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Improvements in Aircraft Fire Safety Derived From FAA Research Over the Last Decade

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16. Abstract

This technical note is an overview of Federal Aviation Administration (FAA) fire safety research over the past 10 or more years, with a focus on in-flight fire safety. The technical note emphasizes research accomplishments that have been, or are being, implemented into commercial aviation, as well as other important fire safety research. The research was driven by fatal accidents and safety concerns associated with new technology, such as:

1. Hidden fire protection research led to the development of an improved fire test method for thermal acoustic insulation, which became a new FAA requirement, and the issuance of airworthiness directives to remove certain flammable insulation.
2. A practical and cost-effective fuel tank inerting system was developed, enabling FAA to issue a regulation requiring flammability reduction in heated center wing fuel tanks. Related studies addressed the limiting oxygen concentration required to prevent a fuel tank explosion and fuel tank flammability.
3. A new test method was developed and mandated by the FAA that measures the burnthrough resistance of thermal acoustic insulation during a postcrash fuel fire.
4. Hazardous materials research led to the adoption of new regulations and advisory material to provide safeguards for the shipment of oxygen generators/cylinders, lithium batteries, and aerosol cans.
5. Research findings on structural composites were employed during the certification of the Boeing 787 to provide safety against a hidden in-flight fire, postcrash fire fuselage burnthrough resistance, and fuel tank flammability.
6. Minimum performance standards were developed for halon replacement agents in lavatories, hand-held extinguishers, engines and cargo compartments, and the effectiveness and safety of replacement agents was evaluated.
7. Long-range fire safety research identified promising new ultra-fire-resistant polymers and improved the science for experimental and theoretical evaluation of material fire performance.

In summary, FAA fire safety research over the past decade (2000-2010) developed technology that resulted in the adoption/issuance of five final regulations, two Airworthiness Directives, two Advisory Circulars, and two Safety Alerts for Operators, which are expected to significantly improve aircraft fire safety. In addition, this research also supported the certification of the all-composite fuselage, new Boeing 787 to ensure a high level of fire safety and the replacement of halon extinguishing agents and made important gains in characterizing and predicting the burning behavior of polymers and in developing ultra-fire-resistant interior materials.

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LIST OF ACRONYMS

AC	Advisory Circular
AD	Airworthiness Directives
BPA	Bisphenol-A
BPC	Bisphenol-C
CSTA	Chief Scientist and Technical Advisor
CWT	Center wing tank
DDE	Dichlorodiphenylethene
FAA	Federal Aviation Administration
GBI	Ground-based inerting
HVAC	Heating, ventilation, and air conditioning
ICAO	International Civil Aviation Organization
LOC	Limiting oxygen concentration
MPS	Minimum Performance Standard
MCC	Microscale combustion calorimeter
NASA	National Aeronautics and Space Administration
NEA	Nitrogen-enriched air
NFS	Nacelle fire simulator
NTSB	National Transportation Safety Board
OBGBI	Onboard ground-based inerting
OBIGGS	Onboard Inert Gas Generating System
OBOAS	Onboard oxygen analysis system
PET	Polyethyleneteraphalate
PHMSA	Pipeline and Hazardous Materials Safety Administration
PI	Polyimide
PVF	Polyvinyl fluoride
SAFO	Safety Alert for Operators
SCA	Shuttle Carrying Airplane

EXECUTIVE SUMMARY

This technical note is an overview of Federal Aviation Administration (FAA) fire safety research over the past 10 or more years, with a focus on in-flight fire safety. The technical note emphasizes research accomplishments that have been, or are being, implemented into commercial aviation, as well as other important fire safety research. The research was driven by three fatal accidents—ValuJet (1996), a cargo compartment fire caused by the improper shipment of oxygen generators; TWA Flight 800 (1996), a center wing fuel tank explosion; and Swiss Air (1998), a hidden fire above the cabin/cockpit ceiling. The research was also extended to fire safety concerns associated with new technology such as composite structure and lithium batteries.

Hidden fire protection research concentrated on more stringent fire test methods for materials (e.g., insulation, wiring, and air-conditioning ducts) found in hidden areas. An improved fire test method was developed for thermal acoustic insulation, which became a new FAA requirement that was supported by an advisory circular for insulation fasteners and tape. After tests showed that two particular types of insulation covers could be ignited with a small electrical arc, the FAA issued airworthiness directives to remove these flammable materials. Improved fire test methods were also developed for electrical wiring and air-conditioning ducts. Tests were also conducted to examine the effectiveness of hand-held extinguishers using ports to access hidden fires above the cabin ceiling.

Major research was conducted by the FAA to protect against fuel tank explosions, driven largely by the TWA Flight 800 accident. Initial research was on a ground-based inerting system concept followed by an onboard ground-based inerting system with the capacity to also inert the cargo compartment. The ground-based inerting technology led to the development of a practical and cost-effective onboard fuel tank inerting system that would provide protection throughout the entire ground/flight profile. This important technology, which was demonstrated by flight tests, supported a major regulation requiring flammability reduction in heated center wing fuel tanks. A critical related study addressed the limiting oxygen concentration required to prevent a fuel tank explosion, which had a major impact on the size and complexity of the inerting system. Research was also conducted to better understand and predict fuel tank flammability.

A new test method was developed that measured the burnthrough resistance of thermal acoustic insulation during a postcrash fuel fire. The FAA specified the test in a final rule that contained a new requirement for burnthrough-resistant insulation. In addition, to support the effective implementation of the rule, an advisory circular was developed to provide guidance on installation details and techniques for thermal acoustic insulation.

Hazardous materials research led to the adoption of new regulations and advisory material. FAA tests led to a ban on the shipment of chemical oxygen generators in passenger-carrying aircraft cargo compartments. Later, a test standard was developed and adopted for shipping containers that protect oxygen storage devices from being activated during a suppressed cargo fire. Testing revealed the explosive hazards of aerosol cans involved in a cargo compartment fire and the effectiveness of halon, leading to an FAA mandate to retrofit transport aircraft with cargo compartment fire detection and extinguishing systems. The FAA has also examined the fire

hazards of lithium batteries. Since primary (nonrechargeable) batteries involve burning lithium metal, their shipment as bulk cargo has been banned on passenger carrying airplanes because the halon fire suppression system in cargo compartments was found to be ineffective against a primary battery fire. Conversely, it was found that burning lithium ion (chargeable) batteries involve a hydrocarbon electrolyte fire, which can be extinguished with halon; however, water must also be used to cool down and prevent the hot batteries from re-igniting, which would be a great concern during a laptop fire in the cabin. Perhaps the finding that raises greatest concern is that thermal runaway (self-ignition) of a single primary or ion battery shipped in a typical cardboard box will spread to the remaining batteries.

Research findings on structural composites were employed during the certification of the B-787 to ensure safety against a hidden in-flight fire, fuselage burnthrough resistance, and fuel tank vapor flammability. In addition, FAA developed a test method to measure the in-flight fire resistance of composite fuselage structure. A second test method was also developed to measure the postcrash fire burnthrough (penetration) resistance and the production of toxic gases that accumulate within the cabin. Overall, the carbon fiber/epoxy composite fuselage material displayed superior fire burnthrough (penetration) resistance and relatively good fire resistance. Heating and cooling experiments on fuel tanks showed that a composite tank is more flammable than a typical aluminum tank when heated by the sun, but both types of tanks cooled down quickly under simulated flight conditions and became nonflammable.

Minimum performance standards (MPS) were developed for halon replacement agents in lavatories, hand-held extinguishers, engines and cargo compartments, and the effectiveness and safety of replacement agents was evaluated. Lavatory extinguishers containing replacement agents qualified by MPS tests are being installed in newly manufactured aircraft. FAA also developed an updated advisory circular for hand-held extinguishers with guidance for the selection of halon replacement agents. MPS tests in FAA's unique engine nacelle fire simulator identified two promising agents earmarked by Boeing and Airbus for new aircraft models. However, the only approach that passed the MPS for cargo compartments was a water mist/nitrogen gas hybrid system concept that would require significant development.

