

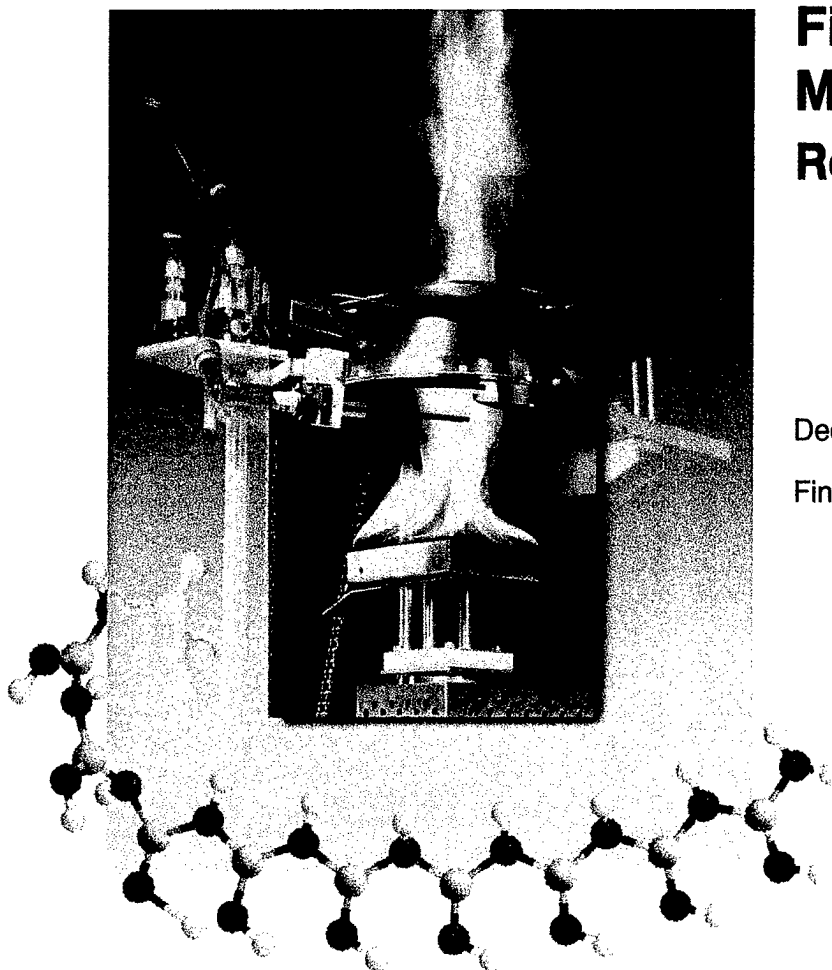
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Fire-Resistant Materials: Research Overview

December 1997

Final Report



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16. Abstract This report provides an overview of the research being conducted by the Federal Aviation Administration (FAA) to develop fire safe cabin materials for commercial aircraft. The objective of the Fire-Resistant Materials program is to eliminate burning cabin materials as a cause of death in aircraft accidents. Long-term activities include the synthesis of new, thermally stable, low fuel value organic and inorganic polymer systems. The synthesis effort is supported by fundamental research to understand polymer combustion and fire resistance mechanisms using numerical and analytic modeling and the development of new characterization techniques. Aircraft materials which are targeted for upgraded fire resistance are (1) thermoset resins for interior decorative panels, secondary composites, and adhesives, (2) thermoplastics for decorative facings, telecommunication equipment, passenger service units, molded seat parts, transparencies, and electrical wiring, (3) textile fibers for upholstery, carpets, decorative murals, tapestries, and (4) elastomers/rubber for seat cushions, pillows, and sealants. During the first 2 years of the program (1995-1996) we have made significant progress in achieving our interim goal of a 50 percent reduction in the heat release rate of cabin materials by 2002 and zero heat release rate cabin materials by 2010 with respect to the 1996 baseline for new aircraft. A follow-on detailed report, Fire-Resistant Materials: Progress Report, DOT/FAA/AR-97/100, documents the technical efforts of all of the investigators in the program.					
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EXECUTIVE SUMMARY

Forty percent of the passengers who survive the impact of an aircraft accident subsequently die in a postcrash fire. Unless this percentage is reduced or the accident rate decreases, the number of fire fatalities will increase by 4 percent each year with the expected growth in passenger air traffic. Compounding the upward trend in aircraft fire fatalities is the additional fire load associated with the 1 percent annual growth in the use of lightweight, combustible polymers and composites for aircraft interiors and structures. Current aircraft utilize several tons of combustible plastics for cabin interior components (figures I and II). This is a fire load comparable to the equivalent weight of aviation fuel. The cabin fire load will approximately double in the very large (800 passenger) airplanes under development by airframe manufacturers unless ultra fire-resistant materials become available. The use of materials with improved fire resistance (relative to commodity plastics) was

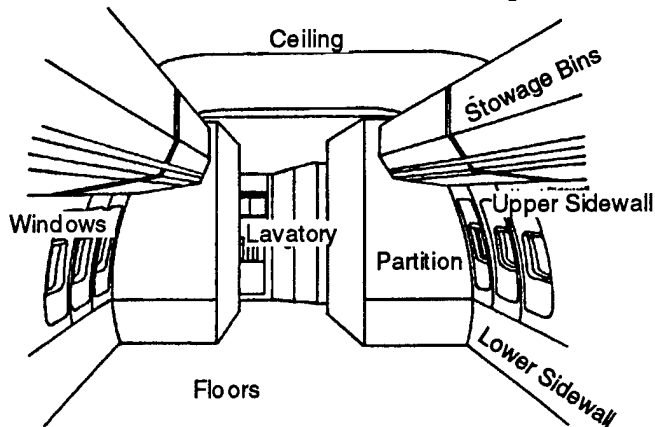


FIGURE I. FLAMMABLE CABIN COMPONENTS

situation, the FAA has initiated a proactive, long-range research effort in Fire-Resistant Materials to identify and develop the enabling materials technology for a cost-effective, fireproof passenger aircraft cabin. In combination with other fire-safety system improvements, ultra-fire-resistant materials will eliminate catastrophic inflight fuselage fires and provide a minimum of 10 minutes of passenger escape time in a postcrash fire.

The objective of the Fire-Resistant Materials program is to eliminate burning cabin materials as a cause of death in aircraft accidents. The research is basic in nature and focuses on the synthesis, modeling, processing, and characterization of new materials and materials combinations. In accord with the recommendations of the National Research Council's Materials Advisory Board in their report "Fire- and Smoke-Resistant Interior Materials for Commercial Transport Aircraft," (NMAB-477-1, National Academy Press, 1995) near term technical approaches include modification of specialty and commodity polymers using additives and processing routes. Databasing of materials' fire performance in micro-, bench-, and full-scale testing supports science-based studies of polymer combustion and identifies critical fire performance properties to guide development. Long-term activities include the synthesis of new, thermally stable, low fuel value organic/inorganic polymer systems. The synthesis effort is supported by fundamental research to understand polymer combustion and fire resistance mechanisms using numerical and analytic modeling and the development of new characterization techniques.

