon Replacement Agents in Protecting Against an Aerosol Can Explosion

In December 2003, the Fire Safety Branch at the FAA William J. Hughes Technical Center evaluated two halon replacement agent candidates (fire suppression agents) to determine their effectiveness in protecting against an aerosol can explosion. Bromotrifluoropropene (BTP) and pentafluoroethane (HFC-125) were selected by members of the International Aircraft Systems Fire Protection Working Group as possible candidates to replace Halon 1301 as the suppression agent used in an aircraft cargo compartment.

The simulated aerosol can explosion test is one of four fire test scenarios required by the FAA Minimum Performance Standard (MPS) for Aircraft Cargo Compartment Halon Replacement Fire Suppression Systems (DOT/FAA/AR-TN03/6, Reinhardt, J., April 2003). Before running this particular MPS test with the candidate agents in the required 2000-ft^3 aircraft cargo compartment, a preliminary test series was conducted in a 353-ft^3 pressure vessel (see figure 1) located in the FAA William J. Hughes Technical Center Pressure Fire Modeling Facility. This pressure vessel is capable of withstanding a working pressure of 600 psig. The objective of this test series was to determine if the candidate agents had any unusual behavior before proceeding with the required MPS tests inside the 2000-ft^3 aircraft cargo compartment, which is a weaker structure than the pressure vessel.

Baseline tests were conducted to establish a comparison benchmark. These baseline tests were conducted by letting the simulated aerosol can explode without the presence of a suppression agent. The results showed

Figure 1. Pressure Vessel

overpressures between 23 and 25 psig. A second benchmark test was conducted using 2.5% volumetric concentration Halon 1301, which is below its inerting concentration. At this volumetric concentration, a subdued explosion event occurred, resulting in an overpressure of 4 psig.

The reported inert concentration of BTP, when evaluated against propane, is 8.5% volumetric concentration. It was decided by the testing team that the initial agent volumetric concentrations should be below 8.5% to determine if BTP would be as effective as Halon 1301 in this particular test scenario. Testing at the FAA William J. Hughes Technical Center has shown that Halon 1301 is capable of suppressing this particular propane explosion with as little as 3.1% volumetric concentration. (The published inert concentration value for Halon 1301 is 6.7% at stoichiometric fuel (propane) to air ratio.) The initial volumetric concentration selected for the first explosion test was 2.5% BTP.

The first explosion test resulted in an estimated overpressure of 49.3 psig (the pressure transducer was saturated). After replacing the pressure transducer, other tests were conducted that included 3%, 4%, 5%, and 6% volumetric concentrations. Figure 2 shows that their associated overpressures were 63, 63, 100, and 93 psig, respectively.

Thus, BTP enhanced the explosion event (as much as 4 times greater pressures than the unsuppressed event and 23 times greater than the Halon 1301 benchmark concentration).

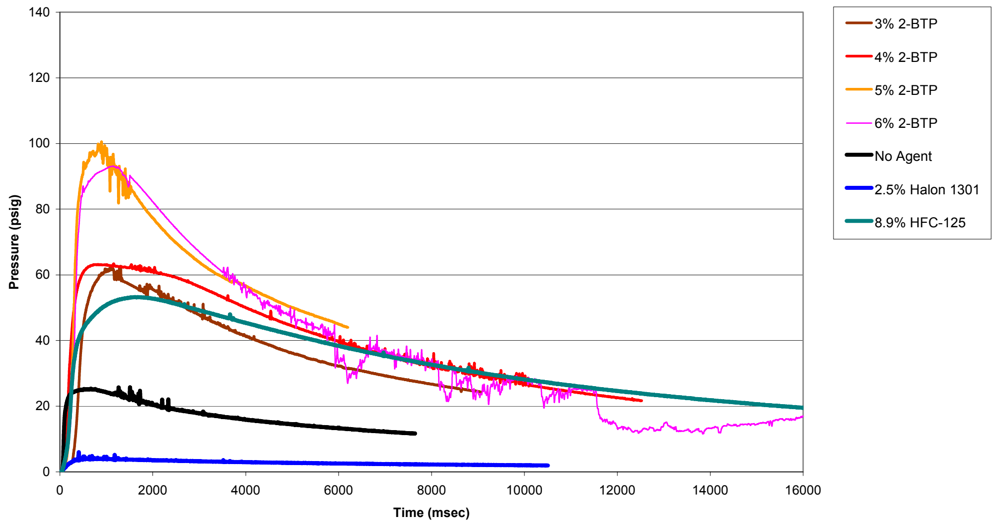


Figure 2. Comparison of Agent Explosion Suppression Capability at Below Inert Concentrations