Long-range fire safety research identified promising new ultra-fire-resistant polymers and improved the science for experimental and theoretical evaluation of material fire performance. Various polymers based on bisphenol-C, a chlorinated chemical building block, were synthesized and evaluated, demonstrating a marked reduction in flammability with no reduction of thermal and mechanical properties. However, because of environmental and health concerns associated with halogens (i.e., chlorine) in plastics, FAA is pursuing and supporting the development of non-halogen, fire-safe plastics. FAA researchers developed, patented, and licensed (for commercial manufacture) a microscale combustion calorimeter to measure the flammability of milligram-sized samples. In addition, a numerical pyrolysis model called ThermaKin was developed to provide a practical tool for prediction, analysis and/or extrapolation of the results of material fire tests.

In summary, as detailed in this report, FAA fire safety research over the past decade (2000-2010) developed technology that resulted in the adoption/issuance of five final regulations, two Airworthiness Directives, two Advisory Circulars, and two Safety Alerts for Operators, which are expected to significantly improve aircraft fire safety. In addition, this research also supported the certification of the all-composite fuselage, new Boeing 787 to ensure a high level of fire safety and the replacement of halon extinguishing agents and made important gains in characterizing and predicting the burning behavior of polymers and in developing ultra-fire-resistant interior materials.

INTRODUCTION

Commercial aviation has experienced steady improvements in safety in recent years. The likelihood of an accident resulting in a “hull loss” (destruction of the airplane) in western-built commercial jet transports has been reduced to about 1 in 2 million flights, although the improvement appears to have leveled off [1]. Moreover, when accidents occur, the chances for survival have also improved dramatically. Based on an analysis of worldwide accidents, the probability of dying in a survivable accident has decreased by a factor of two over a 30-year period [2]. This increased survivability rate is due, in large part, to the improvements in aircraft fire and impact survivability that has been implemented through the regulatory process resulting from research conducted by the Federal Aviation Administration (FAA). In 2000, an article was published in *Fire Protection Engineering* that reviewed FAA fire research and regulatory accomplishments over a 20-year period [3]. Most of the improvements described in that article enhanced postcrash fire survivability.

This report is an overview of FAA research since the 2000 *Fire Protection Engineering* article. It covers the past 10 or more years, which focuses more on in-flight fire safety. It emphasizes accomplishments that have been, or are being, implemented into commercial aviation, and addresses other important fire safety research, as well. As in the past, FAA research is driven by accidents and incidents, new technology, and new aircraft designs. In particular, the following tragic in-flight accidents, which caused the destruction of the aircraft and the loss of all passengers and crew members, were major drivers for this research.

- ValuJet DC-9, 5/11/96, 110 fatalities—The aircraft caught fire shortly after takeoff from Miami and crashed in the Everglades. The accident was attributed to the improper shipment of chemical oxygen generators in the cargo compartment.

- TWA B-747, 7/17/96, 230 fatalities—The aircraft exploded shortly after takeoff from New York and crashed off the coast of Long Island. The accident was attributed to the explosion of the center wing tank (CWT).

- Swiss Air MD-11, 9/2/98, 229 fatalities—The aircraft caught fire after takeoff from New York and crashed off the coast of Nova Scotia. The accident was attributed to an electrical problem in the in-flight entertainment system, located above the ceiling in the aft cockpit and forward cabin.

The newest Boeing airplane—the 787—has numerous innovations, including the construction of the fuselage and wings with lightweight, noncorrosive composite materials. The replacement of noncombustible aluminum alloy structure with graphite epoxy composite raised concerns regarding fire safety in both the in-flight and postcrash environments. How the epoxy resin would behave in an aircraft fire was of interest because past studies have shown epoxies to be relatively flammable and heavy smoke producers. Although still in the early stages of evaluation, new fire-resistant, lightweight magnesium alloys are being considered as a replacement for aluminum in seat structure and possibly air-conditioning ducts. Another rapidly expanding technology that has fire safety implications are lithium batteries and cells that are being produced with increasing energy densities. Lithium batteries are carried onboard by passengers in their laptops or cell phones, stowed in passenger luggage in the cargo compartment, used in aircraft emergency battery systems, and shipped in large quantities as cargo in freighter aircraft.

The following sections describe FAA fire research activities and accomplishments over the past 10 years.

HIDDEN FIRE PROTECTION.

FAA regulations require that large commercial transport aircraft have fire detection and extinguishment/suppression systems in the engine nacelles and cargo compartments because of the potential for fire in these inaccessible areas. Similarly, lavatories have a number of required fire safety design features, including smoke detectors and a fire-hardened design of the waste paper receptacle unit, which also contains a built-in fire extinguisher. When smoking was permissible in transport aircraft, lavatory waste paper receptacles were the origin of several fatal in-flight fires. Today, the greatest concern is an in-flight fire originating in a hidden area of the cabin or cockpit, such as above the ceiling or under the floor, whose location cannot be determined by the crew members, as in the Swiss Air MD-11 accident. Usually, a fire of unknown origin is sensed in the cabin or cockpit as visible smoke or by a burning odor. In 2006, there were over 800 incidents of smoke or odor in the cabin or cockpit. Although most of these incidents were not fire related, in 34% of those cases, the aircraft were diverted or returned to the departure airport, imposing risks and financial losses to the airline. Pilots are trained to land the aircraft at the nearest airport whenever there is an apparent fire of undetermined origin [4].

Thermal Acoustic Insulation. The primary fire load in aircraft hidden areas is thermal acoustic insulation; heating, ventilation, and air conditioning (HVAC) ducts; and electrical wires and cables. Since insulation blankets line the entire fuselage shell to attenuate noise and provide thermal insulation, it is the predominant hidden material in terms of surface area. Invariably, a hidden in-flight fire involves the thermal acoustic insulation (figure 1). Consequently, the FAA focused its initial hidden fire protection research on insulation blankets, which are comprised of fiberglass batting encapsulated within a thin plastic film. Moreover, previous tests had shown that the FAA-required vertical Bunsen burner flammability test produced erratic results between different test laboratories and marginal pass/fail results for the insulation film, an aluminum-coated (metallized) polyethyleneteraphalate (PET), on the Swiss Air MD-11 accident aircraft [5].

Figure 1. Hidden In-Flight Fire Incident Involving Thermal Acoustic Insulation

A series of large-scale fire tests were conducted on different types of insulation blankets in an open-ended mock-up of the attic area above the passenger cabin ceiling. This scenario was selected because small-scale tests demonstrated that insulation films would ignite and propagate flame in a confined space. By contrast, it is very difficult to ignite a thermoplastic film with a stationary flame in an open space because most of the films are thermoplastics, which tend to melt and shrink away from the flame. In a confined space, ignition and flame propagation can occur because of feedback of radiant heat and containment of melted film. It was apparent that the attic area has a number of confined spaces covered with insulation that may be prone to ignition and flame spread. A relatively severe ignition source was used for the test, consisting of a urethane foam block soaked with hexane. (It was adopted as the fire threat standard for the evaluation of HVAC ducting and wiring and cables.) In general, the PET films were the most flammable, but the more fire-resistant films, such as polyvinyl fluoride (PVF) and polyimide (PI), prevented flame propagation [6 and 7].

The next step was to develop an improved flammability test method for thermal acoustic insulation with pass/fail criteria that would identify materials capable of resisting a severe ignition source (urethane foam block). In seeking a new fire test method for insulation films, several candidate tests were considered and evaluated. The radiant panel test method for flooring materials gave a good correlation with large-scale fire test data [8]. In this test, the material was ignited with a pilot flame while being heated with a radiant panel. The criterion that was adopted is stringent, disallowing any flaming beyond a 2-inch length from the point of flame application or continued flaming after removal of the pilot flame.

Electrical arc testing was an important part of this program due to the number of reported incidents involving flame spread on thermal acoustic insulation blankets caused by electrical failures, such as short circuits. The types of thermal acoustic insulation blankets were subjected to 115- and 208-volt electrical arcing tests. The data showed that the metallized PET blankets consistently ignited with significant flame spread at both voltages. In contrast, the PI and metallized PVF blankets did not ignite at either voltage; the non-metallized PET blankets ignited at both voltages, but with minimal flame spread and self-extinguished within seconds. Thus, the metallized PET blanket was the only insulation blanket that consistently ignited and experienced significant flame spread when subjected to an electrical arc [9].

