An Overview of Twenty Years of R&D to IMPROVE AIRCRAFT FIRE SAFETY

By Constantine P. Sarkos

A national goal has been set to reduce the aviation fatal accident rate by 80% within 10 years.[1] This goal was based on a number of considerations. Although commercial aviation is the safest form of transportation – a fatal accident rate of only 0.3 per million departures in the United States – that rate has remained low, but unchanged, over the last 20 years. Because of the projected increase in airline traffic, unless the fatal accident rate is reduced, the actual number of accidents will rise. This is particularly true outside the United States where the safety record is not as good and the traffic gains are expected to be greater. Fire protection is an integral part of aviation safety, having impacted the past safety record, while being an important element of future challenges.

Aircraft fires fall into two major categories: in-flight fire and postcrash fire.

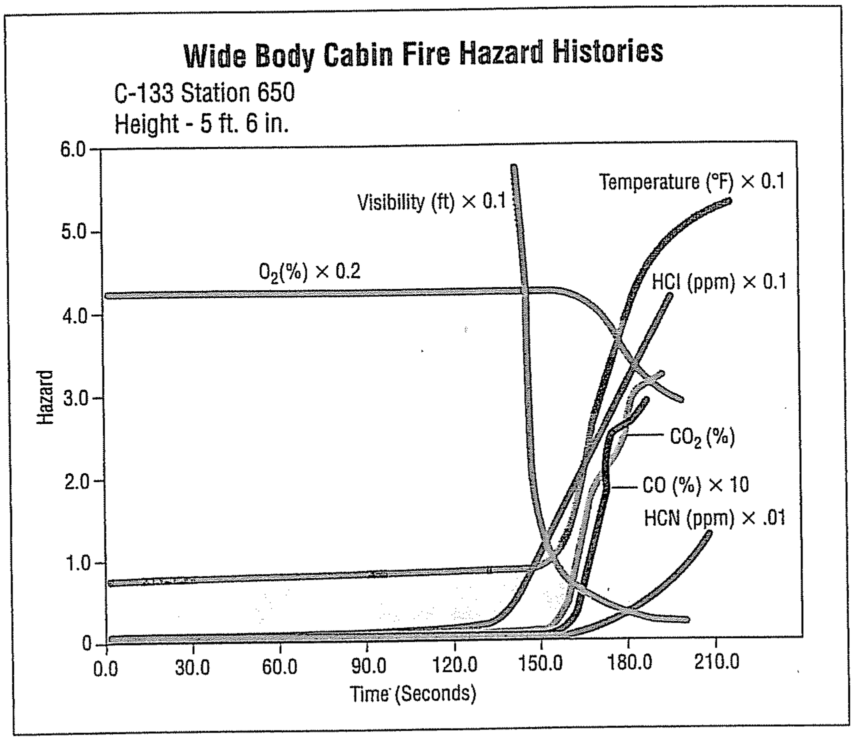

FIGURE 1

Fatal accidents have been caused by in-flight fires originating in hidden or inaccessible areas and by fuel tank explosions. A Boeing analysis of worldwide airline fatalities covering the period of 1987 through 1996 indicated that in-flight fire was the third leading cause of fatalities. In-flight fire was responsible for 760 worldwide fatalities, accounting for more than 10% of all fatalities.[2] Postcrash or ground fires are usually caused by hard landings or aborted takeoffs, involving spilled jet fuel in most (but not all) cases. Once the fuel fire penetrates into the fuselage and involves the interior materials, passenger escape may be inhibited or prevented. The Boeing analysis of worldwide accident issues also showed that on-ground fire was an issue in about 25% of all accidents, and in these fire accidents, there were 1,422 fatalities from 1985 to 1994.[2]

A commercial airliner presents a unique fire protection design challenge. The cabin interior is furnished and lined with polymeric materials. Passengers are confined inside a relatively small enclosure. Inaccessible areas contain potential ignition sources. Combustible luggage and cargo, including hazardous materials, are carried in the cargo compartments. Wing tanks are laden with thousands of gallons of flammable jet fuel. All of these features underline the importance of aircraft fire safety.

Since its inception, the Federal Aviation Administration (FAA) has had a major research and development (R&D) program in aircraft fire safety. As in the past, the primary goals of the Fire Safety Program are twofold: (1) prevent fatal in-flight fires and (2) improve postcrash fire survivability.

REGULATORY PRODUCTS

Over the past 15 years, the FAA has adopted an unprecedented series of fire safety regulations that were mainly products of the Fire Safety Program. An essential element in the development of each of the regulatory products was the conduct of full-scale aircraft fire tests.