After the BTP explosion events, HFC-125 was evaluated to determine if it would behave in the same fashion. HFC-125 also enhanced the explosion event when it was below its inert concentration (15.6%). The agent produced explosion overpressures of 53 psig at 9% and 11% volumetric concentrations. Another test was conducted with 13.5% of HFC-125, but there was no explosion event after the simulated aerosol can was activated. Thus, HFC-125 prevented the blast at 13.5%, even though its reported inert concentration for a propane explosion is 15.6% (at a stoichiometric fuel-to-air ratio).

In summary, at concentrations below the inerting level, both BTP and HFC-125 enhanced explosions by creating higher overpressures than measured in air alone. In contrast, Halon 1301, the currently used aircraft cargo compartment fire suppression agent, mitigated the explosion, even though it was below its inert concentration. It reduced the overpressure of the event. Since aircraft cargo compartment suppression agents may be present at subinerting design concentrations, because of stratification or larger than normal leakage, it is important that replacement agents be selected that do not increase the overpressure caused by an exploding aerosol can at concentrations below the inerting value. Unless a means can be found to avoid the problem of subinerting concentrations of extinguishing agent, BTP and HFC-125 would not be suitable candidates for halon replacement extinguishing agents in the cargo compartment.

The test results are documented in an FAA technical note titled "Behavior of Bromotrifluoropropene and Pentafuoroethane When Subjected to a Simulated Aerosol Can Explosion," DOT/FAA/AR-TN04/4, Reinhardt, J., May 2004. The MPS standard is currently being modified to address this behavior in the acceptance criteria section.

John Reinhardt, ATO-P, (609) 485-5034

Effectiveness of Hand-Held Extinguishers Against Hidden Cabin Fires

Improved fire test standards for transport category aircraft have been mandated by the FAA over the past 10-15 years. As a result, implementation of newer, more fire-resistant materials has taken place on a consistent basis. Fire-blocking seat cushions and low heat release interior panels have resulted in a much more fire-resistant cabin in the event of an impact-survivable postcrash fire. In addition, by mandating the retrofit of all Class D compartments to include fire detection and suppression systems, the hazards associated with an in-flight cargo compartment fire have been reduced. Although these mandates have improved overall cabin safety from a fire standpoint, there are still concerns over the ignition of materials and the propagation of fire in hidden or inaccessible areas. In recent years, numerous incidents and several accidents involving in-flight fires have originated in inaccessible areas such as the electronics and engineering (E/E) bay, the cheek area, behind cabin sidewall panels, and above the cabin ceiling.

The FAA is approaching the problem of hidden-area fires from two paths. One current research task is aimed at developing newer, more stringent fire tests for materials located throughout hidden areas such as above the ceiling, cabin, cheek, and E/E bays. This research will target the flammability of materials such as ducting, wires, panel closeouts, clamps, and other hardware located in hidden and inaccessible areas to bring these materials to an equivalent level of fire resistance as recently adopted for thermal acoustic insulation. The intent of the research is to passively reduce the likelihood of an in-flight fire from occurring by substantially and completely improving the materials in these areas.

The other approach is to actively control hidden-area fires. In contrast to the passive approach, this effort would determine which inaccessible areas of the aircraft could actually benefit from active detection and suppression, and then develop and test appropriate concepts. Since the area above the cabin ceiling is the largest inaccessible area in a transport aircraft, the initial task was to assess the capabilities of existing hand-held extinguishers and determine ways to make them more effective against a fire located in this area.

One main problem associated with fire suppression in the cabin overhead area is accessibility. In several recent incidents, access to the cabin overhead area was gained forcibly (i.e., using some type of tool or device to cut through the ceiling panel). Once access is gained and the fire source located, the threat is greatly reduced, since the extinguishing agent can be applied directly to the fire. Fires in inaccessible areas may initially be very small and of little threat, but the difficulty in accessing them allows sufficient time for growth, leading to a much more dangerous and difficult situation. A more efficient method of accessing the cabin overhead area needed to be devised so crew members can quickly locate and extinguish any hidden fires.