On May 26, 2000, the FAA released two Airworthiness Directives (AD) that required the replacement of metallized PET used in insulation blankets on over 700 aircraft [10 and 11]. The ADs were a direct result of FAA tests that showed the vulnerability of metallized PET when exposed to an electrical arc as well as ground and in-flight fire incidents. Also, Federal Aviation Regulations were improved by requiring the new radiant panel test method and criteria for thermal acoustic insulation, which replaced the Bunsen burner test method [12]. (The regulation was also made applicable to damping system materials.) After September 2, 2005, any large transport aircraft manufactured in the United States was required to be lined with insulation blankets compliant with the radiant panel test criteria. A radiant panel test methodology was also developed to evaluate the insulation tape and “hook and loop” methods used to install the insulation blankets, which were found to contribute significantly to the insulation blanket’s flammability. The test method was issued in an Advisory Circular (AC) in 2005 [13]. In 2008, another AD was adopted to require the replacement of another PET-made insulation blanket, the AN-26, because of its vulnerability to ignition and fire spread from an electrical arc or spark [14].

HVAC Ducting and Electrical Wiring. Improved fire test methods were developed for HVAC ducting and electrical wiring, which are material systems used in relatively large quantities in hidden areas and which constitute a significant fire load. Similar to thermal acoustic insulation, large-scale fire tests using the foam block ignition source demonstrated that the FAA Bunsen burner fire test requirement did not always discriminate between poor- and well-performing materials [15 and 16]. Nevertheless, aircraft wiring was found to be highly fire-resistant despite of the deficiencies of the Bunsen burner test. (However, nonaircraft wiring, which was compliant with the Bunsen burner test, was found to be flammable under realistic fire test conditions.) Some types of aircraft ducting were found to be flammable, apparently because ducting is heavier than either insulation or wiring and, if ignited, can produce high levels of heat release. For both applications, a modified version of the radiant panel fire test was shown to give a reasonably good correlation with large-scale fire test results [17 and 18]. At this writing, the improved fire tests are not yet an FAA requirement.

Active Fire Extinguishment. The FAA requires the use of hand-held extinguishers to fight in-flight cabin fires. In the past, a number of incidents have occurred where Halon 1211 hand-held extinguishers were successfully used by the cabin crew to extinguish hidden in-flight fires. In some of these incidents, the agent was discharged through an available opening, such as an air return grill, but in others, a hole was cut in the overhead paneling using a passenger’s pen knife in one case and a crash axe in another. The use of cutting devices to access hidden areas for fighting a fire is highly problematic since 9/11. Following an analysis of a number of in-flight fires, the National Transportation Safety Board (NTSB) issued several recommendations to the FAA, including the issuance of an AC to improve crew member training in fighting hidden fires (Recommendation A-01-83) and the development of a means of accessing in-flight fires to improve the effectiveness of firefighting (Recommendation A-01-86) [19].

In response to the NTSB recommendation, the FAA developed and issued an AC entitled “In-Flight Fires” [20]. It contains valuable information for the crew in dealing with hidden in-flight cabin fires. A complementary training video was developed to enhance the information presented in the AC. It discusses the importance of recognizing hidden in-flight fires and the conditions associated with them. It stresses taking immediate and aggressive action to locate the fire source, gaining access to it, and effectively applying an extinguishing agent. The FAA issued the training video in an Information for Operators [21].

A preliminary series of tests were conducted to examine the use of ports, openings in the cabin ceiling, to allow the discharge of Halon 1211 hand-held extinguishers into the attic area. Not surprisingly, it was shown that ports could be effective in the relatively small volume that exists in a standard-body aircraft (e.g., a B-737 or A320); but in a wide-body aircraft (e.g., a B-747), this approach would not be effective because the agent is diluted by the large volume of the attic area [22]. Additionally, to make the ports practical and effective in a standard-body aircraft, a detection system would be needed to locate the fire, and the ports would have to be spaced to optimize the effectiveness of the available extinguishers.

FUEL TANK EXPLOSION PREVENTION.

A major research program was conducted by the FAA to protect against fuel tank explosions. It was largely driven by TWA Flight 800 and two other fatal CWT explosions; viz., B-737, Manilla, 1990 and B-737, Bangkok, 2001. The three accidents had striking similarities—the explosions occurred in near-empty, heated CWTs on a hot day after the air-conditioning system had been running for an extended period of time. It was determined that the hot engine bleed air, which is ducted beneath the CWT, heated the small amount of residual fuel in the tank, creating a flammable fuel vapor mixture in the ullage space. In all three cases, the ignition source that triggered the explosion could not be determined.

Fuel tank inerting is a concept used by the military to protect against fuel tank explosions caused by gunfire and incendiary rounds. Inerting takes place when the ullage space is rendered incapable of propagating a reaction given the presence of a flammable mixture and an ignition source. In large military cargo aircraft, inerting is achieved by using gaseous nitrogen to dilute the concentration of oxygen in the ullage to a level that cannot support combustion. However, the technology for storing/generating the nitrogen, cryogenic nitrogen in the C-5A and the hollow fiber membrane in the C-17, was used in a manner that resulted in a large weight penalty and poor system reliability, which made the direct application of these approaches impractical for civil aviation.

Ground-Based Inerting. For the reasons outlined above, ground-based inerting (GBI) was the initial concept examined for civil aircraft fuel tank protection. Briefly, the GBI concept involved piping nitrogen into the CWT before each flight while the aircraft was parked at the gate. Protection would be provided on the ground and during ascent, which appeared to be the most critical stages based on the aforementioned accidents. A detailed cost analysis corroborated an earlier advisory committee determination that GBI would likely be cost-effective [23]. The FAA then addressed several issues that required resolutions before GBI flight tests could be undertaken. One issue was the quantity and purity of the nitrogen-enriched air (NEA) required to inert a vented aircraft fuel tank. Based on tests conducted in a quarter-scale model of a simple fuel tank, it was shown that the NEA requirements could be determined from a simple model [24]. Later, additional model experiments in a compartmentalized fuel tank, similar to a B-747 fuel tank, also showed that a more sophisticated theoretical model could reasonably predict the NEA requirements. Moreover, it was shown that depositing NEA at a single point in the tank effectively distributed the inert gas throughout the multicompartmented fuel tank [25]. The FAA also developed an onboard oxygen analysis system (OBOAS), an accurate and safe eight-channel instrument to measure the concentration of oxygen in a fuel tank during flight tests [26]. This unique instrument was successfully used during the GBI flight tests and four subsequent fuel tank inerting flight test programs. The GBI flight and ground tests, conducted in a B-737-700 by Boeing with FAA support, showed that the oxygen concentration in the fuel tank remained somewhat constant under quiescent conditions. However, modifications of the Boeing cross-venting system was required under certain wind conditions on the ground or cross-flow conditions in flight to prevent the loss of inerting capability [27].

Onboard Inerting. The concept of an onboard ground-based inerting (OBGBI) system was the next approach pursued because industry concluded that a dedicated mechanic would be required to inert every commercial aircraft before flight with a GBI, raising the costs significantly. A team of FAA and industry experts designed an OBGBI, which also had the capability of suppressing a cargo compartment fire, in an attempt to reduce overall costs [28]. The OBGBI was designed for and installed in the FAA B-747SP, a fully operational but nonflyable aircraft specifically purchased for the inerting program. It evolved into a more practical and effective full inerting system, the Onboard Inert Gas Generating System (OBIGGS), which was capable of providing protection throughout the entire flight and ground profile, based on an approach conceived by the FAA Chief Scientist and Technical Advisor (CSTA) for Fuel Systems [29].