In the 1980s, the main focus was on the development of improved fire test criteria for cabin materials in order to improve postcrash fire survivability. Numerous full-scale tests were conducted in support of this effort. A scenario was developed that consisted of an intact fuselage with an external fuel fire adjacent to a fuselage opening under quiescent wind conditions. The full-scale tests consistently showed that cabin flashover was the critical factor affecting occupant survivability during a postcrash fire dominated by burning interior materials. It was also evident that incapacitation was largely driven by toxic gases generated by the flashover event (see **Figure 1**). Therefore, the approach taken by the FAA was to develop improved material requirements that serve to delay the onset of flashover with the aim of providing more time available for passengers to evacuate during a postcrash cabin fire. A review of past FAA full-scale fire tests, containing an analysis of the incapacitation effects of temperature and toxic gas measurements, is contained in Reference 3.

Research products mandated by the regulatory process initially focused on improvements in postcrash fire survivability. The greatest gains were made on more stringent and realistic fire test standards for cabin materials. In recent years, more emphasis has been placed on in-flight fire safety. The following is a summary of the development and implementation of the regulatory products.

Seat Cushion Fire-Blocking Layers. Progress to retard the burning behavior of aircraft polyurethane foam seat cushions was rather limited until the fire-blocking layer concept was advanced. Basically, a fire-blocking layer is a lightweight fire-resistant material that encapsulates the polyurethane foam, preventing ignition or reducing the burning rate, depending on the strength of the ignition source. Initial full-scale tests evaluated the effectiveness of fire-blocking layers under the aforementioned postcrash fire scenario.[4] The test aircraft was lined and furnished with actual aircraft materials. The introduction of a fire-blocking layer – with all remaining variables unchanged – extended the survival time (delay in flashover) by a significant 40-60 seconds. Additional tests demonstrated that fire-blocking layers could also prevent ramp and in-flight fires, originating at a seat that would otherwise burn out of control if