One approach that was investigated to more effectively apply an agent in the cabin overhead area was to use panel-mounted ports that would allow an extinguisher nozzle to be inserted, thereby eliminating the need to forcibly gain access to this area. Originally designed to allow agent discharge into a circuit breaker panel, these devices have recently been adapted for use in the cabin overhead area. Although the agent can be applied more readily, determining the appropriate point of discharge is still a challenge. This problem is magnified since there is often significant ventilation in the cabin overhead areas, making it difficult to accurately locate the fire source. An accurate method of detecting the fire location would greatly compliment the port system approach.

Twenty hand-held extinguisher tests were performed in the cabin overhead area of both narrow- and wide-body aircraft. The tests simulated a typical hidden fire in the inaccessible area above the cabin ceiling using a number of small, controllable candle lanterns (figures 1 and 2). The purpose of the tests was to determine the performance of FAA-required hand-held Halon 1211 extinguishers against a fire in this area when using a ceiling-mounted port to discharge the agent. The port design was modified as testing progressed to maximize agent performance.

Figure 1. Agent Being Discharged Through a Port in a Wide-Body Aircraft

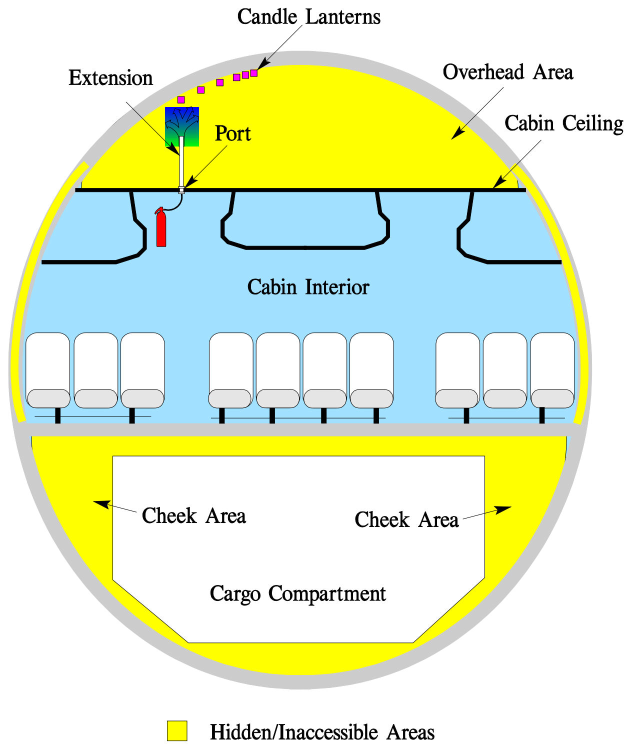


Figure 2. Cut-Away Schematic of a Wide-Body Aircraft Showing the Extinguisher Port Test Configuration

The tests indicated that individual hand-held extinguishers were incapable of providing adequate protection against fires in large overhead areas typical of wide-body aircraft, regardless of the port design. However, using ceiling-mounted discharge ports in combination with hand-held extinguishers was quite effective against fires in the more confined overhead area of a typical narrow-body aircraft.

Tim Marker, ATO-P, (609) 485-6469

Proposed Regulation to Protect Oxygen Cylinders and Generators Against a Cargo Compartment Fire

On May 6, 2004, a Notice of Proposed Rulemaking (NPRM) was issued to require that oxygen cylinders and oxygen generators be shipped in containers that meet flame penetration and thermal resistance requirements. The purpose of the NPRM is to ensure the fire-safe shipment of oxygen cylinders and generators in an inaccessible cargo compartment protected with an onboard fire detection and suppression system. Protective containers would prevent the accidental discharge of oxygen that could cause a suppressed fire to intensify and burn out of control. The NPRM was issued by the Research and Special Programs Administration, which is responsible for the transport of hazardous materials, and was developed jointly with the FAA. The need and criteria for flame and thermal protection are based on tests conducted by the Fire Safety Branch.

In one series of tests, oxygen cylinders were exposed to air temperatures that would exist during a suppressed cargo compartment fire. It was shown that the pressure relief device activated when the surface temperature reached 300°F (figure 1), discharging the contents of the cylinder. In a second series of tests, the oxygen cylinder quantities previously measured were discharged in a deep-seated fire suppressed with Halon 1301in an LD-3 container. Under certain conditions, the introduction of oxygen caused the fire to burn out of control and destroy the LD-3 container (figure 2). The findings are documented in the technical note titled "Oxygen Enhanced Fires in LD-3 Cargo Containers," DOT/FAA/AR-TN98/29, Marker, T. and Diaz, R., May 1999.