The FAA-developed OBIGGS is a simple, lightweight, and practical system that utilizes available engine bleed air to continuously provide NEA to inert the CWT (figure 2). The NEA is generated by the Air Separation Modules, which contain hollow fiber membranes capable of separating nitrogen from oxygen in air. A principle called selected permeation separates fast gases (e.g., oxygen), which more readily dissolve and permeate through the membrane wall, from slow gases (e.g., nitrogen), which have a greater tendency to remain within and flow down the length of the fiber. However, the critical feature of the FAA OBIGGS was a dual-flow capability—low flow rate, high NEA purity during ground, ascent, and cruise conditions and high flow rate, low NEA purity compatible with the required inerting concentration during descent. Other components include a heat exchanger for reducing the bleed air temperature to a value that can be tolerated by the membranes, a filter to eliminate contaminants from the bleed air, and a means of disposing the oxygen-enriched air overboard. Because there are only a few moving parts, the FAA OBIGGS is very reliable. Moreover, the simple design ensures relatively low weight (about 160 pounds) and cost ($150,000-$200,000) for a B-747. The FAA OBIGGS was considered a “breakthrough” by the FAA Administrator and was viewed positively by the industry.

Modeling computations performed by the CSTA predicted the FAA OBIGGS would provide the required protection [29]. However, aircraft flight tests were needed to corroborate the predictions and more conclusively demonstrate its capability throughout an aircraft operational envelope. The FAA OBIGGS was initially tested in an Airbus A320 and later in the National Aeronautics and Space Administration (NASA) B-747 Shuttle Carrying Airplane (SCA). A series of ground and flight tests were conducted in the A320 with the FAA OBOAS used to measure the concentration of oxygen at eight CWT locations [30]. The impressive results from one test are shown in figure 3. Since the measured oxygen concentrations at eight locations coincided, the ullage air mixture was homogeneous. At the low-flow NEA setting, during ground, ascent, and cruise, the oxygen concentration continuously decreased. At the onset of descent, the NEA flow rate was set at the high setting. The oxygen concentration increased as air rushed into the CWT during descent; however, the higher NEA flow rate was great enough to prevent the oxygen concentration from exceeding the limiting oxygen concentration (LOC) of 12%, which is the level required to prevent a chemical reaction and explosion (see discussion on limiting oxygen concentration). It was evident from the flight tests that the OBIGGS was effective and performed, essentially, as expected.

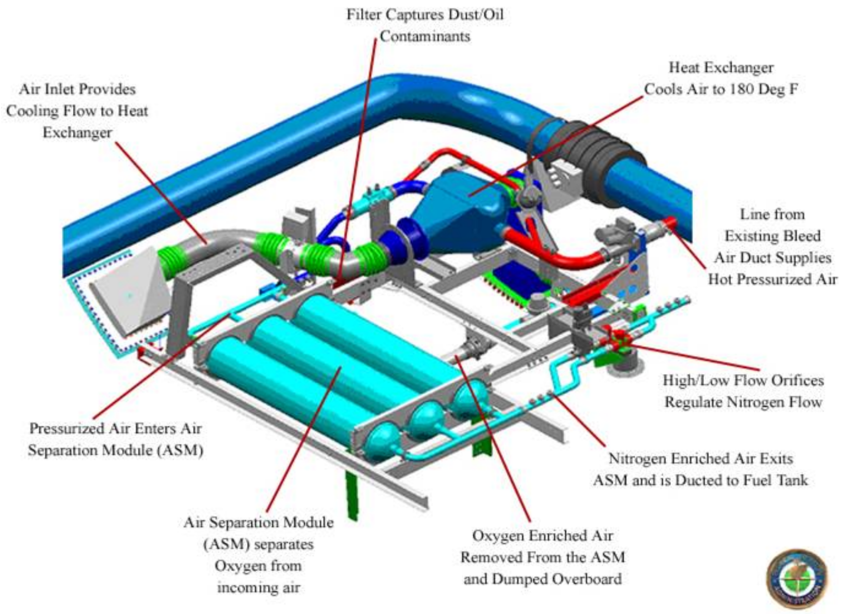

Figure 2. The FAA OBIGGS

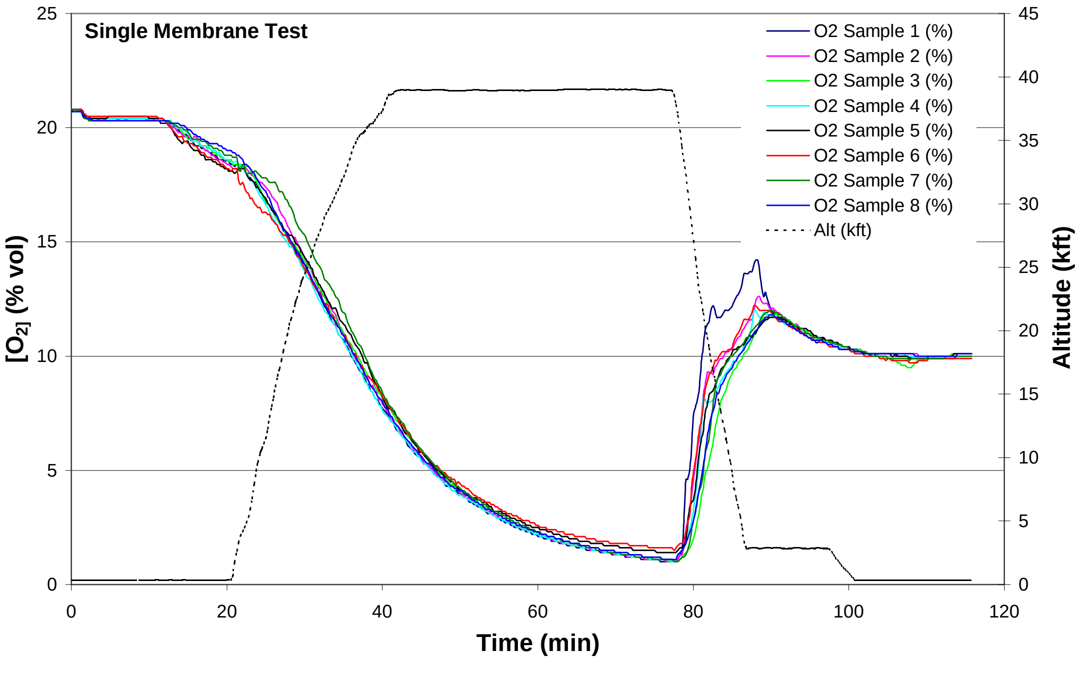

Figure 3. The A320 Oxygen Concentration Histories in CWT

The OBIGGS was installed in the NASA B-747 SCA at a location aft of the CWT in the lower quadrant of the fuselage (figure 4) [31]. The results were again largely predictable, but unlike the A320, there were variations in oxygen concentrations between the six bays in the large CWT. Additionally, the flammability of both the CWT and one inboard wing fuel tank was measured; it is believed this had never been done before. The flammability data showed that the heated CWT was more flammable than the wing tank.

Figure 4. The FAA OBIGGS Installed on NASA B-747 SCA

Jet Fuel Flammability and the LOC. Jet fuel is a complex mixture comprised of hundreds of hydrocarbon compounds whose properties are tightly specified by ASTM D 1655. The FAA assembled a team of combustion and fuel experts to investigate the flammability and explosiveness of jet fuel in aircraft fuel tanks that resulted in a number of interesting findings [32]. A simple and approximate measurement of fuel flammability is the flash point, which is the minimum fuel temperature at which the application of an ignition source causes the fuel vapor to ignite under a specified set of conditions. The specified flash point temperature in ASTM D 1655 of Jet A fuel used in commercial aviation is 100°F. An accurate prediction of when a fuel tank is flammable is problematic. Although methodologies exist for determining the relative probability of a flammable mixture, the flash point, fuel temperature, and altitude are varied [32].