The output of this research will be an order-of-magnitude reduction in cabin fire hazards relative to current cabin materials at comparable cost and functionality. Since the heat release rate of burning materials is the primary fire hazard indicator, the technical objective is to develop low-cost, lightweight, serviceable polymers and composite materials with zero heat release rate as measured by FAR 25.853(a-1), "Heat Release Rate Test for Cabin Materials." Materials with a zero heat release rate will provide sufficient passenger escape time in a postcrash fuel fire to ensure

survivability. With respect to the 1996 baseline for new aircraft, individual fire-resistant materials will demonstrate a 50 percent reduction in heat release rate by the year 2002. Prototype cabin components fabricated from combinations of fire-resistant materials will demonstrate zero heat release rate by the year 2010. The potentially higher initial cost of fire-resistant cabin materials will be offset by user financial incentives which include shorter process cycles, better durability, and lower heat release rate.

The fire-resistant materials program is executed from an in-house technology base at the W.J. Hughes Technical Center, Atlantic City International Airport, NJ, through FAA-industry partnerships and university-based research consortia. Direct funding by several Fortune 100 aircraft and chemical companies to the FAA-university-industry consortia covers about 30 percent of research costs for fire safe materials. During the first 2 years of the program (1995-1996) we have made significant progress in achieving our interim goal of a 50 percent reduction in the heat release rate of cabin materials by 2002 and zero heat release rate cabin materials by 2010.

The progress to date in this program reflects the commitment of Congress, the FAA, and the materials and aircraft industries to improving the safety of air transportation. This collaboration has resulted in the outstanding technical work which is summarized in this report. The FAA is grateful to all of the participating researchers in government, industry, and academia whose ideas and hard work are creating the enabling technology for a fireproof passenger aircraft cabin.

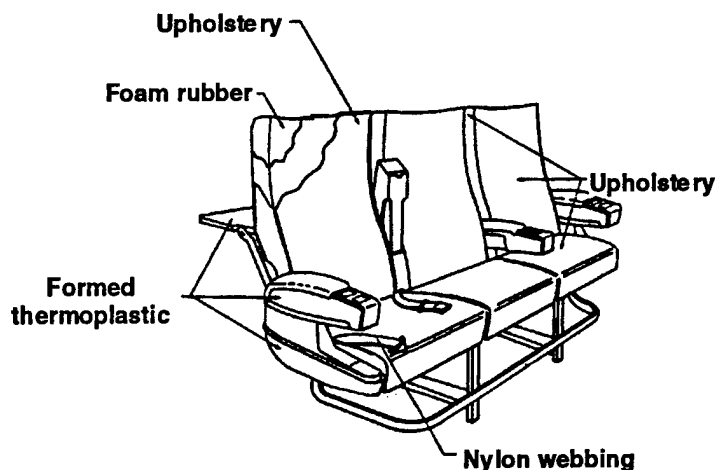


FIGURE II. FLAMMABLE SEAT COMPONENTS

BACKGROUND

PROBLEM STATEMENT.

Approximately 20 percent of the 1153 fatalities on U.S. transport airlines between 1981-1990 were caused by fire. If the aircraft fatal accident rate remains constant, the total number of fire deaths will grow at an annual rate of 4 percent with the expected increase in commercial air passenger traffic. This is an unacceptable prospect, and the Federal Aviation Administration (FAA) has taken a bilateral approach to reduce the aircraft fatal accident rate. The first approach is to prevent new factors from increasing the accident rate through programs such as Aging Aircraft, Structural Airworthiness, Engine Reliability, and Catastrophic Failure Prevention. The second approach is to reduce the number of accidents of the type that have been occurring and to increase the survivability of such accidents through programs in Airplane Crashworthiness, Cabin Safety, Fire Safety, and Fire Research.

Aircraft cabin fires fall into three general categories: ramp, inflight, and postcrash. Ramp fires occur when an aircraft is parked at the ramp during servicing. One past example was a smoldering cigarette in a trash bag which ignited an adjacent passenger seat in the unattended aircraft. To date ramp fires have resulted in the loss of property but not the loss of life. However, considering the current cost of a commercial aircraft ($\approx$ \$100 million), ramp fires are a rare but expensive problem.

Inflight fires most often occur in accessible areas such as the galley and are detected and extinguished promptly. On rare occasions inflight fires originating in inaccessible areas become uncontrollable leading to large loss of life; for example, a cargo compartment fire claimed all 301 occupants when fire penetrated the cabin floor and ignited seats and other materials. Inflight fire incidents are typically caused by electrical failures, overheated equipment, or improper cargo.

In the United States the vast majority of fatalities attributable to fire have occurred in postcrash fire accidents [1]. Fuel fires which penetrate the passenger cabin are the primary ignition source in these accidents and it is estimated that 40 percent of these fire fatalities can be attributed to smoke and toxic combustion products of burning cabin materials and jet fuel [2] and urethane seat cushions the major cabin material contributor in these accidents [3]. Newer regulations require a number of fire safety improvements in aircraft cabins including materials flammability upgrades in aircraft manufactured after 1990 which, depending on the accident scenario, may extend the passenger escape time by two or more minutes in a postcrash accident involving a fuel fire. Recent full-scale aircraft fire tests indicate that further incremental improvements in material fire-resistance would do little to increase passenger escape time [4]. Consequently, it is anticipated that the fire safety goal of eliminating burning cabin materials as a cause of death in aircraft accidents will require order-of-magnitude improvements in material fire resistance. In the following sections we review the types of materials found in passenger aircraft cabins and the socioeconomic factors which impact the fire performance requirements of present and future aircraft cabin materials.

AIRCRAFT CABIN MATERIALS.

The aircraft interior is the area within the pressure hull that includes the passenger compartment, cockpit, cargo compartments, and the various accessory spaces between the passenger compartment and pressure hull. A compilation of materials used in transport category aircraft cabins, their construction, flammability requirements, and certification is published in the FAA Aircraft Materials Fire Test Handbook [5]. Table 1 lists combustible cabin materials and their weight range in commercial passenger aircraft cabins [6]. From table 1 we see that there is about 7000 kg (15,000 pounds) of combustible cabin materials in an average passenger aircraft. Polymeric cabin materials have an effective heat of combustion of about 35 MJ/kg in a fire. The fire load represented by the cabin materials is therefore, $7000 \text{ kg} \times 35,000 \text{ kJ/kg} = 2.5 \times 10^8 \text{ kJ}$

(2×10^8 Btu). An average aircraft at takeoff carries 50,000 gallons (150,000 kg) of aviation fuel with a heat of combustion of 43,000 kJ/kg, so that the takeoff fuel fire load is 6.5×10^9 kJ. If between 10 and 50 percent of the takeoff fuel remains at descent and landing when two thirds of the accidents occur, then the fire load represented by the cabin materials is on the order of 20 percent of the aviation fuel load at landing. This calculation shows that the fire load of the cabin materials is not insignificant in comparison to the fire load of the jet fuel in a typical postcrash accident scenario. Moreover, the location of combustible materials in the enclosed cabin environment makes the fire hazard particularly high. Carryon luggage represents an additional fireload, neglected in the calculation, which would be minimized by containment in fireproof stowage bins.

Thermoset composites form about 80 to 90 percent of the interior furnishings in today's commercial aircraft. Typically these composites are sandwich panels made of fiberglass-reinforced phenolic resin skins on Nomex honeycomb core which are surfaced with an adhesively bonded poly(vinyl fluoride) decorative film or painted to provide color, texture, and cleanability. These honeycomb decorative laminates are used as ceiling panels, interior wall panels, partitions, galley structures, large cabinet walls, structural flooring, and in the construction of overhead stowage bins. Until 1986 these large-area component materials were only required to be self-extinguishing in a vertical 60-second Bunsen burner test. Recently enacted regulations based on correlation of small-scale reaction-to-fire test and full-scale aircraft cabin fire test data by the FAA specify maximum smoke and heat release values for large-area materials in an effort to delay the cabin flashover and provide increased escape time for passengers. Cabin flashover is a nonsurvivable condition characterized by localized ignition of the hot smoky layer containing incomplete combustion products and rapid fire growth through the cabin interior. It is the aircraft industry's opinion that these stringent regulations, which required materials upgrades over a relatively short period of time, have resulted in less than optimum design solutions in many areas—the cost of which is passed along to passengers. Based on this experience there is a need for aircraft industry participation early in the current research program.