Oxygen cylinders stowed in carrying cases, commonly called overpacks, were subjected to air temperatures that would exist during a suppressed cargo compartment fire. Overpacks are designed to protect oxygen

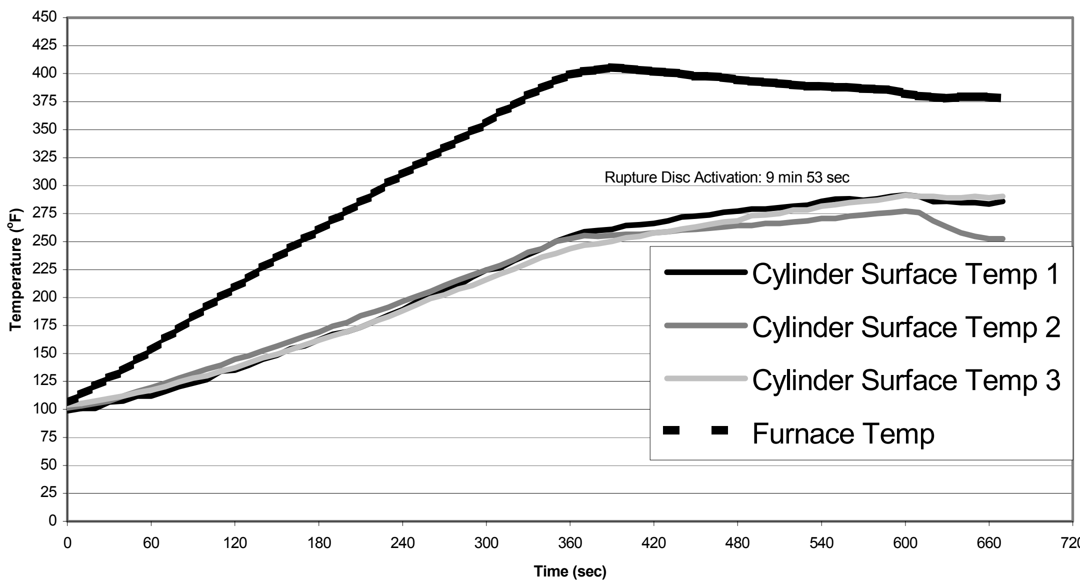


Figure 1. Furnace Test Results Using a 76.5-Cubic-Foot Cylinder

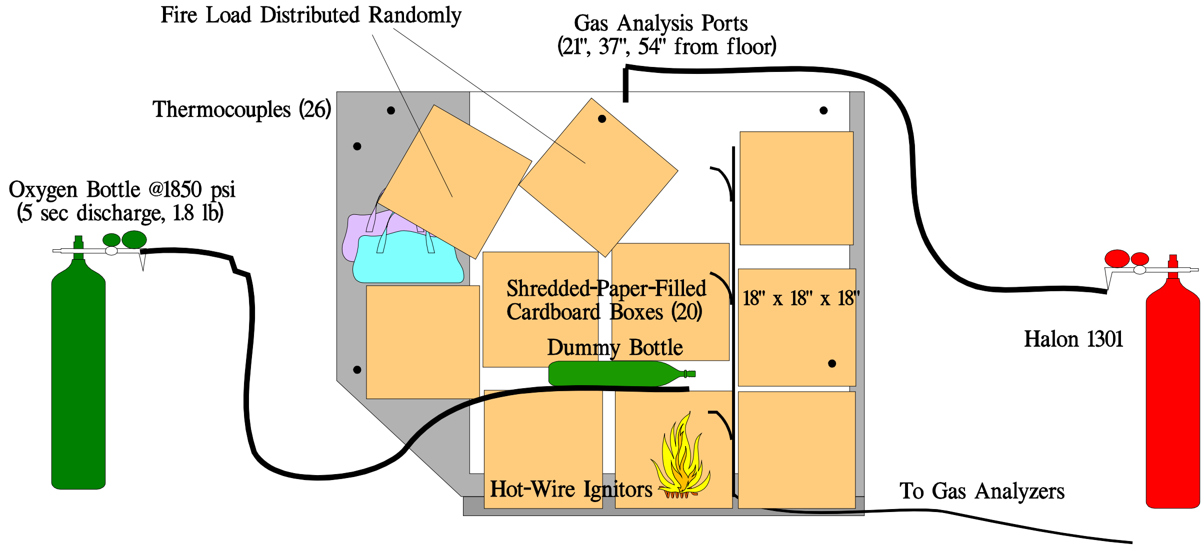


Figure 2. Oxygen-Fed Fire Test Arrangement in an LD-3 Cargo Container

cylinders against impact damage during shipment. Conventional overpacks prevented activation of the pressure relief device for as long as 60 minutes. However, significant additional protection was provided when the overpacks were modified with insulating materials. The findings are documented in the technical note titled "Evaluation of Oxygen Cylinder Overpacks Exposed to Elevated Temperature," DOT/FAA/AR-TN98/30, Marker, T. and Diaz, R., June 1999.