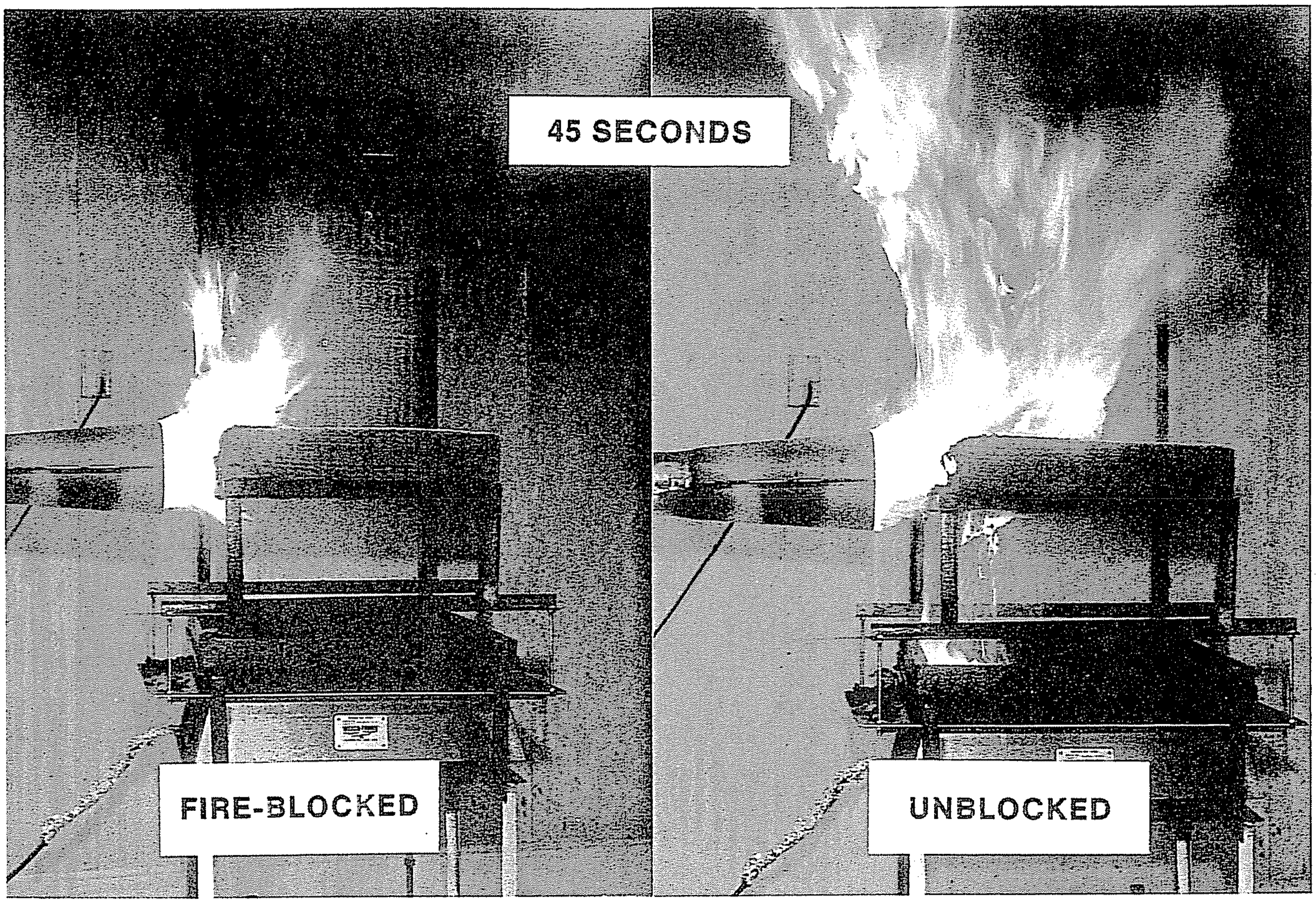

FIGURE 2

left unattended.[4]

A small-scale flammability test method was developed as a basis for selecting seat cushion materials. The test subjects a standard seat geometry to an intense burner flame that creates the heating conditions produced by a large fuel fire (**Figure 2**). A good correlation was seen between seat cushion flammability and large-scale test results.[5] Acceptance criteria were selected to match the behavior of fire-blocking layer materials proven effective in full-scale fire tests.

The FAA adopted a seat cushion flammability regulation, based on the new fire test method, requiring a retrofit with fire-blocking layers of all passenger seats in the U.S. fleet.[6] Over a three-year period, extending from November 26, 1984, to November 26, 1987, 650,000 seats were protected with fire-blocking layers at a cost to the airlines of $75 million. In the first fire accident involving an aircraft with fire-blocked seats, it was estimated that 32 passengers were saved because of the additional available escape time provided by the protected seats.[7]

Low-Heat Release Panels. The interior panels of an aircraft cabin, such as the sidewalls, ceilings, stowage bins and partitions, are significant contributors to a cabin fire because of their large surface area and, in some applications, their location in the upper cabin where fire temperatures are highest. Interior panels are composites comprised generally of a Nomex honeycomb core, resin-impregnated fiberglass facings and a decorative laminate finish. Again, full-scale postcrash fire tests demonstrated potential fire safety benefits by changes in the composition of the panel components.[8,9] **Figure 3** (page 9) depicts the fractional effective dose (FED) histories of five types of panels under full-scale fire test conditions.[9] The FED model relates the measured hazards, consisting of various gas concentrations (CO, CO_2, HCN, etc.) and elevated temperature, to survivability.[10] The results show that the phenolic/Kevlar and epoxy/fiberglass panels experienced the earliest flashovers, whereas the phenolic/fiberglass panel delayed flashover by about 3 minutes.

Figure 3 also depicts data for these same panels tested in the Ohio State University (OSU) rate-of-heat release apparatus. An inverse relationship exists between OSU heat release measurements and full-scale test survival times, which essentially reflect the time to flashover. Final selection of the OSU apparatus for use in testing large surface area cabin materials was based on the established relationship between heat release and flashover along with a number of practical considerations. The phenolic/fiberglass panel that had performed so well in full-scale tests was used as a benchmark for setting performance criteria. The final rule issued by FAA — which also contained a smoke test requirement — primarily impacted all large transport aircraft manufactured on or after August 20, 1990.[11] Most cabin materials impacted by the rule had to be redesigned, leading to improved decorative laminates, resins and thermoplastic molded parts.

During the early implementation of

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the FAA/OSU test requirement, a relatively large disparity was observed in data gathered by different laboratories. Following a series of round-robin test programs, an acceptable level of reproducibility was achieved by making a number of modifications related to the design, calibration and operation of the OSU apparatus.[12] This exercise led to the establishment of the FAA-sponsored International Aircraft Material Fire Tests Working Group, which, among other responsibilities, updates the Aircraft Material Fire Tests Handbook, a description of all FAA-required and other available fire test methods for aircraft materials.[13]

Floor Proximity Lighting. Buoyant hot smoke from a cabin fire clings to the ceiling obscuring overhead emergency illumination and exit signs, and causing a reduction in passenger visibility and prolonged evacuation time. FAA full-scale tests demonstrated the effectiveness of emergency lighting placed below the smoke layer in proximity to the cabin floor. In one study, people evacuated a cabin simulator filled with buoyant theatrical smoke in 20% less time when the simulator was illuminated with floor proximity lighting than when conventional overhead lighting was used.[14] The FAA issued a final rule requiring floor proximity lighting that would enable passengers to visually identify emergency escape paths along the cabin aisle and the emergency exit locations.[15] In some later accidents, the floor-level emergency lighting has been an aid to passenger evacuation.