TABLE 1. AIRCRAFT CABIN MATERIALS

Cabin Material	Kilograms Weight per Aircraft	Cabin Material	Kilograms Weight per Aircraft
Acoustical insulation	100-400	Paint	5
Blankets	20-250	Passenger service units	250-350
Cargo liners	>50	Partitions and sidewalls	100-1000
Carpeting	100-400	Pillows	5-70
Ceiling	600	Thermoplastic parts	≈ 250
Curtains	0-100	Seat belts	5-160
Ducting	450	Seat cushions	175-900
Elastomers	250	Seat upholstery	80-430
Emergency slides	25-500	Seat trim	40-200
Floor panels	70-450	Wall covering	≈ 50
Floor coverings	10-100	Windows	200-350
Life rafts	160-530	Window shades	100
Life vests	50-250	Wire insulation	150-200
		Total combustibles	3300-8400

The remaining 10 to 20 percent of aircraft cabin interior materials include floor coverings, textiles, draperies, upholstery, cushions, wall coverings, blankets, thermoacoustic insulation, cargo compartment liners, air ducting, trim strips, and molded and thermoformed plastic parts such as

overhead passenger service units and seat components which are often painted to comply with aesthetic design requirements. These interior materials are not governed by the new heat release and smoke generation rules and are only required to pass a Bunsen burner ignitability test or, in the case of upholstered seat cushions and cargo liners, an oil burner impingement test for ignitability. Aircraft seats have been the primary fuel load in a cabin fire and are typically constructed of fire-retarded polyurethane foam encapsulated with a fire-blocking layer and covered with upholstery fabric. Prior to 1984, seating materials were required to be self-extinguishing in a vertical Bunsen burner test after 12 seconds of ignition. Since then the FAA has established an oil burner test for seat back and bottom cushions in a chair configuration which more accurately simulates real fire conditions.

The use of a fire-blocking layer material to encapsulate and delay ignition of the polyurethane foam was a practical alternative to inherently fire-resistant foam. Aramid quilts or polybenzimidazole felt/fabric are now used as fire-blocking layers over fire-retarded urethane foam in passenger aircraft. These seat fire-blocking layers prevent ignition of both fire-retarded and nonfire retarded urethane foams when subjected to small to medium ignition sources such as cigarettes, newspapers, or a pint of gasoline. In simulated postcrash cabin fires the seat fire-blocking layers slow fire growth and can provide 40-60 seconds of additional passenger escape time before full involvement of the seat cushions [7]. Fire retardant chemicals have been added directly to the foam to reduce the vulnerability to small ignition sources. However, this approach translates into minimal fire safety improvement in real cabin fires because once ignited, a fire-retarded foam core burns readily and significantly contributes to the spread of the fire [8]. Neoprene (chloroprene) foam provides a significant improvement in seat cushion fire safety at one-quarter the heat release rate of urethane, but they are considered by airframe manufacturers and airlines to be unsuitable for aircraft use because of their 3-4 times higher density. New combustion-modified urethane foams pass the kerosene burner ignitability test without fire-blocking layers and their use in aircraft passenger seating is increasing.

FIRE HAZARDS OF AIRCRAFT CABIN MATERIALS.

Compartment fires in aircraft, ships, ground vehicles, and buildings are the most severe from a fire safety perspective because enclosed spaces hold heat and combustion products which increase the severity of the fire and its impact on those exposed [2]. Fires in aircraft, space vehicles, ships, and submarines are particularly hazardous because of the small size of the compartments and the difficulty or impossibility of escape. In aircraft, postcrash cabin fires ignited from spilled jet fuel become life-threatening when the cabin materials become involved and the fire propagates through the cabin generating heat, smoke, and toxic decomposition products. Hot combustion products rise from the fire entraining air and form a distinct, hot, smoky layer just below the ceiling, and it deepens as the fire continues to burn. The availability of air influences the products of combustion as well as the intensity of a fire. As oxygen is depleted during combustion, the fraction of carbon monoxide in the smoke increases appreciably and becomes the primary toxicant in a fire. Burning panels fall and ignite seats causing total involvement of the interior. FAA full-scale aircraft cabin measurements of fire hazards—temperature, smoke, oxygen deprivation, carbon dioxide, carbon monoxide, and irritant gases such as HCl and HF—indicate that these hazards increase markedly at flashover and exceed individual and combined tolerance limits [9] at that time. Consequently the time required to reach flashover is a measure of the time available for escape from an aircraft cabin fire.

Figure 1 shows FAA data for chemical heat release rate of interior cabin materials plotted versus the reciprocal of the time to flashover measured in full-scale aircraft cabin fire tests. Heat release rate data are peak values from oxygen consumption calorimetry at an external heat flux of 50 kW/m², which is representative of an external fuel fire. Samples were 6-mm-thick Nomex honeycomb with resin/fiber skins of epoxy, phenolic, or polyimide resin on glass or carbon fabric

reinforcements to which were adhesively bonded a 50-micron (0.002-inch)-thick decorative film of PVF or PEEK. Time-to-flashover data were obtained in separate full-scale aircraft cabin tests using the indicated panel materials in a realistic cabin configuration with upholstered seats and carpeting, and ignited through an open door by a kerosene fire [10]. Incident heat fluxes of $50 \pm 10 \text{ kW/m}^2$ were measured near the bottom and center of the open door exposed to the kerosene pan fire [9].

The polyimide/glass skin-Nomex honeycomb sandwich with PEEK decorative film barely ignited under FAR 25.853(a-1) test conditions (35 kW/m^2 irradiance) and exhibited a factor of ten lower heat release rate than conventional materials. This reduced ignitability increased the time to flashover (escape time) in the full-scale fire tests from about 4 minutes to greater than 10 minutes (no flashover was observed). Unfortunately, the ultra-fire-resistant PEEK/polyimide sandwich panel fabricated for demonstration purposes would be prohibitively expensive for aircraft manufacturers to purchase and manufacture at present and would not possess the durability and aesthetics needed for interior constructions. Other correlations of heat release rate with time to flashover of materials in enclosure fires include using the peak heat release rate divided by the time to ignition in a bench-scale test, the total heat release, and the time to reach a heat release rate of one megawatt in a room-corner fire test of the same materials [11]. In any case it is clear that the escape time from a burning aircraft cabin is limited by the heat release rate of the cabin materials.