Oxygen generators were heated in a furnace to determine the temperature that would cause self-activation. Based on the test results, consideration of other designs, and the physical properties of sodium chlorate, it was recommended that generators be protected from temperatures above 400°F. The findings are documented in the technical note titled "The Response of Aircraft Oxygen Generators Exposed to Elevated Temperatures," DOT/FAA/AR-TN03/35, Blake, D., April 2003.

Stored oxygen is used extensively and located throughout the airplane. Moreover, it is shipped by the airlines to support maintenance and service of oxygen systems and as a service to passengers undergoing oxygen therapy. Oxygen cylinders provide oxygen to the cockpit crew during specified and emergency conditions. Also, medical oxygen cylinders are used for emergencies and are shipped by dependent passengers. Chemical oxygen generators furnish emergency oxygen to passengers in the event of a cabin depressurization. The goal of the NPRM is to provide safe shipment of oxygen cylinders and generators in cargo compartments equipped with a fire detection and suppression system.

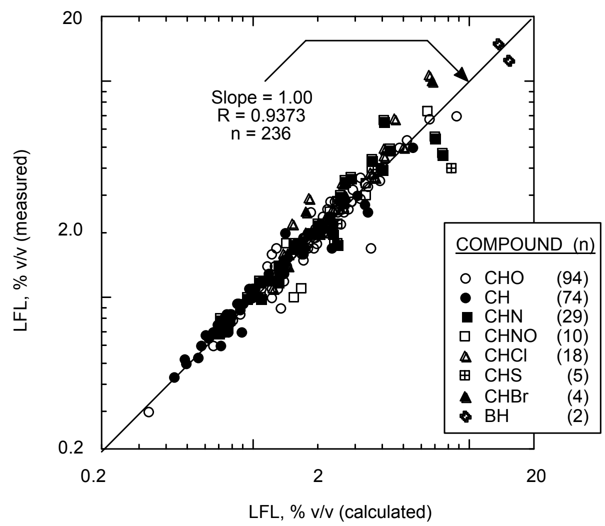
Gus Sarkos, ATO-P, (609) 485-5620

Piloted Ignition of Plastics

The ignition of fuel-air mixtures occurs when the rate of heat produced per unit volume of the mixture during burning exceeds the rate at which that heat is transferred out of the combustion volume at the burning temperature. In terms of physical quantities, the condition for ignition is met when the heat of combustion of the fuel gases (J/kg) multiplied by their concentration in air (kg/m^3) reaches a critical value Q''' (J/m^3) at the source of ignition, which could be a spark, flame, or hot surface. If the fuel vapor has density ρ_f (kg/m^3), molar mass M_f (kg/mole), molar heat of combustion H_c^0 (J/mole), and behaves as an ideal gas, the minimum volume fraction of fuel gas in air that will ignite, i.e., the lower flammability limit (LFL) of the fuel, at standard temperature (298 K) and pressure (STP), is simply given by the following equation:

$$LFL = \frac{M_f}{\rho_f H_c^0} Q''' \qquad (1)$$

Figure 1 compares the measured LFL of 236 gases and vapors at STP with those calculated from equation 1, assuming a constant energy density at ignition Q''' = 1.9 MJ/m^3 and the reported H_c^0 and ρ_f for each fuel. Figure 1 shows good (94%) agreement between the measured and the calculated LFL using the energy density Q''' = 1.9 MJ/m^3 at ignition for equilibrium mixtures of air and vapors of alkyl and aromatic hydrocarbons as well as vapors of hydrocarbons containing oxygen, nitrogen, sulfur, and halogen. The result (equation 1) is directly applicable to a quasi-static environment, such as an aircraft fuel tank, where the fuel vapor/air ratio changes relatively slowly.



(The legend shows the number (in parentheses) and atomic composition (carbon/C, hydrogen/H, oxygen/O, nitrogen/N, sulfur/S, chlorine/Cl, Bromine/Br, boron/B) of the fuels plotted in the graph.)