Heat-Resistant Evacuation Slides. Pressurized emergency evacuation slides provide for rapid passenger egress during an aircraft fire. However, the slides may no longer be functional if radiant damage causes a loss in pressurization. From a series of full-scale tests in which pressurized slides were subjected to a jet fuel fire, it was determined how slides fail and the time duration for failure.[16] Also, it was demonstrated that an aluminized reflective coating significantly improved the air-holding qualities. A laboratory test method was developed to foster the development and prescribe the qualification of heat-resistant slide fabrics.[16] Over the past 15 years, evacuation slides have been manufactured to a radiant heat requirement that more than doubles the time that the slides are inflated when heated by a large jet fuel fire.[17]

Cargo Compartments. The fire safety of inaccessible cargo compartments in transport aircraft is a concern because of the large quantity of various combustible materials present in passenger luggage, mail and cargo, including hazardous materials. In large transport aircraft, the cargo compartments are located in the belly of the aircraft underneath the passenger cabin. FAA regulations are designed to prevent fires from spreading outside the cargo compartment, to protect flight-critical systems and to prevent passengers and crew from being subjected to hazardous quantities of smoke and toxic gases so that the aircraft can be safely landed.[18]

A critical factor in the containment of cargo compartment fires is the burnthrough resistance of wall and ceiling lining materials. Past FAA requirements based on a Bunsen burner test method did not adequately gauge the fire-penetration resistance of cargo liners. For example, under realistic full-scale test conditions, lightweight Nomex and Kevlar liners, compliant with the Bunsen burner test method, were penetrated by a cargo fire.[19,20] Under some fire scenarios the availability of a fire-detection and suppression system does not negate the need for liner burnthrough resistance.[20] A new small-scale test method was developed to more realistically assess burnthrough resistance.[21] The test method was the basis for more strin-

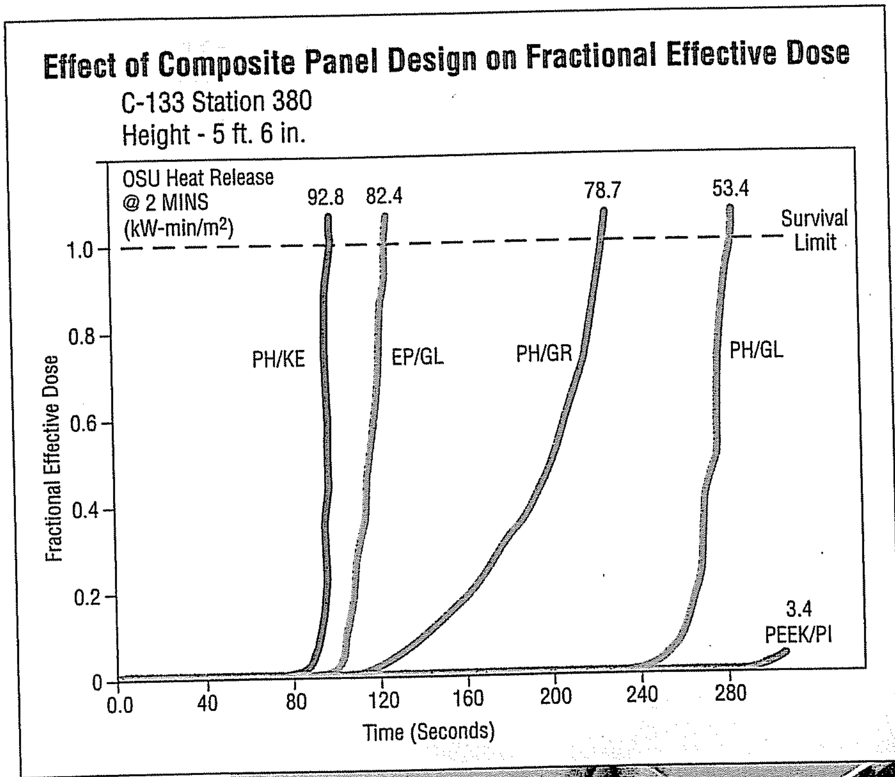
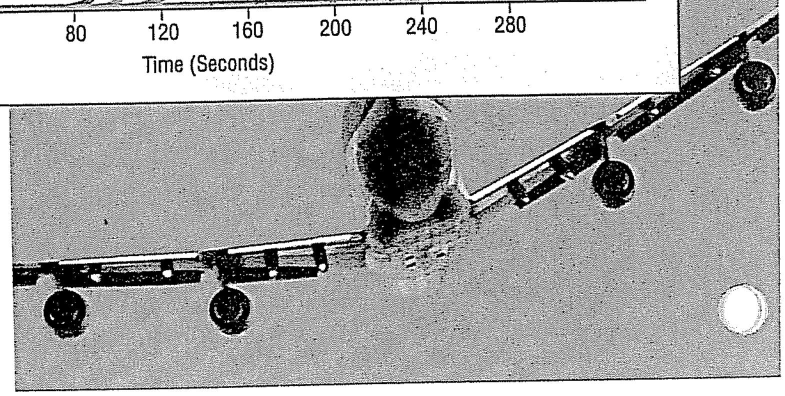