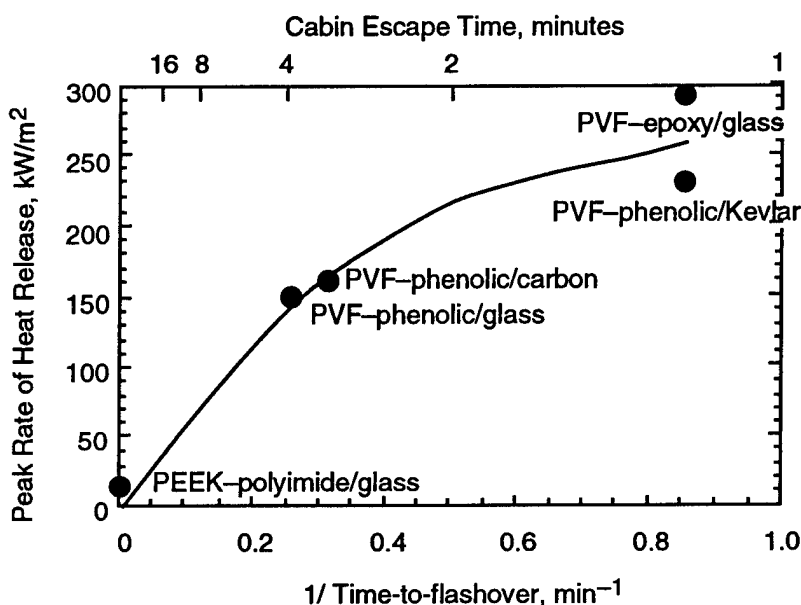


FIGURE 1. PEAK HEAT RELEASE RATE VERSUS RECIPROCAL TIME TO FLASHOVER (ESCAPE TIME) OF DIFFERENT PANEL MATERIALS IN A FULL-SCALE, POSTCRASH FIRE SIMULATION

MATERIALS FIRE SAFETY NEEDS FOR FUTURE AIRCRAFT.

Aircraft operators and manufacturers are sensitive to cost and cost-effectiveness. Aircraft operators estimate that each pound of weight on a commercial aircraft costs between \$100 to \$300 in operating expenses over the service life of the aircraft. Consequently, fire safe materials for use in aircraft must be extremely lightweight. Aircraft manufacturers have made a large investment in processing equipment so that to be cost-effective new materials must be similar to previous

materials in procurement costs, fabrication flexibility, scrap disposition, and recycling capabilities [12-14]. Fire safe materials cannot be used in aircraft no matter how desirable their properties if processing and manufacture cannot be performed efficiently and economically.

Current installed costs for aircraft materials average \$300/lb, of which over 60 percent is manufacturing cost including processing and fabrication. Less than 20 percent of the product cost is attributable to design, development, and analysis in a successful aircraft program. The remaining 20 percent, or \$60/lb, is materials costs. The complexity of aircraft and the potentially catastrophic consequences of errors demand that part fabrication be reliable and repeatable. To implement aircraft fire safety improvements through material upgrades without regulatory intervention, new materials need to deliver substantial benefits to the aircraft engineering, manufacturing, and interior design communities in addition to providing improved fire safety. The central objective in developing new materials is to deliver cost-effective technology which adds value to the product manifested in improved fire safety, reduced installed part cost, and enhanced in-service performance. The speed of technology development will be facilitated by working in a collaborative environment with the aircraft and materials industries, academia, and government agencies [13-15].

As the design and analysis tools for fiber-reinforced structural composites mature over the next decade and production becomes more efficient, aircraft manufacturers will use increasing amounts of lightweight structural composites in airframes and skins to improve fuel efficiency. Future aircraft will require significant reductions in materials flammability to maintain even current cabin and airframe fire loads since the use of combustible, lightweight organic materials is expected to rise dramatically to achieve the high-strength, lightweight structures and interiors required in large subsonic and advanced supersonic aircraft. Boeing Aircraft Co. projections for the structural weight fraction of polymer composites in subsonic commercial airplanes show increases from about 7 percent currently to about 20 percent over the next 15 years. The fireworthiness of these structural composites in ramp, inflight, and postcrash fires will become an issue as their usage increases because of their flammability and unique thermal- and fire-response characteristics such as anisotropic thermal conductivity [16] and persistent smoldering after flame extinguishment. Future fireworthiness problems relate to the relatively high heat release of current structural composite materials, such as carbon fiber-reinforced epoxies and bismaleimides [17], and a lack of knowledge concerning the structural performance of these materials during and after fire exposure. Fiber composites made from high-temperature resins such as poly(ether ether ketone) (PEEK), polyimide, or phenolic are more resistant to ignition at realistic fire heat fluxes [18] but suffer from low compressive strength, poor fracture toughness, and low damage tolerance related to their processing characteristics.

Semistructural and nonstructural applications of polymers and composites in cabin interiors are certain to increase in the form of passenger electronics and telecommunications equipment such as seat-mounted flat panel displays for broadcast and recorded information, faxes, computers, and telephones, all of which will have plastic screens, housings, circuit boards, and wiring. Associated with the projected increase in passenger electronics and the recent introduction of fly-by-wire control systems is a higher risk of electrical fires in and around the passenger compartment and an increase in the consequences of these inflight fires. The current ban on the production of ozone-depleting Halon® 1211 and Halon®1301 fire suppression agents currently used for extinguishing cabin, cargo compartment, and engine fires may result in the use of less efficient agents and increased need for fire-hardened components in inaccessible areas.

Postcrash fire-hardening of cabin materials may be necessary if a proposed double-deck widebody aircraft holding 600-800 passengers is introduced by U.S. airframe manufacturers. Factors such as crowd control and overlapping of deployed evacuation slides may unexpectedly increase the evacuation time of a large aircraft in a real accident to greater than the 90-second certification requirement for escape of a full passenger load through one-half of the installed passenger exits.

Consequently, human and mechanical factors peculiar to a double-deck widebody aircraft could necessitate significant materials flammability upgrades to increase the time to flashover of the cabin interior and provide additional time for passenger escape in a postcrash fuel fire.

The recent move in Europe to eliminate all halogen containing materials and chemicals as potential ozone depleters indicates a desire to develop halogen-free fire safe materials. Halogenated polymers and polymers modified with halogenated additives are highly resistant to ignition, particularly in synergistic combination with other additives. However once ignited, combustion of halogenated materials produces toxic acid gases (HCl, HF, HBr) which cause respiratory and eye irritation in passengers and corrosion of the aluminum airframe and electronic components [19].

A multipurpose, universal polymer system with superior fire resistance, toughness, strength, facile processing, and recycleability needs to be developed which could be used alone or in combination as a structural composite matrix resin, adhesive, coating, fiber, and molding compound. A flammable polymer which could be used for the majority of these applications if its fire resistance was improved is epoxy. Advantages of the multipurpose polymer approach include a broad economical supplier base, redundant certification, reduced inventory, joining compatibility, processing knowledge base, and design familiarity. Current activity within the aircraft industry to develop a universal fire-resistant polymer centers around polyetherimide thermoplastic molding compounds for seat parts, passenger service units, and as a matrix resin for fiber-reinforced composite skins on honeycomb sidewall panels and stowage bins [20]. Fire safe thermoplastic polymers have advantages over thermosets as a universal polymer such as less expensive tooling; more versatile production cycles; short process cycles; elimination of hand finishing; durability without weight penalty; integral color, pattern, and texture; recycleable materials usage; and better specific fire behavior without loss of durability or appearance. Factors favoring thermosets include lower cost and the ability to use existing processing machinery and technology. The universal polymer concept is analogous to the aircraft aluminum alloy which has processing-dependent properties and obviates the need for a large inventory of different alloys and materials forms [12].