A factor affecting fuel tank flammability is mass loading, which is the weight of fuel divided by the ullage volume. In TWA Flight 800, the residual amount of fuel in the CWT was about 50 gallons, corresponding to a mass loading of 3 kg/m^3. Research was conducted to determine if the residual amount of fuel could be reduced to a level that would prevent the creation of flammable mixture. Reduced-scale tests, conducted by the FAA, determined that a mass loading of 0.08-0.15 kg/m^3 would be required to substantially reduce fuel tank flammability [33]. Unfortunately, these values translated to the elimination of all but 1-2 gallons of fuel in a B-747 CWT, which was believed to be unattainable. The FAA also conducted similar experiments to examine the effect of cold fuel temperatures, such as those that would exist at altitude, on fuel tank flammability, demonstrating that the effect was significant at small mass loadings [34]. A model was subsequently developed that accounted for the effect of fuel vapor condensation on vapor ullage concentration [35]. Experiments conducted in an altitude chamber showed that the model gave reasonable agreement with experimental fuel vapor measurements for different flight profiles [36].

The LOC is the minimum concentration of oxygen in air that will allow the fuel vapors to burn. Normal air is 21% oxygen, which is well above the LOC for jet fuel, so a fuel tank explosion is possible under ambient conditions if an ignition source is present. It was the most critical parameter affecting the complexity and size and weight of an OBIGGS. For example, a very low LOC value could make an OBIGGS impractical—too heavy and unreliable because of its complexity. The FAA conducted tests in a simulated fuel tank to determine the LOC at various pressures corresponding to a range of altitudes. A flammable mixture of jet fuel was subjected to numerous ignition sources that had a range of spark intensities and durations. It was determined that the LOC was 12% at sea level to 10,000 feet, and increased approximately linearly thereafter to 14.5% at 40,000 feet [37 and 38]. The 12% value is consistent with LOC values in the literature for the hydrocarbon constituents of jet fuel. However, it is higher than the 9% value used in military transport aircraft outfitted with an OBIGGS, such as the C-5A and the C-17, apparently because of the more severe ignition threats (e.g., ground fire and incendiary rounds) and the imposition of a safety factor. The 12% LOC was an enabling factor in the development of a simple and cost-effective OBIGGS for commercial transport aircraft.

FAA Regulation to Prevent Fuel Tank Explosions. On July 21, 2008, the FAA issued a regulation entitled “Reduction of Fuel Tank Flammability in Transport Category Airplanes” [39]. Issuance of the regulation was made possible because of FAA research that resulted in the development of a simple and cost-effective OBIGGS. Boeing began installing OBIGGS, based on the FAA design, in production airplanes before the final rule notice was published [40]. It was estimated that the regulation would prevent 1-2 catastrophic fuel tank explosions over a 35-year period. Five thousand aircraft in the U.S. fleet would be impacted by the regulation, including 2700 in-service aircraft and 2300 production aircraft.

THERMAL ACOUSTIC INSULATION BURNTHROUGH RESISTANCE.

A new test method was developed to measure the burnthrough resistance of thermal acoustic insulation during a postcrash fuel fire [7]. Prior to this work, full-scale tests showed that improved insulation materials and barriers could substantially delay the penetration of an external fuel fire through the fuselage and into the cabin, providing significantly more time for passengers to escape during a survivable postcrash fire [41]. The new test method used an existing burner that is used to test seat cushions and cargo liners, but the operating conditions were altered so that the time of burnthrough measurements with the burner matched full-scale fire test results. Tests with the altered burner indicated that a variety of materials could provide the proposed 4 minutes of burnthrough protection, demonstrating the feasibility of this approach. The 4-minute value was based on an analysis of past accidents, which showed that the evacuation times varied considerably—depending on many factors—but rarely exceeded 5 minutes and accounted for the protection provided by the time to melt the aluminum fuselage. A thin, lightweight ceramic barrier was particularly effective, but pointed to the need for a radiant heat flux criteria as well, which was added to the requirement. A replacement burner, the Next Generation Burner, was also developed from readily available materials because the altered burner specified by FAA is no longer manufactured (figure 5) [42]. The Next Generation Burner proved to be an equivalent test method for measuring the burnthrough resistance of thermal acoustic insulation materials.

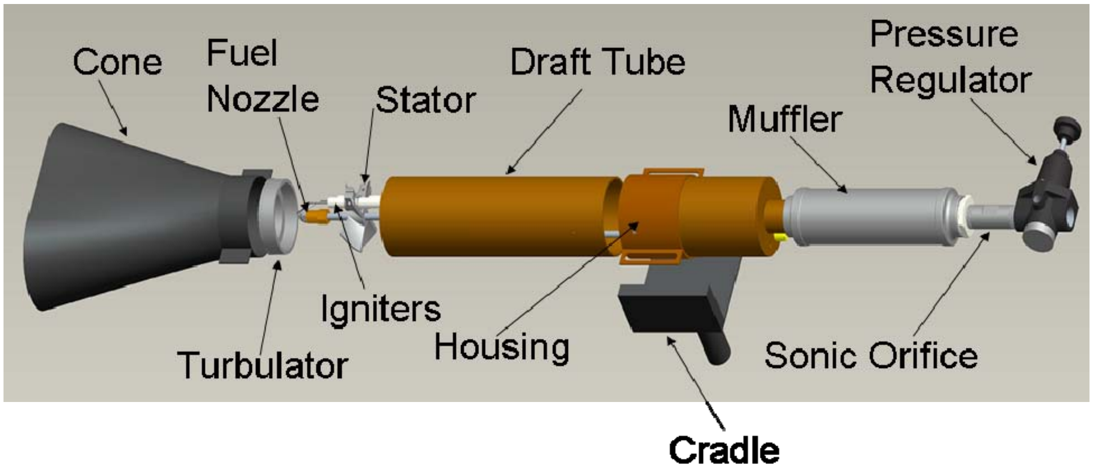

Figure 5. The FAA Next Generation Burner for Insulation Fuel Fire Burnthrough Resistance Evaluation

The FAA adopted a final rule that contained a new requirement for burnthrough resistance insulation installed in commercial transport aircraft. Newly manufactured aircraft were required to have burnthrough resistance after September 2, 2009 [12 and 43]. The burner test criteria developed by the FAA was used as the method of compliance. In addition, an AC was developed and published that provides guidance on the "installation details and techniques that have been found to be acceptable to realize the full potential of materials having satisfactory fire-resistant properties" [44]. The AC contains guidance on fasteners, overlapping, and testing of unique installation configurations. It also contains a description of the Next Generation Burner as an equivalent fire test method to demonstrate compliance with the rule.

HAZARDOUS MATERIALS FIRE SAFETY.

A threat to aircraft fire safety exists from hazardous materials, including oxygen, aerosol cans, and lithium batteries:

- The inadvertent discharge of oxygen has been the cause of a single fatal accident and numerous aircraft hull losses during ground servicing of the system, and has caused the significant intensification of a postcrash fire and, likely, passenger fatalities following a landing accident.

- Since aerosol cans, which are commonly carried in passengers' luggage contain hydrocarbon gases as propellants, an explosive reaction can occur if aerosol cans are involved in a cargo compartment fire.

- Lithium batteries/cells have become a fire safety concern because malfunctioning lithium batteries can experience thermal runaway (self-ignition), resulting in high temperatures, fire, and even explosive hazards. These batteries/cells are carried onboard by passengers in portable electronic devices, shipped in large quantities in the cargo compartment, and used in aircraft emergency battery systems.

Oxygen Systems. The ultimate potential fire hazard of aircraft oxygen systems was realized in the ValuJet accident (110 fatalities, 1996). The NTSB concluded that the probable cause of the accident was a fire in the cargo compartment that was “initiated by the actuation of one or more oxygen generators” [45]. At the request of the NTSB, the FAA recreated the ValuJet cargo compartment fire, which contained over 100 improperly shipped oxygen generators packed in five cardboard boxes. Activation of a single oxygen generator ignited the packing material, which, in turn, caused the remaining oxygen generators to activate, creating an intense fire with temperatures in excess of 3300°F [46]. The FAA also conducted small-scale fire tests to characterize the fire hazards of the oxygen generators [47 and 48]. The results of these tests showed that, to prevent oxygen generator activation during a suppressed cargo compartment fire, temperatures in the cargo compartment had to be maintained below 400°F [48].