FIGURE 3



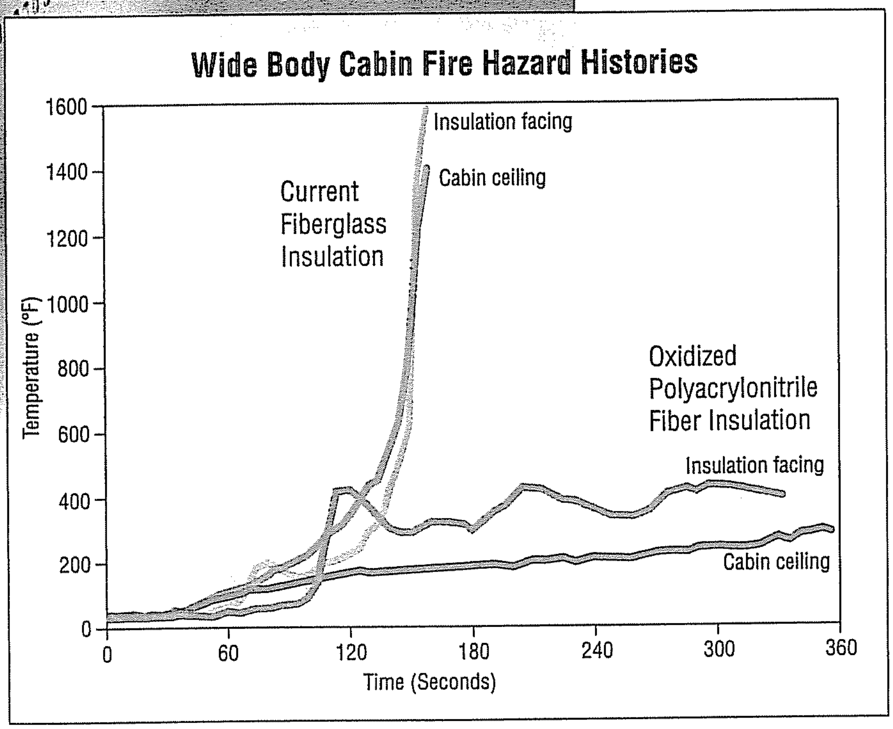


FIGURE 4

gent test requirements, which were initially limited to newly certified aircraft before being applied to the entire fleet.[22] The test method was subsequently adapted to test cargo compartment design features that could be the weak link to flame penetration such as seams, joints, fasteners, lighting fixtures, and corners.

Recently, the FAA adopted a regulation requiring the installation of cargo compartment fire-detection and suppression systems in approximately 75% of U.S. commercial transport aircraft over a three-year period ending on March 19, 2001.[23] A major consideration in the issuance of the rule was the potential explosive hazards of aerosol cans, commonly containing hydrocarbon propellants, carried in passenger luggage and the demonstrated effectiveness of Halon fire-suppression in controlling cargo fires involving aerosol cans.[24] From full-scale fire tests, it was shown that failure of aerosol cans subjected to a cargo fire could cause damage to the cargo liners, either due to overpressure associated with ignition of the propellant or if the can should behave as a rocketing projectile.[25] Instrumental in the airlines' concurrence with the proposed rule were assurances from the Environmental Protection Agency (EPA) that there would be no future mandate to replace the Halon with an environmentally acceptable agent. FAA testing of a popular gaseous replacement agent indicated a severe weight penalty and, more importantly, anomalous agent behavior.[26] The EPA also encouraged expanded research efforts to find and certify alternatives to Halon in aviation.