TECHNICAL APPROACH

The Fire-Resistant Materials Program is a long-range research effort within the Department of Transportation's Federal Aviation Administration to develop fire safe materials for use on future commercial aircraft. The FAA Fire-Resistant Materials Program goal is to eliminate burning cabin materials as a cause of death in aircraft accidents over the next 10 to 15 years. In accord with the National Research Council recommendations [13, 14] for improved fire-resistant materials for commercial transport aircraft, the following technical objectives were developed: (1) Discover the fundamental relationships between the composition and structure of materials and their behavior in fires and, using this knowledge, (2) identify and design new materials and material combinations which provide an order-of-magnitude improvement in aircraft fireworthiness. (3) Develop the processing technology to ensure manufacturability and recycleability of advanced fire safe materials.

Only when research provides adequate knowledge about the relationship between the constitution of materials and their response to the fire environment can the scientific design of functional new materials for aircraft use be successful. Aircraft materials which are targeted for upgraded fire resistance are:

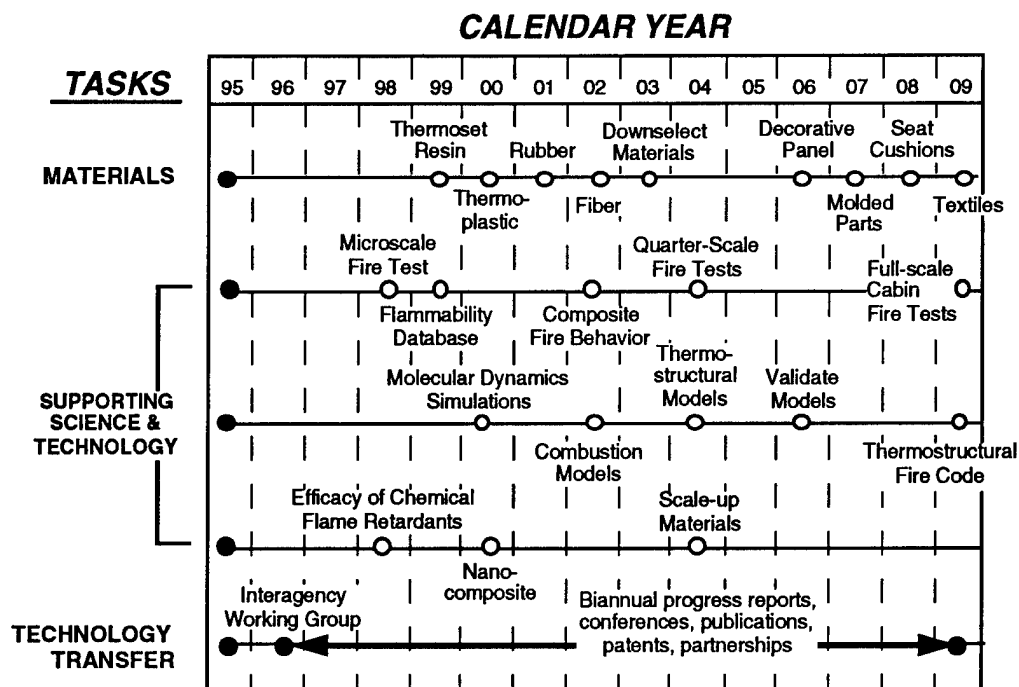
- THERMOSET RESINS for interior decorative panels, secondary composites, and adhesives.
- THERMOPLASTICS for decorative facings, telecommunication equipment, passenger service units, molded seat parts, transparencies, and electrical wiring.

- TEXTILE FIBERS for upholstery, carpets, decorative murals, and, tapestries.
- ELASTOMERS (rubber) for seat cushions, pillows, and sealants.

Supporting research will explore the solid-state burning process of materials and identify material properties which govern fire resistance. Early and direct involvement of the materials and aviation industries in the program (i.e., concurrent engineering) will facilitate technology transfer and provide market opportunities for fire-resistant materials outside of civil aviation (e.g., ground transportation, military, building and construction, consumer products, etc.). Expanded markets will ensure affordability and availability of new technology through market pull and result in voluntary flammability upgrades without costly regulatory burdens for the airlines.

A timeline identifying major product milestones is given in table 2. Materials milestones in years 1999-2003 refer to the demonstration of a 50 percent reduction in heat release rate compared to current cabin materials when measured in laboratory- or bench-scale tests. Downselection to the most promising candidate in each category (e.g., resin, plastic, rubber, fiber) will be made over this period on the basis of functionality, cost, and potential to meeting the above fire performance guidelines. Scale-up of the most promising fire-resistant materials beginning in 2004 will be required to fabricate material assemblies (e.g., decorative panels, molded parts, seat cushions, textiles) for component demonstration of zero heat release rate in the years 2006-2009. Full-scale testing is scheduled for 2010 but is contingent upon the availability of program funds or commercial interest from the private sector. Milestones for Supporting Science and Technology in table 2 refer to technology demonstration at the laboratory scale or in a personal computing environment. Commercialization of fire test instrumentation and analytical tools from the program will depend on private sector interest.

TABLE 2. FIRE-RESISTANT AIRCRAFT MATERIALS PROGRAM MILESTONES



RESULTS

THERMOSET RESINS FOR DECORATIVE PANELS.

The flammability of organic polymer matrix, fiber-reinforced composites limits their use in commercial aircraft where a fire hazard is an important design consideration because of restricted egress. At the present time, affordable, processable resins for fire-resistant aircraft interiors are unavailable since most organic polymers used for this purpose ignite and burn readily under fuel fire exposure conditions.

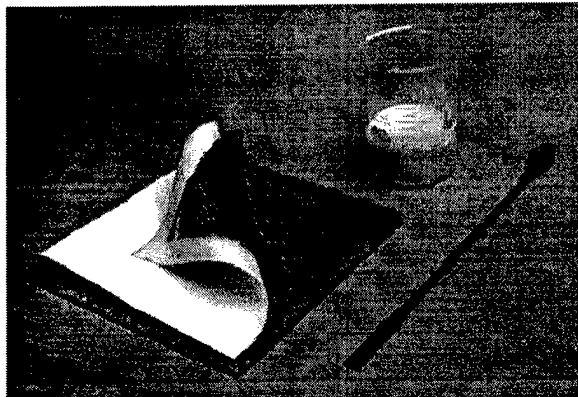


FIGURE 2. INTERIOR PANEL CONSTRUCTION

Carbon fabric-reinforced Geopolymer crossply laminates were found to have comparable initial strength to phenolic resin composites currently used in aircraft interiors. Unlike the phenolic laminates, however, the Geopolymer composites did not ignite, burn, or release any heat or smoke even after extended exposure to high heat flux. Geopolymer composites retained 67 percent of their original flexural strength after fire exposure while organic (e.g., phenolic) composites and aluminum had no residual strength after the test. Geopolymer composites have higher strength and stiffness per unit weight, higher temperature capability, and better fatigue resistance than steel or aluminum.

Future work will focus on understanding how Geopolymer resin protects the carbon fibers from oxidative degradation at 800°C (1500°F) in air, how to optimize the processing to obtain maximum strength, and improve the toughness of laminated composites (Rutgers University/FAA)

Additional results on fire-resistant resins include:

- **Polybenzoxazine resins** are a new, low-cost phenol-formaldehyde (phenolic) substitute for use in aircraft interior decorative panels. Polybenzoxazines have demonstrated 80 percent lower heat release rate, lower toxicity, and better surface finish due to the absence of volatile reaction products. A patent has been filed on this technology (Case Western Reserve University).