Following the ValuJet accident, the Department of Transportation prohibited the shipment of chemical oxygen generators onboard passenger-carrying aircraft [49]. Furthermore, in tests conducted by the FAA, it was shown that a cargo compartment fire suppression system using Halon 1301 may not prevent activation of an oxygen cylinder due to overheating by a suppressed cargo compartment fire. The discharge of oxygen caused the suppressed fire to flare up and burn out of control, essentially defeating the halon fire suppression system [50]. Subsequent FAA tests demonstrated that “overpack” carrying cases used by the airlines to transport oxygen cylinders would delay the activation of the pressure release device during a suppressed cargo compartment fire. Moreover, even greater protection would be provided by overpacks fitted with additional thermal protection. Consequently, an overpack fire protection standard was recommended with two requirements: (1) thermal protection during a suppressed cargo compartment fire and (2) flame penetration protection before detection and discharge of halon [51]. The Pipeline and Hazardous Materials Safety Administration (PHMSA), the federal agency responsible for the safe transportation of hazardous materials, adopted a regulation with the aforementioned requirements for transporting oxygen cylinders in passenger-carrying aircraft, and oxygen cylinders and oxygen generators in freighter aircraft, which became effective on November 16, 2009 [52].

Aerosol Cans. The explosive hazards of aerosol cans involved in a cargo compartment fire and the effectiveness of halon in preventing an aerosol can explosion was previously reported [3]. These findings were a major factor in the FAA mandate to retrofit large commercial transport aircraft with cargo compartment fire detection and extinguishing systems in those aircraft lacking this protection, which comprised approximately 75% of the U.S. fleet [53]. By March 2001, the cargo compartments of 3483 airplanes were retrofitted with fire detection and suppression systems at a total cost of about $300 million.

Lithium Batteries. Due to their high-energy density and power capacity, malfunctioning lithium batteries can experience thermal runaway (self-ignition), resulting in high temperatures, fire, and even explosive hazards. The incident that initially raised concerns regarding the dangers of lithium batteries in aviation occurred at the Los Angeles International Airport in 1999. Two off-loaded pallets of lithium batteries from an incoming flight caught fire. It took airport firefighters about 25 minutes to extinguish the difficult fire. In 2006, the loss of a DC-8 freighter aircraft and most of its cargo, following an in-flight fire and emergency landing at Philadelphia International Airport, caused the NTSB to issue recommendations related to the safe shipment of lithium batteries. Most recently, in 2010, a B-747 freighter carrying a large quantity of lithium batteries experienced a fire in the main cargo compartment and crashed in Dubai, United Arab Emirates, killing both pilots and destroying the aircraft. Since 1991, the FAA and PHMSA have identified 44 air transport-related battery fire incidents, with the majority occurring on freighter aircraft [54].

The FAA conducted tests on two types of lithium batteries: primary (nonrechargeable) [55] and lithium ion (rechargeable) [56]. Thermal runaway of a single primary battery in a typical slotted cardboard box resulted in thermal runaway and ignition of the remaining batteries in the box (figure 6). This battery-to-battery propagation behavior also occurred with lithium-ion batteries. However, the primary batteries were found to be far more hazardous than the lithium-ion batteries because a primary battery fire involves burning lithium metal. The burning primary batteries often ejected their contents as molten lithium and caused overpressures that could breach the cargo compartment liner, raising the likelihood of the fire spreading to other areas of the aircraft. Of even greater concern was that Halon 1301, the fire-extinguishing agent used in aircraft cargo compartment fire suppression systems, had no observable effect on a primary battery fire [55]. Conversely, when a lithium-ion battery overheats, the flammable electrolyte vents (as designed) and ignites in the presence of an ignition source. However, Halon 1301 extinguishes the electrolyte fire and prevents re-ignition of the electrolyte at a concentration of 3%, which is the minimum concentration required to be maintained by a cargo compartment fire suppression system [56]. The primary battery test results revealed the inability of a halon fire suppression system to control a fire involving primary lithium batteries. In 2004, an Interim Final Rule was issued that prohibited the cargo shipment of primary lithium batteries on passenger-carrying aircraft [57].

Bulk Load Configuration Before Testing

Bulk Load Configuration After Testing

Figure 6. Thermal Runaway Propagation in Bulk-Loaded Lithium Batteries

The FAA also conducted shipping container tests to ascertain if they were capable of withstanding the effects of lithium batteries in thermal runaway [58]. Typical cardboard shipping boxes will burn and be consumed by lithium batteries in uncontrolled thermal runaway. Available robust shipping containers, such as metal pails and drums recommended by the International Civil Aviation Organization (ICAO), were ineffective against lithium primary battery fires because the build-up of pressure caused the sealed lid to fail and expel the burning batteries. However, burning lithium-ion batteries were contained when placed in a foil/ceramic-lined cardboard box designed to safely ship oxygen generators, as specified in the overpack regulation [52]. A preliminary performance standard for a lithium-ion cell shipping container was developed, which is partly based on the overpack regulation. The documented findings in reference 58 were the primary source of information for the FAA Safety Alert for Operators (SAFO) entitled, “Risks in Transporting Lithium Batteries in Cargo by Aircraft” [59].

Because of the preponderance of portable electronic devices powered by lithium-ion batteries onboard aircraft, particularly laptop computers, the FAA conducted tests to determine the best means of extinguishing a laptop fire. Transport aircraft are required to have at least two hand-held Halon 1211 extinguishers onboard. Similar to past results, although the halon extinguished the lithium-ion electrolyte fire, the halon was incapable of preventing the heating and ignition of adjacent batteries. Therefore, it was recommended that a water extinguisher, or a halon extinguisher followed by a cooldown with any available water or liquids, would be effective against this type of fire. The FAA issued an SAFO [60], describing the proper firefighting procedures, which referenced an FAA training video demonstrating these techniques.

Aircraft manufacturers are increasing the use of lithium batteries as power sources in aircraft. The FAA conducted tests to examine the fire hazards of rechargeable cylindrical lithium-ion batteries and polymer lithium-ion batteries. Test results showed that the polymer battery could be more hazardous in a fire because the electrolyte is released instantaneously through an opened seam compared to the cylindrical battery where the release is in a metered fashion through vent openings. The measured temperature and pressure was much higher with the polymer battery because of their greater energy density and power capacity [61].

Fuel Cells. Fuel cells are considered to be the portable electrical power source of the future with potential applications ranging from cell phones to aircraft auxiliary power units. A fuel cell is an electrochemical device that converts fuel and oxygen into electricity using fuel supplied in rechargeable or replaceable cartridges. The FAA conducted fire hazard tests on prototype cartridges (donated by industry) using a wide variety of chemistries. The tests demonstrated that the fire hazards varied significantly and depended on the fuel chemistry and cartridge material, demonstrating the fire safety advantages of specific fuel cell technologies [62].

STRUCTURAL COMPOSITE MATERIALS.

The fuselage and wings of the new Boeing 787 are constructed of composite. Significant operational cost savings are gained from lower weight, corrosion resistance, and less maintenance due to increased fatigue strength compared to conventional (aluminum) aircraft structure. The composite consists of multiple, alternately directed layers of epoxy-impregnated continuous graphite fibers. The epoxy within the graphite fiber can burn under accidental aircraft fire conditions. During the FAA certification of the B-787, Boeing was required to demonstrate that the level of fire safety in the B-787 was equivalent to a conventional transport (aluminum) aircraft. The FAA conducted research and performed tests to characterize and better understand the fire behavior of this type of composite structure and to support the certification process.

In one study, the heating and burning characteristics of the epoxy-graphite composite were examined in a number of test apparatuses [63]. It was found that the epoxy-graphite composite behaved like a charring material, which is a favorable characteristic in that it reduces its flammability. When subjected to an external heat flux, the epoxy vaporizes and burns, leaving behind an insulation layer of graphite fibers that are essentially inert. This causes a continual reduction in internal heating of each subsequent ply of epoxy-graphite composite, which results in the burning rate decreasing with time. An important characteristic of the epoxy-graphite composite is that the critical heat flux for flame spread is on the order of the heat flux from a small fire. This means that the epoxy-graphite composite will only burn when it is in direct contact with a flame and will self-extinguish as it burns away from the flame, as evidenced in Bunsen burner tests. Overall, the epoxy-graphite composite displayed superior fire burnthrough (penetration) resistance and relatively good fire resistance [63].