Thermal Acoustical Insulation. Aircraft thermal acoustical insulation blankets typically consist of fiberglass encapsulated within a thin-film cover material. The entire fuselage is layered with insulation blankets to deaden noise and insulate against cold/heat. Thermal acoustical insulation may be a factor during an aircraft fire under two different scenarios – as a path for in-flight fire propagation and as a potential barrier against burnthrough by a postcrash external fuel fire. A number of aircraft fire incidents have raised questions about the adequacy of the vertical Bunsen burner test method currently specified for insulation. Also, tests conducted by a number of laboratories showed that one particular type of cover material, metallized Mylar, exhibited erratic results under the FAA-required test procedure and consistently failed an industry standard.[27] These concerns and findings prompted the FAA to recently develop improved fire-test criteria comprised of separate burnthrough and in-flight flammability test methods.

As shown in **Figure 4**, full-scale tests showed that new insulation blanket materials or current blankets protected with a fire barrier can significantly prolong the time for fuselage burnthrough thereby providing additional time for passengers to evacuate during a postcrash fuel fire.[28] Based on the promising full-scale test findings, a small-scale test method was developed to measure the burnthrough resistance of insulation blankets.[29] The new test utilizes an intense burner calibrated to reproduce the melting time of aluminum fuselage skin subjected to a large jet-fuel fire. Pass/fail criteria are based on the maximum required evacuation time determined from an analysis of past accidents. Testing has shown that the method of securing the blanket to the fuselage structure is critical to ensuring that the blanket provides a protective barrier against flame penetration throughout the exposure period.

Similarly, full-scale and mockup tests were conducted to evaluate the behavior of the insulation blanket films during a hidden in-flight fire in the "attic" space above the cabin ceiling.[29] Because of their extremely low weight, the behavior of films subjected to heat or flame is dominated by physical effects such as melting and/or contraction. The flammability of the films was found to depend on chemical composition, thickness (weight) and type of scrim (tear-stopper). A radiant-panel test method was selected that produces data on the films that correlates with the mockup test results and in which the dominant physical effects can readily be observed.[30] Acceptable

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films must not ignite when subjected to the specified test exposure conditions (radiant heat and piloted ignition source).

On August 11, 1999, the FAA proposed to require the operators of 699 aircraft to replace the metallized Mylar insulation blankets within four years.[31] Replacement materials must meet the new criteria based on the radiant-panel test. The FAA plans to propose an even higher standard for testing insulation on all new aircraft that will include burnthrough resistance as well as in-flight fire ignitability.

Flight Recorders. Accident investigators rely on flight data and cockpit voice recorders to provide valuable information that may lead to a determination of the probable cause of an accident. Based in part on realistic fire tests[32], the FAA issued new design criteria for flight recorders to ensure greater recorder survivability in accidents accompanied by postcrash fire. Recorders must be capable of withstanding a jet-fuel fire and a long-term smouldering fire.

ADDITIONAL SELECTED RESEARCH ACTIVITIES

The preceding discussion described a number of FAA fire safety R&D deliverables that have been implemented into civil aviation. The following is a description of selected R&D accomplishments in active areas and/or of current interest.

Halon Replacement. For over 35 years, Halon has been the agent of choice in fixed-wing aircraft fire extinguishing systems, which are mandated in cargo compartments, engines and lavatories; and Halon is required in hand-held extinguishers. Since the international agreement to ban Halon in 1994, the FAA has been working closely with the aviation industry to evaluate promising new agents under full-scale fire test conditions and to develop the basis for demonstrating equivalent firefighting effectiveness with Halon in each of the four aircraft applications. A working group called the International Halon Replacement Working Group, chaired and administered by the Fire Safety Section, is providing the forum for coordinating this research with industry as well as with other government agencies and foreign airworthiness authorities.[33] The final product is a minimum performance standard, which details the fire test procedures that must be followed to demonstrate equivalent performance. To date, a performance standard for Halon replacement agents in lavatory waste receptacles has been developed and published.[34] Standards for cargo compartment and hand-held extinguisher replacement agents are near completion, and a standard for engines should be completed in the year 2000. The cargo compartment standard requires the most extensive tests and is comprised of four separate fire threats/tests: cargo containers, bulk-loaded luggage, surface burning and aerosol cans.[35] Replacement agents used in hand-held extinguishers will be required to pass two tests: a gasoline-soaked seat fire test and a hidden fire test.[36] Near completion is an engine test simulator for evaluating replacement agent effectiveness against fuel spray and residual (pool) fires. The simulator mimics the engine operational parameters deemed crucial to agent performance.[37]