The Geopolymer resin in the beaker in figure 2 is being evaluated as a matrix for fireproof, fiber-reinforced composites which can be used in aircraft cabin interior panels and cargo liners. A successful cargo liner test of a Geopolymer composite is shown in figure 3. Geopolymer is a two-part, water based, liquid inorganic (polysialate) resin which hardens at 80°C (176°F) to a ceramic having twice the density of water. The fire response and mechanical properties of Geopolymer composites were measured and compared to lightweight organic matrix composites and aluminum used in aircraft.

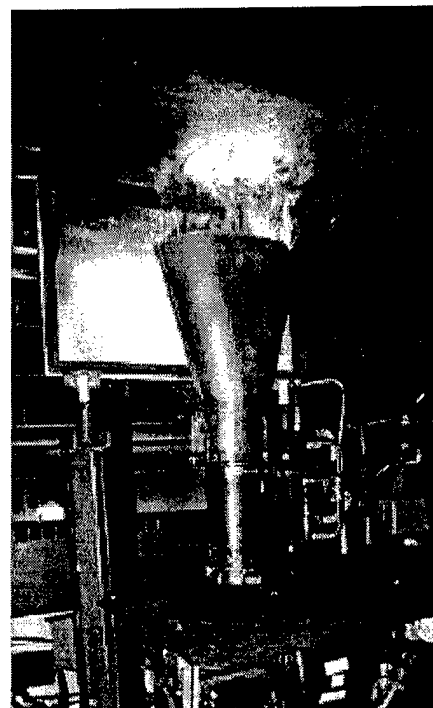


FIGURE 3. OIL BURNER TEST OF FIREPROOF COMPOSITE

- **A zero heat release carbon-silicon resin** has been synthesized which has 97 percent char yield when burned. A patent has been filed on this technology (Dow Corning).
- **Ethynyl polymers** give off only 25 weight percent of combustible gases when burned (75 percent char yield). A patent has been filed on these materials (University South Carolina).
- **A low fuel value polymer is obtained from renewable sources** by reacting silica sand or rice hulls with ethylene glycol (antifreeze) in the presence of an amine base to yield semi-inorganic monomers in essentially quantitative yield. Subsequent curing produces a variety of inexpensive silicon-containing polymers ranging from hard transparent films to low-density foams. A patent disclosure has been filed on this technology (University of Michigan).
- **Polycyanurate resins** were prepared from polystyrene and evaluated for flammability along with commercial cyanate esters (Richard Stockton College of New Jersey/National Institute of Standards and Technology (NIST)/FAA).
- **Inorganic fire retardants based on zirconia and boron oxides** are highly efficient, environmentally benign additives which reduce the peak heat release rate by 60-80 percent in commodity (nylon, PE, polypropylene) and engineering (cyanate esters, ULTEM PEI) polymers at low concentrations without increasing smoke or carbon monoxide. A NIST patent is being filed on this technology.

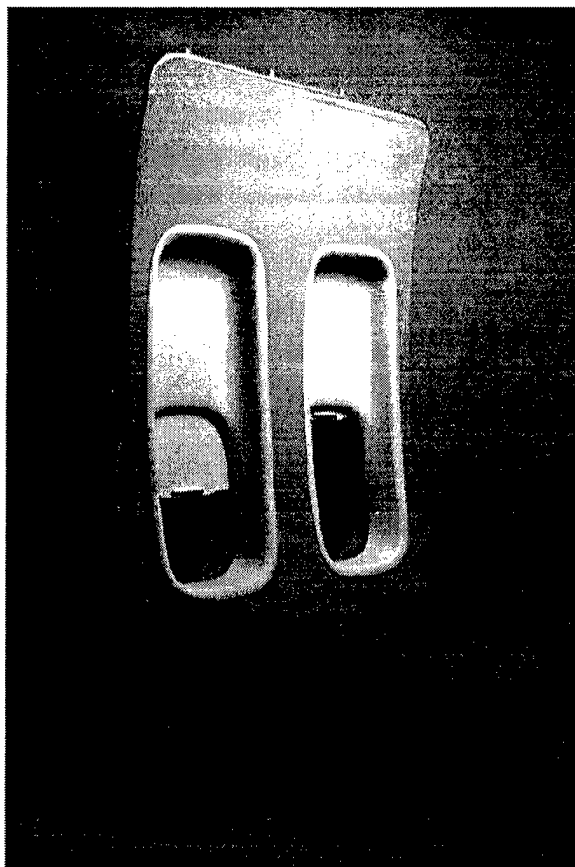


FIGURE 4. CABIN INTERIOR PANEL

THERMOPLASTICS FOR MOLDED PARTS.

Commercial transport aircraft contain between 1500 and 2500 pounds of flammable plastics as seat trim, windows, window shades, wire insulation, and miscellaneous parts. At present these molded parts are not required to meet the heat release rate regulations imposed on large-area interior panels (figure 4), and stowage bins, ceilings, and partitions because of their small size. High-temperature plastics which pass the heat release rate test do not have the requisite toughness, durability, environmental resistance, and aesthetics to function effectively in aircraft interiors.

Nanocomposite technology is an entirely new generic approach to reducing the flammability of polymeric (plastic) materials using environmentally friendly, chemical-free additives. The fire-retardant effect of nanometer sized clay particles in plastics was discovered by the FAA through a research grant to Cornell University. The National Institute of Standards and Technology (NIST) has subsequently confirmed the effect in fire calorimeter testing. The approach is to disperse individual, nanometer-sized, layered silicates in a molten polymer to create a clay-plastic nanocomposite (figure 5). The clay particles are about the same size as the polymer molecules

themselves (less than one millionth of an inch) so they become intimately mixed and chemically bonded. This has the overall effect of increasing the thermal stability and viscosity of the plastic while reducing the transmission of fuel gases generated during burning.

The result is a 60 to 80 percent reduction in the rate of heat released from a burning plastic nanocomposite containing only 5 to 10 percent clay by weight. This extraordinarily high degree of fire-retardant efficiency comes with reduced smoke and toxic gas emissions and at no sacrifice in mechanical properties. Plastic nanocomposites have twice the stiffness and strength of the original material and a higher softening temperature (Cornell University/NIST).

Additional results related to fire-resistant thermoplastics include:

- **Ultrahigh modulus thermoplastic molecular composites** have been tested which have low heat release rates and three times the strength and stiffness of high-temperature engineering plastics (MAXDEM, Inc.).
- **New phosphineoxide-polyetherimide thermoplastics** have significantly lower heat release rate when burned than commercial polyetherimides (ULTEM) currently used in aircraft interiors (Virginia Polytechnic and State University, Blacksburg).
- **Polycarbodiimides are carbon-nitrogen backbone polymers** which can be flexible elastomers or rigid resins have been prepared from inexpensive starting materials. Polymers depolymerize cleanly to monomers with extremely low fuel value upon heating to 200°C. Molecular modeling shows that thermal stability can be increased through stereochemistry (University of Massachusetts, Amherst).
- **Novel organic-inorganic interpenetrating networks (IPN's)** have been synthesized by separately polymerizing organic and inorganic monomers in the same reaction mixture to give a co-continuous morphology. The reaction is solvent free and the inorganic (silica) phase is atomically dispersed so that the material is transparent, rigid, and has higher thermal stability than the organic phase alone (University of Massachusetts, Amherst).
- **Surface active flame retardants** concentrate at a burning polymer surface using interfacial free energy as the driving force. Migration of surface active flame retardants from the bulk to the burning surface improves flame retardant efficiency by reducing the loading level required for fire resistance (University of Massachusetts, Amherst).