Figure 1. Measured and Calculated LFL for 236 Gases and Vapors

A critical energy density criterion for ignition of solids in a dynamic environment, such as a developing aircraft cabin fire, follows directly from equation 1. Since the fuel concentration and environmental variables (ventilation rate and fire size) change rapidly with time in a fire, the fuel/air ratio must be expressed as a ratio of the flows of fuel and air rather than as a static (equilibrium) volume fraction, as per equation 1. The transient dynamic formulation leads to explicit results for incipient ignition in terms of a critical power density or heat release rate (HRR*) (W/m^2) at which the vaporized fuel/air mixture first becomes ignitable.

$$HRR^* = \frac{\bar{h}}{\rho_a c_a} Q''' \qquad (2)$$

In equation 2, $\bar{h}$ is the rate that heat is removed from the surface of the solid by the movement of air, while ρ_a and c_a are the density and heat capacity of the air, respectively. Equation 2 is a criterion for the ignition of solid fuels in a particular dynamic environment that is completely independent of the type of solid fuel (plastic). For the controlled conditions in a fire calorimeter, $\overline{h}$ = 10 W/m^2-K and for typical ρ_a = 1 kg/m^3 and c_a = 1 kJ/kg-K, equation 2 predicts HRR* = 20 kW/m^2 at incipient ignition. Several different plastics were tested in a fire calorimeter, and the HRR* at incipient ignition was taken to be the product of the measured mass loss rate (MLR) (kg/m^2-s) and heat of combustion (HOC) of the fuel gases (J/kg). Table 1 shows that these experimental measurements are in excellent agreement with the HRR = HRR* = 20 kW/m^2 that is predicted for piloted ignition of combustible solids in a fire calorimeter.

Table 1. Heats of Combustion, MLR, and Potential HRR for 21 Plastics

Plastic	HOC (kJ/g)	MLR (g/m^2-s)	HRR (kW/m^2)
Polyoxymethylene	14.4	0.88	13
Polymethylmethacrylate	24.8	0.97-1.01	25
Polyethylene	40.3	0.88	35
Polypropylene	41.9	0.60	25
Polystryene	27.9	0.57	16
Flame Retardant PS	9.6	2.0	19
Polyurethane Rubber	23.7	0.83	20
Polycaprolactam	29.8	0.88	26
Polybutyleneterephthalate	21.7	0.77	17
Polycarbonate	21.2	0.78	17
Polyphenylenesulfide	23.5	0.81	19
Polyphosphazene	15.4	1.23	19
Polyethylenenaphthalate	22.9	0.71	16
Polyetheretherketone	21.3	0.72	15
Polyethersulfone	22.4	0.9	20
Epoxy Thermoset	21.3	1.0	21
Cyanate Ester Themoset	22.8	1.3	30
Polybenzimidazole	16.2	1.5	24
Polyimide	12.0	1.30	16
Polyetherimide	16.7	0.82	14
Polyamideimide	19.3	1.63	31
		Average:	21
		Standard Deviation:	±6

Richard Lyon, ATO-P, (609) 485-6076

FAA Simplified Inerting System Flight Test

Significant emphasis has been placed on preventing fuel tank explosions since the TWA Flight 800 accident in July 1996. Extensive development and analysis have illustrated that fuel tank inerting could potentially be cost-effective if air separation modules (ASM), based on hollow-fiber membrane technology, could be employed in an efficient manner. To illustrate this, the FAA, with the assistance of several aviation-oriented companies, developed an onboard inert gas generation system with ASMs that use aircraft bleed air to generate nitrogen-enriched air at varying flow and purity (oxygen concentration) during a commercial transport airplane flight cycle. Figure 1 gives a block diagram illustrating the primary components of the FAA inerting system.