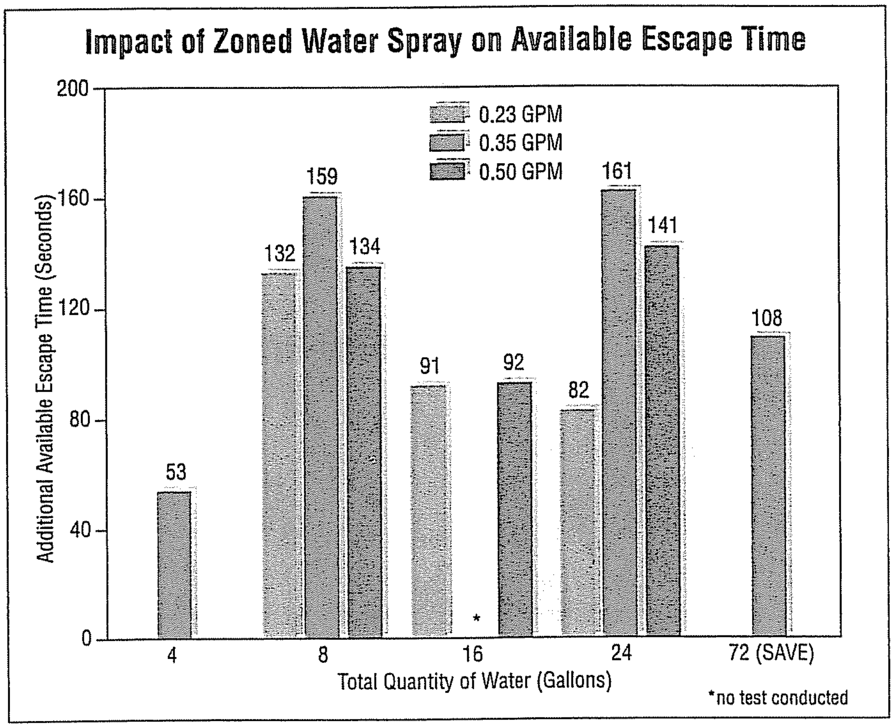


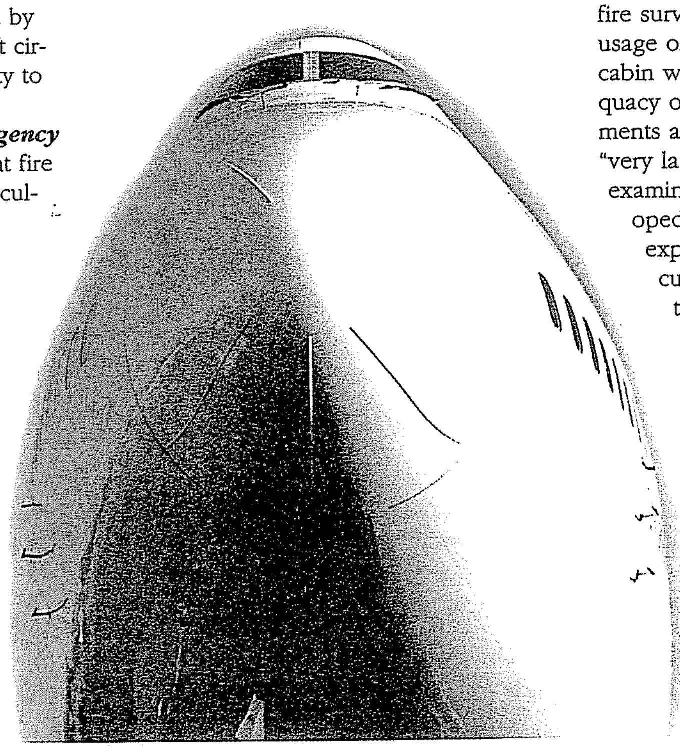
FIGURE 5

Water Spray. An approach for increasing postcrash fire survivability against all fire sources, including jet fuel, is an on-board cabin water spray system. A major program was conducted by FAA and the regulatory authorities in the United Kingdom (U.K.) and Canada to test, develop and evaluate the feasibility of a cabin water spray system. The initial system tested, developed in the U.K., sprayed water from a large number of ceiling-mounted nozzles for a continuous three-minute period. In numerous full-scale fire tests employing wide-body, standard-body and commuter test articles, and over a range of fire scenarios, water spray was shown to increase survival times by 2-3 minutes in all but the most unusually severe fire scenario. Moreover, a zoned system was developed and optimized that actually provided more protection than the original system but used only 10% of the water.[38] The results are summarized in **Figure 5** in terms of the additional available escape time beyond the baseline test without water spray. A number of separate studies were conducted to examine the feasibility of an aircraft cabin water spray system. Of concern were the consequences of an inadvertent discharge, costs, benefits in terms of potential lives saved, impact of water discharge on emergency evacuation and hypothermic effects associated with discharge at low ambient temperatures.[39] When the research was completed, a poor cost-benefit, due largely to the relatively small number of postcrash fire fatalities in recent years, discouraged any further consideration of placing water spray in airliners. Currently, the FAA is evaluating the effectiveness of water spray against cargo fires, as a Halon alternative, which would also help to offset the weight penalty of the cabin water spray system.[40]

Electrical Wiring. Most aircraft in-flight fires are electrical in nature and usually controlled rather quickly and without impacting flight safety. Past studies have shown that some wiring insulation materials are susceptible to arc tracking,[41] while other types of insulation have higher smoke emissions.[42] What constitutes the ideal aircraft wiring insulation in terms of optimal fire safety is a subject of continuing debate and controversy. It is clear, however, that the vast majority of aircraft electrical wiring problems are related to improper installation and inadequate inspection and maintenance. Recently, the FAA has issued a series of airworthiness directives to correct potential wiring problems uncovered by inspection of older airplanes and is striving to improve installation designs, inspection procedures and maintenance. Also, efforts have begun to develop aircraft arc fault circuit interrupters (AFCIs), spurred by the inadequacy of current aircraft circuit breakers, such as the inability to respond to "ticking" faults.[43]