Boeing proposed that the burnthrough resistance of the B-787 composite fuselage provided an equivalent level of safety to the FAA thermal acoustic insulation burnthrough resistance regulation during a survivable postcrash fire. To evaluate this, the FAA developed a small-scale test to expose fuselage constructions to a simulated postcrash fire and collect and analyze gas emissions that could impact survivability [64]. It was shown that the composite gas emissions were actually lower than the emissions from two types of burnthrough-resistant insulation materials. In addition, only 7 of the 13 plies of the composite were thermally decomposed, further demonstrating composite burnthrough resistance. The FAA also conducted full-scale postcrash fire tests to develop scaling factors to use in conjunction with the small-scale test to predict cabin gas concentration levels during a postcrash fire [65]. The full-scale fire tests also demonstrated the superior burnthrough resistance of the epoxy-graphite composite when subjected to a large jet fuel fire (figure 7).

Figure 7. Burnthrough Resistance of Composite Fuselage Subjected to a Jet Fuel Fire for 5 Minutes

The FAA also required Boeing to demonstrate that the B-787 can provide protection against hidden in-flight fires by requiring intermediate-scale tests similar to those performed by the FAA during the development of improved fire test methods for hidden materials. To obviate the need for these intermediate-scale tests in future certification programs, the FAA developed a small-scale fire test method to measure the in-flight fire resistance of composite fuselage structure [66]. The FAA also examined the heat transfer characteristics and integrity of composite and aluminum fuselage skins during a hidden in-flight fire under simulated flight conditions in a wind tunnel. Test showed that airflow-induced cooling caused both materials to remain intact, although the heat transfer characteristics of aluminum and composite are very different, with aluminum being a superior conductor in all directions, whereas composite mainly conducts heat through its thickness [67].

The fuel vapor flammability of composite wing fuel tanks was examined by the FAA and compared with aluminum wing fuel tanks [68]. Fuel vapor concentration was measured in wing tanks made of both materials under conditions that simulated (1) heating on the ground from the sun and (2) cooling by air flow over the wing under simulated flight conditions inside a wind tunnel. Test findings showed that composite wing fuel tanks are more flammable than their aluminum counterparts. It is noted that the composite B-787 will employ a full OBIGGS that inerts and protects both the center wing and wing fuel tanks.

HALON REPLACEMENT.

Halon, a gaseous fire-extinguishing agent, has been used in aircraft fire-extinguishing systems for about 50 years in four application areas: lavatories, cabin/cockpit hand-held extinguishers, engines, and cargo compartments. However, since halon is an ozone-depleting substance, its production has been banned by international agreement since 1994. Aviation was granted a Critical Use Exemption because of its unique safety and operational requirements. To evaluate and approve halon replacement agents, the FAA convened the International Halon Replacement Working Group (now the International Aircraft Systems Fire Protection Working Group) to develop a minimum performance standard (MPS) for each of the four aircraft applications. The main purpose of each MPS is to describe the full-scale fire tests used to demonstrate the conditions under which a replacement agent is equivalent to halon in terms of fire extinguishment/suppression effectiveness, and to develop certification (approval) criteria, if appropriate. Currently, all the fire tests defined in the four MPS's are located at the FAA William J. Hughes Technical Center and are available to the aircraft manufacturers for cooperative testing with the FAA.

There has been virtually no replacement of halon in civil aviation, except for very small quantities of agent in lavatory extinguishers. However, over the past several years, there has been a resurgence of activity because of several drivers. Disappointed with a perceived lack of progress, the European Commission has drafted a proposal to eliminate the Critical Use Exemption and has set dates for the replacement and ultimate removal of halon. Also, the ICAO has proposed specific dates for halon replacement in production aircraft and in new type certificated aircraft (new design). Perhaps of greatest concern was the discovery of contaminated halon in thousands of aircraft hand-held extinguishers furnished by a supplier in Europe [69].

Lavatory Trash Receptacles. The published MPS specifies a fire test article that is representative of a large trash receptacle to evaluate candidate halon replacement agents [70]. Two environmentally acceptable halon replacement agents, HFC-236fa and HFC-227ea, have passed the MPS test; Boeing and Airbus offer lavatory extinguishers containing these agents to its customers in new production airplanes.

Hand-Held Extinguishers. The MPS requires a hidden fire test for extinguishment effectiveness and a seat fire test for agent toxicity [71]. Three halon replacement agents were found compliant with the hand-held MPS: HCFC Blend B, HFC-227ea, and HFC-236fa. However, the industry contends that these replacement agents would impose unjustified penalties and would provide questionable environmental benefits. Each of the three agents would cause a weight penalty (a factor of two or more) and possible stowage issues because the extinguishers are much larger. All three agents are greenhouse gases and two of the agents have a significantly higher global warming potential than Halon 1211. Therefore, Boeing and the FAA are pursuing replacement agents that will fulfill long-term environmental and airline operational requirements. The FAA has also proposed updated guidance material for aircraft hand-held extinguishers, including approaches to determine safe human exposure criteria [72]. In support of the latter, the FAA developed a simple, first-order kinetic model for calculating the blood concentration history of humans exposed to time-varying concentrations of gaseous, halocarbon fire-extinguishing agents [73]. It allows for the computation of human exposure criteria when an extinguishing agent is discharged in a ventilated compartment (cabin) or when the concentration-time history is known.

Engine Nacelles. The MPS uses a unique full-scale test fixture, the nacelle fire simulator (NFS) (located at the FAA William J. Hughes Technical Center), which is capable of providing ventilation flows at elevated temperatures and pool and spray fire threats involving jet fuel, hydraulic fluid, or engine oil. Most recently, the MPS was revised to account for the behavior of agents whose effectiveness is dependent upon the directionality of the agent discharge, such as nongaseous aerosols [74]. Currently, the FAA is working with Boeing and Walter Kidde to evaluate a nongaseous aerosol in the NFS that is earmarked for the B-787. Previously, the effectiveness and certification criteria for HFC-125, CF3I, and Novec 1230 were determined using NFS. Their derived volumetric concentrations for equivalent effectiveness to halon were 17.6%, 7.1%, and 6.1%, respectively [75]. For comparison, the design concentration of Halon 1301 is 6.0%. Airbus has selected Novec 1230 for the A350XWB and is designing the extinguishing system and addressing certification requirements.

Cargo Compartments. The MPS for cargo compartments describes full-scale fire tests and criteria to demonstrate equivalent performance to Halon 1301, under four required fire scenarios: bulk-loaded cargo, containerized cargo, surface-burning fire, and exploding aerosol can [76]. Although a number of halon replacement gases have been tested, the only approach that passed the MPS was a water mist/nitrogen gas hybrid system concept [77]. The concept would use water mist to initially extinguish open flames and nitrogen gas (perhaps available from a fuel tank inerting system) to suppress any deep-seated fires for the duration of a flight. During the evaluation of agents such as HFC-125 and BTP under the exploding aerosol can scenario, a significant finding was the creation of overpressures at subinerting concentrations that were actually higher than the overpressures caused by an unsuppressed explosion [78]. This unexpected, and as yet unexplained, behavior has deterred further consideration of these environmentally acceptable replacement gases for cargo compartment applications. It is evident that the development of a suitable halon replacement agent/system for cargo compartments, which is by far the largest application for halon in aviation, poses a difficult challenge.

FIRE RESEARCH.

The FAA conducts applied research to support the fire safety effort but with the long-range goal of developing the enabling technology for ultra-fire-resistant aircraft interior materials. This program focuses on the interface between materials and fire science with the goal of identifying, developing, and evaluating ultra-fire-resistant polymers with potential aircraft interior applications. To meet the performance goal of a fireproof aircraft cabin, new polymers (plastics) needed to exhibit an order of magnitude reduction in heat release rate compared to current aircraft materials. This level of fire safety improvement cannot be achieved with conventional materials and fire-retardant technology; therefore, a better understanding of the relationship between polymer structure and fire performance and improved computational models and experimental methods for characterizing material fire performance is needed.