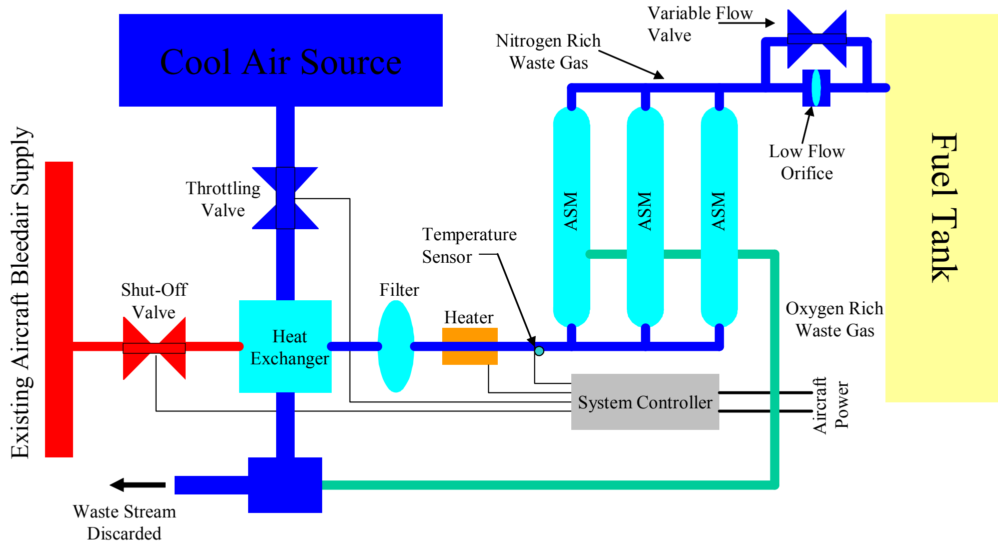


Figure 1. FAA Simplified Inerting System Block Diagram

The FAA performed a series of ground and flight tests designed to prove the simplified inerting concept that is being proposed by the FAA. The FAA-developed system was mounted in the cargo bay of an A320, operated by Airbus for the purposes of R&D, and used to inert the aircraft center wing tank (CWT) during testing, as shown in figure 2. The system and CWT were instrumented to analyze the system performance and the inerting capability. The FAA onboard oxygen analysis system was used to measure the oxygen concentration in the fuel tank continuously during the testing of the inerting system, which was operated using only one or two of its three ASMs.

Figure 2. Inerting System Mounted in A320 Cargo Bay

The primary variables during the 10 hours of flight-testing were the CWT fuel load and the system operational methodology. The results of the tests indicated that the concept of the simplified inerting system is valid and that the ASM dynamic characteristics were as expected. ASM pressure had the expected effect on the on-flow rate, and the dual-flow performance was predictable. Bleed air consumption was greater than expected during the cruise phase of flight.

The fuel tank inerting results shown in figure 3 illustrate that no stratification or heterogeneous oxygen concentrations occurred in the tank for the inerting tests performed, in part due to the essentially rectangular box configuration of the tank, allowing easy distribution of the inert gas. A simple analytical model of the inerting process, developed by the Fire Safety Branch, illustrated good agreement with the measured data. When a single ASM was used during an entire flight cycle with a high rate of descent, the measured effect of the high-flow mode was significant, allowing the system to maintain an inert ullage (less than 12%). When the high-flow mode was not used, the ullage reached a peak of 15% oxygen by volume. The amount of fuel in the tank had virtually no effect on the resulting oxygen concentrations measured in all the tests.