Aircraft Command in Emergency Situations (ACES). Past in-flight fire accidents have shown crew difficulties in identifying the smoke source, and locating and implementing the appropriate emergency procedures. The purpose of an ACES system is to display more timely, reliable and useful information to the flight deck crew in the event of an in-flight smoke emergency. A prototype ACES system was developed. The prototype features include installation of additional sensors in inaccessible areas, interfacing the sensors with flight deck computers and the use of an electronic checklist to guide the crew through appropriate emergency procedures.[44] Future development of the ACES concept would, at the minimum, concentrate on development of the methodology to utilize sensor data in crew decision-making.

Fire-Resistant Materials. The objective of this program is to eliminate burning cabin materials as a cause of postcrash fire fatalities. Long-term activities include the synthesis of thermally stable, low fuel-value organic and inorganic polymers. The synthesis effort is supported by fundamental research to understand polymer combustion and fire resistance mechanisms using modeling and the development of new characterization techniques. Aircraft materials that are targeted for upgraded fire-resistance include: (1) thermoset resins for interior decorative panels, secondary composites and adhesives; (2) thermoplastics for decorative facings, molded parts, insulation covers, transparencies and electrical wiring; (3) textile fibers for upholstery fabric, carpets and decorative murals; and (4) elastomers for seat cushions. During the first two years of the program, significant progress was made in achieving the interim goal of a 50% reduction in the heat-release rate of cabin materials by 2002.[45]



FUTURE RESEARCH

The direction of future research, as in the past, will be influenced mainly by accident experience, new technology and new airplane designs.[46] A greater share will be devoted to in-flight fire prevention as compared to postcrash fire mitigation. Minimum performance standards will be developed for the approval of Halon replacement extinguishing agents in anticipation of diminishing Halon availability and/or a potential future ban on usage. Research on aircraft cargo smoke detectors will focus on both the need for standardized approval criteria and for reducing the high incidence of false alarms. With the new FAA policy seeking to reduce flammable vapors in fuel tanks, research is underway to better define the fuel tank hazards and to determine (and develop, if feasible) the feasibility of explosion-protection systems, including ground-based inerting and on-board inert gas/oxygen generation. Water spray will be evaluated as a Halon alternative in cargo compartment fire-suppression systems. If found to be effective against cargo fires, water spray may be researched further as an on-board cabin water spray system for enhanced postcrash fire survivability, particularly if cargo usage offsets the weight penalty of a cabin water spray system. The adequacy of current fire safety requirements applied to new double-decked, "very large transport aircraft" will be examined and new standards developed, if required. Methods will be explored to protect or replace current emergency oxygen systems, such as the previously mentioned on-board oxygen generation approach. Finally, research will continue to develop the enabling technology for ultra-fire-resistant aircraft interior materials.

Mr. Sarkos is with the Federal Aviation Administration.

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