Ultra-Fire-Resistant Polymers. Bisphenol-A (BPA) is a chemical building block that is widely used to manufacture thermoformed (thermoplastic) and heat-cured (thermoset) polymer resins. Through a combination of laboratory-scale tests and numerical simulations, FAA researchers identified a novel bisphenol containing chlorine (bisphenol-C (BPC)) that proved to be a drop-in replacement for BPA in the synthesis of thermoplastic and thermoset aircraft resins and rendered them ultra-fire-resistant by chemically rearranging the products of combustion to noncombustible gas and char. These BPC-derived polymers were dubbed “fire-smart” because of the unique ability to change from ordinary to fire-safe plastics under high-heat conditions. Various epoxy [79] and cyanate ester [80] resin systems, as well as thermoplastics based on BPC [81], were synthesized and evaluated. These materials demonstrated a marked reduction in heat release rate with no reduction of thermal and mechanical properties under normal conditions. Related studies were conducted to examine the thermal degradation processes, such as synthesizing a number of cyanate ester resins with BPA or BPC [82], to attempt to relate thermal degradation and fire-smart behavior to the chemical structure of polymers. Moreover, it was shown that various polymers based on BPC and/or dichlorodiphenylethene (DDE) have mechanical, thermal, and processing characteristics equivalent or superior to their BPA analogs but are far more fire-resistant [83]. For example, the peak heat release rate of polycarbonate, a thermoplastic used in thermoformed and molded aircraft cabin parts, was reduced by about a factor of 3 when tested in accordance with the FAA heat release requirements specified in 14 CFR 25.853(a-1). Unfortunately, the potential aircraft fire safety benefit of BPC/DDE polymers will probably never be realized because of perceived environmental and health concerns associated with halogens (i.e., chlorine) in plastics. Therefore, the FAA is pursuing and supporting the development of nonhalogen fire-safe plastics [84]. Along these lines, FAA researchers partnered with NASA to demonstrate that phosphorus compounds could reduce the flammability of epoxy resins by several fold when added at levels as low as a few percent [85]. The FAA also demonstrated the superior fire test performance of polyphosphazene elastomers as a replacement for polyurethane aircraft seat cushions and the ability of expandable graphite flakes to impart the same level of improved fire resistance in the polyurethane itself [86]. Recently, FAA-funded university research has produced two new nonhalogen-containing bisphenols that thermally degrade by the same fire-smart mechanism as BPC. These bisphenols are nearly as effective as BPC at reducing flammability in a whole family of plastics and resins used in aircraft [84 and 87]. FAA-funded research was the first to demonstrate that nanometer-sized inorganic clay particles, added at only a few percent by weight, could reduce the flammability of polymers [88]. This discovery launched a large international effort to understand the fire resistance mechanism of these polymer-clay nanocomposites that eventually resulted in commercial products [89]. More recently, FAA-funded research demonstrated that nanometer-sized graphite oxide flame-retardants can also impart fire resistance to flammable, commodity plastics [90].

Experimental and Theoretical Material Fire Performance. To facilitate the development of ultra-fire-resistant materials, FAA researchers developed a microscale combustion calorimeter (MCC) to measure flammability at the molecular level [91 and 92]. The MCC measures the heat release rate of milligram-sized samples and is able to separate the solid state and gaseous phase processes of flaming combustion by rapid controlled pyrolysis of the sample in an inert gas stream followed by high-temperature oxidation of the pyrolysis gases in excess oxygen (figure 8). The unique, patented MCC allows for the rapid evaluation of extremely small samples in a quantitative and highly reproducible manner. Parameters derived from MCC data using milligram (10^{-6} kg) samples have been shown to predict the burning behavior of materials evaluated by standard flammability tests that require kilogram samples [93 and 94]. In 2007, the patented MCC became a national standard test method [95], and the FAA granted two companies nonexclusive licenses to fabricate and sell this versatile fire test device. FAA researchers and their contractors developed TheraKin, a numerical pyrolysis model that couples heat transfer with chemical kinetics to provide a practical tool for predicting, analyzing, and/or extrapolating the results of fire calorimetry tests. The one-dimensional model was initially calibrated using fire calorimetry data for noncharring polymers [96 and 97], but was later extended to char-forming polymers with excellent results [98]. Future plans include extending the model to composite materials and two-dimensional flame spread simulations.

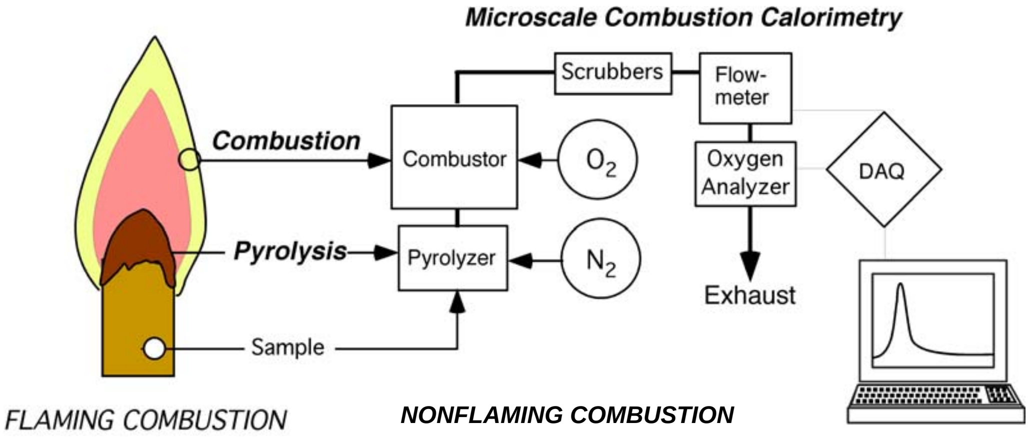

Figure 8. The FAA MCC

Fire Safety Support. FAA research supports fire safety activities by providing a fundamental basis for regulations, forensic analyses in accident investigations, as well as chemical and hazard analyses of combustion products generated in full-scale aircraft fire tests. For example, the kinetic model for human blood concentrations of gaseous halocarbon fire-extinguishing agents in a ventilated aircraft cabin [73] allows the FAA to set safe-use limits on fire-extinguishing agents that have been proposed to replace current ozone-depleting chemicals in hand-held extinguishers [72]. Forensic analyses also extend to the use of fire research products (ThermaKin and MCC) to investigate the effect of contamination on the burning behavior of in-use thermal acoustic insulation discovered after an incident [99]. In addition, support is provided to full-scale fire tests in terms of combustion gas analysis and interpretation of health hazards. Committee work in this area is under the purview of the International Standards Organization.

BENEFITS.

On August 2, 2005, an Air France A340 landed at Toronto Pearson International Airport during a severe thunderstorm, skidded off the end of the runway, and erupted in flames after it came to rest in a ravine. Although every seat on the airplane was occupied and the fire eventually gutted the aircraft, all 297 passengers and 12 crewmembers were able to safely evacuate. Forty-three passengers suffered mainly minor injuries. More than 3 years later, on December 20, 2008, a Continental 737 veered off the runway while attempting to take off from Denver International Airport, and skidded into a ravine. The impact sheared off the landing gear and left engine, and caused a jet fuel fire on the right-hand side of the aircraft. Although the aircraft was substantially damaged, all 110 passengers and 5 crewmembers were able to evacuate successfully; 5 passengers were hospitalized. The substantial improvements in fire safety and crashworthiness in commercial transport aircraft derived from FAA research has shown to be an important factor in preventing fatalities in survivable accidents.

In an attempt to quantify the improvements in postcrash survivability in transport aircraft accidents over the past 40 years, a study was commissioned by the FAA and Transport Canada [2]. This study was based on 1036 worldwide accidents (of which 672 were survivable) that occurred between 1968 and 2007 involving large transport category turbojet and turboprop western-built aircraft operating in a passenger or passenger/cargo role. The survivability of accidents showed a significant improvement over the study period, with a greater proportion of accidents being survivable and a marked increase in the proportion of occupants surviving an accident. Over the period studied, the probability of death in a survivable accident was reduced by a factor of two and the probability of death from the effects of fire was reduced even further—by about a factor of three.

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