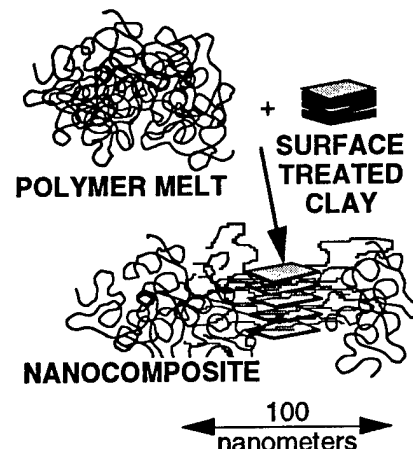


FIGURE 5. PROCESSING ROUTE TO NANOCOMPOSITES

RUBBER FOR SEAT CUSHIONS.

Commercial transport aircraft contain between 1000 and 2500 pounds of flammable elastomers (rubber) which are foamed to make seat cushions and pillows or used at full density as sealants and gaskets. Foamed polyurethane rubber seat cushions are favored for their durability and recovery but they are the primary fire load in aircraft interiors. In 1987 the FAA imposed regulations on the flammability of aircraft seat cushions to delay their involvement in cabin fires. Manufacturers responded to these regulations by wrapping the polyurethane seat cushion in a fire-resistant barrier fabric. Seat fire blocking allowed manufacturers to pass the FAA certification test but the cushions burn vigorously when the fire-blocking layer is consumed after minutes of exposure to a fire.

The flammability of rubber depends on the chemical composition of the polymer from which it is made. Rubbers made from carbon-hydrogen based (organic) polymers are the most flammable because of their high fuel value (figures 6 and 7). Replacing carbon and hydrogen atoms in the polymer with inorganic atoms such as chlorine, silicon, nitrogen, sulfur, or phosphorus, results in a semi-organic polymer with reduced flammability because of the lower fuel value or increased heat resistance. In the Fire Resistant Materials research program we are focusing on semiorganic rubbers for seat cushions.

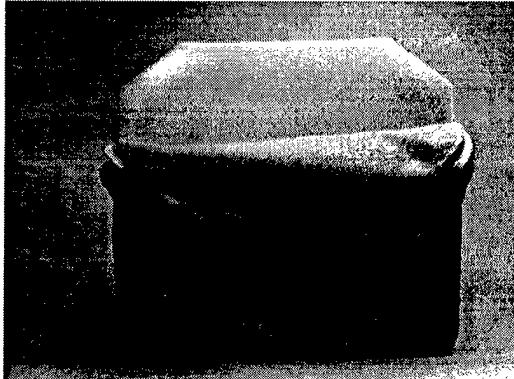


FIGURE 6. TYPICAL SEAT CUSHION CONSTRUCTION



FIGURE 7. FULL-SCALE FIRE TEST OF SEAT ASSEMBLY

Phenyl-silicon-oxygen backbone (silphenylene) elastomers which are crosslinkable and extremely heat resistant have been synthesized. The silphenylene contains only 30 percent combustible material and can withstand temperatures of 600°C (1100°F). A patent is being filed on this composition of matter (University of Massachusetts, Amherst).

Polyphosphazenes are semiorganic rubbers based on a phosphorus-nitrogen backbone which contain an organic group which allows the material to be dissolved or crosslinked. Commercial production of polyphosphazene was recently discontinued despite the extremely low toxicity and ultra fire resistance of these foams because the process for making them was prohibitively expensive. We are pursuing a new low-cost, low temperature, synthetic route to polyphosphazenes which eliminates a costly intermediate from the process and allows control over the molecular weight of the polymer. This new direct synthetic route has provided the first phosphazene copolymers including an 80-20 urethane-phosphazene copolymer which does not ignite in a flame. A patent has been filed on this process (The Pennsylvania State University).

FIBERS FOR CARPETS AND TEXTILES.

Approximately 2000 pounds of combustible textile fibers are used in a modern commercial aircraft interior as seat upholstery, decorative textiles, wall coverings, carpeting, tapestries, blankets, curtains, and seat belts. Typical fabrics include wool, nylon/wool blends, and fire-retarded polyester, wool, and nylon. The chemical fire retardants added to these fibers reduce the propensity for small-scale ignition but increase the smoke density and toxic gas generation once the fibers catch fire and have little or no effect on the heat release rate. Our research in fibers focuses on materials with unusually high thermal stability which have intrinsic fire resistance without the need for chemical additives. Research includes:

- **Zero heat release polyimide fibers** are melt and solvent processable for spinning ultrahigh-strength, thermally stable fibers and casting films. Fibers of this material exhibit the lowest (microscale) heat release rate of any polymer tested to date—ten times lower than

aramid (Kevlar™) fibers and 150 times lower than nylon used in seat fabrics (University of Akron).

- **Substituted polyhydroxyamides generate flame retardant compounds in a fire** through a thermally activated chemical reaction which produces a zero heat release polymer (polybenzoxazole) during heating (University of Massachusetts, Amherst).

SUPPORTING SCIENCE AND TECHNOLOGY.

A microscale combustion calorimeter has been developed to measure flammability parameters of milligram polymer (plastic) samples under conditions which approximate aircraft cabin fires. The test takes only a few minutes to run and provides a quantitative measure of the aircraft fire hazard of research materials which are only available in milligram quantities from university and industrial polymer scientists. Quick feedback on flammability of new materials has helped guide the synthetic effort towards improved fire resistance. Figure 8 is a photograph of the microscale combustion calorimeter. A sharp, quantitative, and reproducible heat release rate peak is obtained in the microscale heat release rate test. After normalizing the curves for the sample size the results are independent of the physical form of the material (e.g., powder, film, fiber, etc.). The microscale heat release rate data are expressed in kilowatts per gram of original material.

Figure 9 compares the peak microscale heat release rate (HRR) measured on milligram samples of pure plastics in the microcalorimeter to the heat release rate measured for 100 gram samples of the same material in a conventional fire calorimeter. The heat release rate plotted along the vertical axis is the steady-state or average value obtained in a fire (cone) calorimeter at 50 kW/m² incident heat flux according to standard procedures.

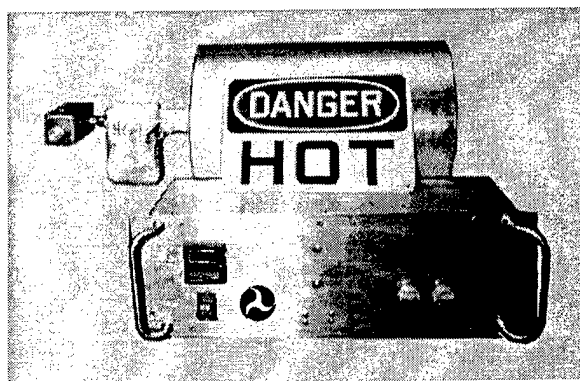


FIGURE 8. FAA'S MICROSCALE COMBUSTION CALORIMETER

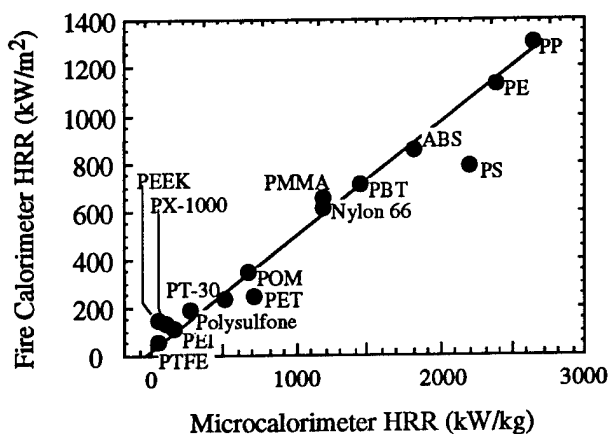


FIGURE 9. CORRELATION BETWEEN FIRE TEST AND MICROSCALE CALORIMETER RESULTS FOR HEAT RELEASE RATE OF PLASTICS

FAA full-scale fire tests have shown that the heat release rate of interior materials measured in a fire calorimeter correlates with passenger escape time in a simulated postcrash fuel fire. The good correlation between fire- and micro-calorimeter results shows that the microcalorimeter is also a good predictor of passenger escape time and, therefore, of full-scale fire hazard. A DOT/FAA patent has been filed on this invention (FAA/Galaxy Scientific Corporation).