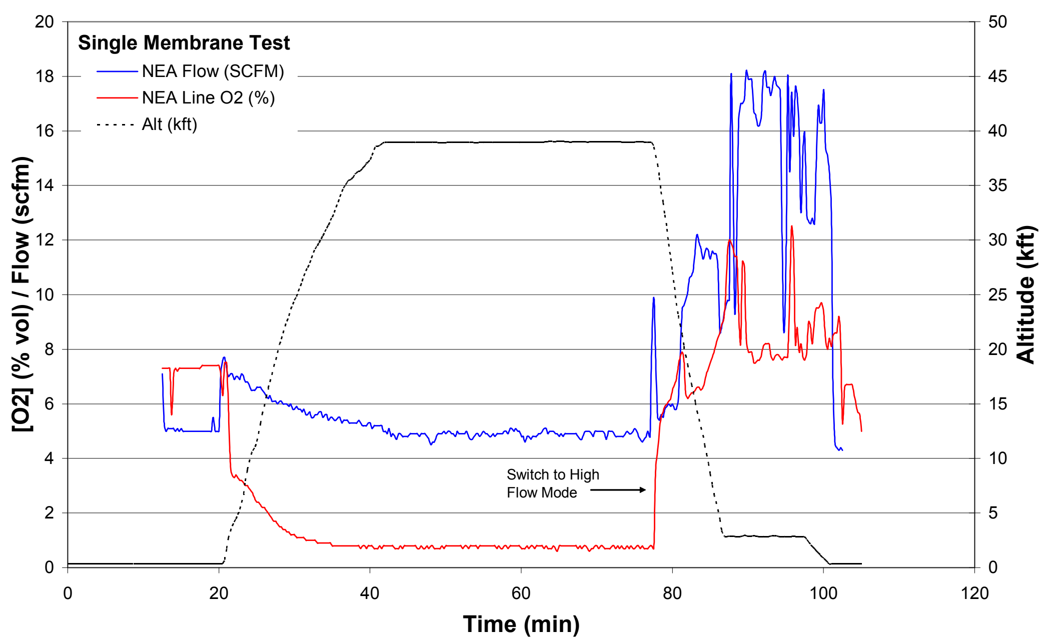


Figure 3. FAA Simplified Inerting System Measured Performance

William Cavage, ATO-P, (609) 485-4993

Flammability Assessment of Primary Lithium Batteries

Primary lithium batteries are a popular power source for many small electronic appliances. Primary lithium batteries, as shown figure 1, are defined as nonrechargeable, single-use batteries.

Figure 1. CR2 and PL123A Primary Lithium Batteries

The batteries are packed in bulk-corrugated cardboard containers, stacked on pallets, and shipped in the cargo holds of passenger and cargo aircraft. Thirty thousand batteries or more may be contained on a single pallet. The packaging allows close contact between individual batteries in each row with only thin cardboard separating the rows. The packaging itself is flammable. There has never been a known in-flight fire associated with shipping the batteries in this manner; however, a ramp incident involving palletized batteries has drawn attention to the flammability hazard of primary lithium batteries.

The ramp incident occurred at the Los Angeles International Airport in April 1999. A pallet of batteries caught fire while being handled between flights. There was no known external ignition source. The nature of lithium fires makes them very difficult to extinguish. All common fire-extinguishing agents are ineffective in controlling a lithium fire, including the onboard Halon 1301 fire suppression systems installed in aircraft cargo compartments. Based on this incident, the Fire Safety Branch was asked to conduct a series of flammability tests on primary lithium batteries.

The flammability tests were conducted to assess the flammability characteristics of primary lithium batteries and the potential hazard associated with shipping them on transport aircraft.

A relatively small fire source was found to be sufficient to start a primary lithium battery fire. The outer plastic coating easily melts and fuses adjacent batteries together and then ignites, contributing to the fire intensity. The burning plastic coating helps raise the battery temperature to the self-ignition temperature of lithium. Once the lithium in a single battery begins to burn, it releases enough energy to ignite adjacent batteries. The propagation continues until all batteries have been consumed.

Halon 1301 is ineffective in suppressing or extinguishing a primary lithium battery fire, though it extinguishes any burning packaging materials.

The air temperature in a cargo compartment that has had a fire suppressed by Halon 1301 can still be above the autoignition temperature of lithium. Because of this, the batteries that were not involved in the initial fire can still ignite, and the fire can propagate.

The ignition of a primary lithium battery releases burning electrolyte and a molten lithium spray. Depending on its thickness, the cargo liner material may be vulnerable to perforation by the molten lithium. The perforation of the cargo liner can allow the Halon 1301 fire suppressant agent to leak out of the compartment, reducing the agent concentration within the cargo compartment and the effectiveness of the agent. Holes in the cargo liner may also allow flames to spread outside the compartment.

The ignition of primary lithium batteries creates a pressure pulse that can raise the air pressure within the cargo compartment. The ignition of only a few batteries was sufficient to increase the air pressure by more than 1 psi in an airtight pressure vessel with a volume of 10 cubic meters. Cargo compartments are only designed to withstand approximately a 1-psi pressure differential. The ignition of a bulk-packed primary lithium battery shipment may compromise the integrity of the compartment by activating the pressure relief panels. The opening of the pressure relief panels has the same effect as perforations in the cargo liner, allowing the Halon 1301 fire suppressant to leak out, reducing its effectiveness.

In summary, the presence of a shipment of primary lithium batteries can significantly increase the severity of an in-flight cargo compartment fire. An FAA technical report, "Flammability Assessment of Bulk-Packed, Nonrechargeable Lithium Primary Batteries in Transport Category Aircraft," DOT/FAA/AR-04/26, Webster, H., was published in June 2004 and describes tests conducted by the Fire Safety Branch to assess the danger posed to passenger and cargo aircraft by the shipment of bulk-packed primary lithium batteries.

Harry Webster, ATO-P, (609) 485-4183