Figure 10 shows microcalorimeter results for some of the new materials being developed in the program and how they compare materials currently being used in aircraft. It is clear that most of

the new materials tested show significantly lower heat release rate when combusted than do the current (baseline) aircraft materials.

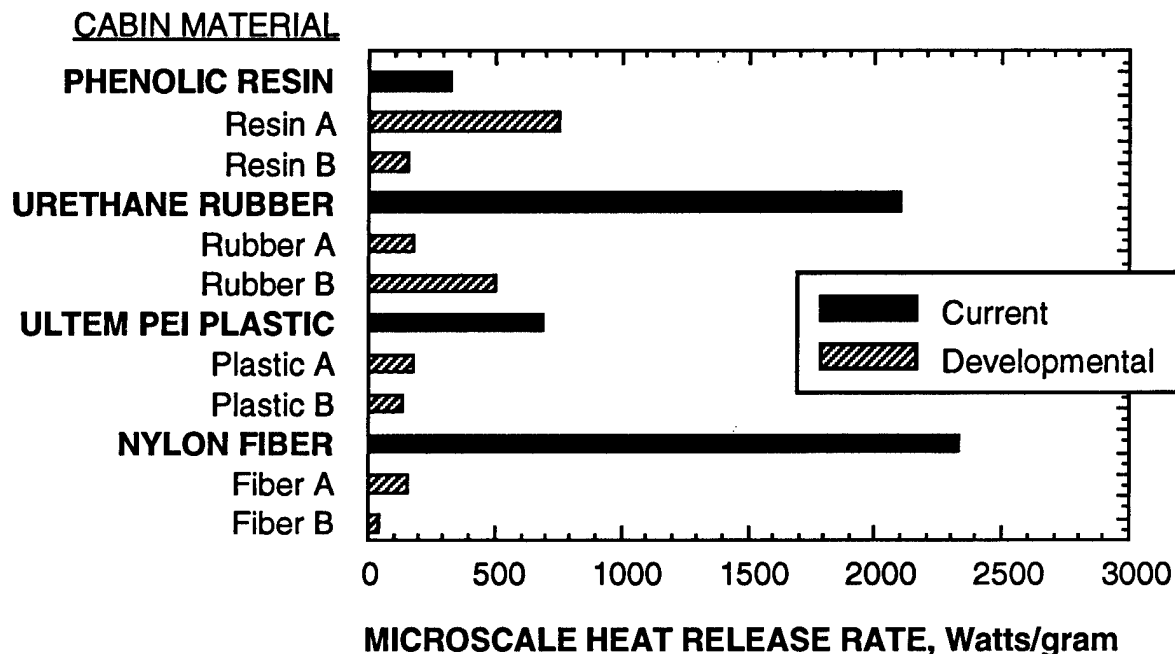


FIGURE 10. HEAT RELEASE RATE OF CURRENT AND DEVELOPMENTAL AIRCRAFT CABIN MATERIALS

In addition to creating a metric for materials development (i.e., the microscale calorimeter), the Supporting Science and Technology component of the program provided the following technology base:

- **Thermal degradation of polymers was modeled by computer** to study the process which generates combustible fuel in a fire. The computer code (MD REACT) uses a commercial program (Discover 95, Molecular Simulations) to create the polymer chains for the model and then simulates the thermal degradation process at fire temperatures. This code will provide insight into the process and products of thermal degradation to allow the design of thermally stable, less toxic, fire-resistant polymers (NIST)
- **A mechanistic fuel generation model** was developed for polymers in fires which includes the competing processes of gasification and char formation. The simple analytic result provides the fuel generation rate of a burning polymer from conventional laboratory thermal analysis data (FAA William J. Hughes Technical Center).
- **Molecular modeling of flammability** utilizes computational quantum chemistry to predict the thermochemistry and kinetics of solid- and gas-phase combustion processes of burning polymers. Initial results for the effects of chain size and stereoregularity on the bond dissociation energy of novel polycarbodiimides were obtained (University of Massachusetts, Amherst).
- **Atomistic models of polybenzoxazine** have been developed and solved on a computer which provide insight into the high thermal stability and unusual volumetric expansion on polymerization (University of Akron).

- **Computational modeling of intumescence** has shown the importance of bubble nucleation kinetics and thermal properties on the insulation value of this important commercial fireproofing technology (NIST).
- **Thermomechanical stability of fire-exposed resins and composites** are studied using a new noncontact technique—ultrasonic spectroscopy. Results indicate surface embrittlement of the resin in a fire initiates surface cracks which mechanically destabilize the composite (University of Massachusetts, Amherst).
- **An integral method of nonisothermal kinetic analysis** provides a new, semiexact solution of the mass loss integral which is useful for extracting flammability parameters from laboratory thermal analysis data (FAA William J. Hughes Technical Center).
- **In situ flame chemistry by remote laser spectroscopy** has been successful at identifying flame species in burning polymers to study the chemical reactions which lead to combustion inhibition and toxic byproducts in flame retarded polymers. A patent is being filed on this technology (University South Carolina).
- **Fire calorimetry of flame-retardant polymers** showed that fire-retarded (FR) polymers ignited and burned readily under aircraft cabin fire exposure conditions with increased smoke and toxic gas production compared to the original (non-FR) material—validating the FAA's focus on inherently fire-resistant polymers and composites (Omega Point Labs).

TECHNOLOGY TRANSFER.

- Eight patents have been filed on fire-resistant materials and technology developed by the FAA or through FAA-sponsored research during the first 2 years of the program.
- An Interagency Working Group on Fire and Materials has been created in which 40 government agencies meet semiannually to share research results and information. A memoranda of understanding (MOU) has been signed. The group is FAA-chaired.
- Published National Research Council Study on Improved Fire- and Smoke-Resistant Materials for Commercial Aircraft Interiors (NMAB-477-1, 1995).
- Formed university-government-industry consortium on Fire Safe Aircraft Materials at University of Mass., Amherst. Several Fortune 100 companies (including Boeing Aircraft Co.) are contributing directly to FAA program to share research costs.
- Joined EPIC (university-government-industry) Consortium at Case Western Reserve University, Cleveland, OH.
- Sponsored four FAA sessions on New Developments in Fire-Resistant Polymers at Society of Plastics Engineers Annual Technical Conference, Indianapolis, IN, May 1996.
- Three sessions on Fire Safe Materials at Society for the Advancement of Materials and Process Engineering (SAMPE) International Symposium, Anaheim, CA, March 1996.
- International FAA Symposium on Fire Calorimetry, Gaithersburg, MD (DOT/FAA/CT-95/46).
- Published over 100 journal and proceedings articles describing FAA and FAA-sponsored fire-resistant materials research since 1995.

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