

DOT/FAA/AR-95/98

Office of Aviation Research
Washington, D.C. 20591

Advanced Fire-Safe Aircraft Materials Research Program

Richard E. Lyon

Airport and Aircraft Safety
Research and Development Division
FAA Technical Center
Atlantic City International Airport, NJ 08405

January 1996

Final Report

This document is available to the U.S. public
through the National Technical Information
Service, Springfield, Virginia 22161.



U.S. Department of Transportation
Federal Aviation Administration

1. Report No. DOT/FAA/AR-95/98		2. Government Accession No.		3. Recipient's Catalog No.	
4. Title and Subtitle ADVANCED FIRE-SAFE AIRCRAFT MATERIALS RESEARCH PROGRAM				5. Report Date January 1996	
				6. Performing Organization Code AAR-423	
7. Author(s) Richard E. Lyon				8. Performing Organization Report No. DOT/FAA/AR-95/98	
9. Performing Organization Name and Address Airport and Aircraft Safety Research and Development Division FAA Technical Center Atlantic City International Airport, NJ 08405				10. Work Unit No. (TRAVIS)	
				11. Contract or Grant No.	
12. Sponsoring Agency Name and Address U.S. Department of Transportation Federal Aviation Administration Office of Aviation Research Washington, D.C. 20591				13. Type of Report and Period Covered Final Report	
				14. Sponsoring Agency Code	
15. Supplementary Notes					
16. Abstract <p>The goal of the Federal Aviation Administration's Fire Research Program is to eliminate fire as a cause of death in aircraft accidents. The Fire Research Program is a long-range research effort which includes advanced materials in a systems approach to improved aircraft cabin fire safety along with fire prevention, detection, and control. The objective of the Advanced Fire-Safe Materials portion of the program is to discover the fundamental relationships between the composition and structure of materials and their behavior in fires to enable the design of a totally fire-resistant cabin for future commercial aircraft. Research will be basic in nature and will focus on synthesis, characterization, modeling, and processing of new materials and materials combinations to improve the fire performance, increase the functionality, and reduce the cost of next-generation cabin materials.</p>					
17. Key Words Fire, Fire safety Flammability, Aircraft materials			18. Distribution Statement This document is available to the public through the National Technical Information Service (NTIS), Springfield, Virginia 22161.		
19. Security Classif. (of this report) Unclassified		20. Security Classif. (of this page) Unclassified		21. No. of Pages 26	22. Price

TABLE OF CONTENTS

	Page
EXECUTIVE SUMMARY	v
BACKGROUND	1
AIRCRAFT CABIN MATERIALS	1
FIRE RESPONSE OF MATERIALS	3
FIRE HAZARDS OF AIRCRAFT MATERIALS	7
MATERIALS FIRE SAFETY NEEDS FOR FUTURE AIRCRAFT	9
FIRE-SAFE MATERIALS RESEARCH	11
Synthesis	13
Characterization	14
Modeling	15
Processing	16
REFERENCES	18

LIST OF FIGURES

Figure		Page
1	$\dot{Q}_c^{8/3}$ of Decorative Panels Versus Reciprocal Time to Flashover in Full-Scale Aircraft Cabin Fire Tests	9
2	$\dot{Q}_c^{peak} / t_{ign}$ of Decorative Panels Versus Reciprocal Time to Flashover in Full-Scale Aircraft Cabin Fire Tests	9

LIST OF TABLES

Table		Page
1	Aircraft Cabin Materials	2
2	Fire-Safe Aircraft Materials Program Milestones	17

EXECUTIVE SUMMARY

The goal of the Federal Aviation Administration's Fire Research Program is to eliminate fire as a cause of death in aircraft accidents. The Fire Research Program is a long-range research effort which includes advanced materials in a systems approach to improved aircraft cabin fire safety along with fire prevention, detection, and control. The objective of the Advanced Fire-Safe Materials portion of the program is to discover the fundamental relationships between the composition and structure of materials and their behavior in fires to enable the design of a totally fire-resistant cabin for future commercial aircraft. Research will be basic in nature and will focus on synthesis, characterization, modeling, and processing of new materials and materials combinations to improve the fire performance, increase the functionality, and reduce the cost of next-generation cabin materials.

BACKGROUND

Approximately twenty percent of the 1153 fatalities on U.S. transport airlines between 1981-1990 occurred in impact-survivable accidents involving fire. If the aircraft accident fatality rate remains constant, the total number of fire deaths will grow at an annual rate of five percent with the expected increase in commercial air passenger traffic. This is an unacceptable prospect and the FAA has taken a bilateral approach to reduce the aircraft accident fatality rate by a factor of two by the year 2000. 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, in-flight, 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 significant.

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

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 forty percent of these fire fatalities can be attributed to smoke and toxic combustion products of burning cabin materials and jet fuel[2], with urethane seat cushions the major cabin material contributor in past 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 aircraft fire safety goal of eliminating cabin fire fatalities will require order-of-magnitude improvements in material fire resistance.

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. Table 1 lists combustible cabin materials and their weight range in commercial passenger aircraft cabins[5]. Multiplying the total weight of combustible textiles,

foams, films, plastics parts and composites in the aircraft cabin by a typical heat of combustion of 15×10^6 Joules/kilogram for current cabin materials, it is found that the fuel load from combustible materials in an aircraft cabin fire is on the order of 100 billion Joules.

Thermoset composites form about eighty to ninety 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 tests 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. 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—indicating 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 twenty 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 as well as 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 1987 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 a kerosene 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 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[5]. However, once ignited a fire-retarded foam core burns readily and significantly contributes to the spread of the fire[6]. Consequently the twenty percent additional weight of the fire-retardant additive in the foam core can reduce the vulnerability to small ignition sources but translates into minimal fire-safety improvement in real cabin fires with regard to heat release. Neoprene (chloroprene) foams provides a significant improvement in seat cushion fire safety at one-quarter the heat release rate of urethane although they are considered by airframe manufacturers and airlines to be unusable on aircraft because of their 3-4 times higher density. New exfoliated graphite-filled urethane foams pass the kerosene burner ignitability test without fire blocking layers and their use in aircraft passenger seating is increasing.

FIRE RESPONSE OF MATERIALS

Materials fire and thermal characteristics which can influence the development of fire hazards in a cabin include ignition temperature, heat release and mass loss rate during combustion, flame spread rate, thermal conductivity, specific heat, density, emissivity, optical properties of smoke, toxicity of combustion products, response to suppressants, and fire endurance. The high incident heat fluxes ($75 \pm 50 \text{ kW/m}^2$) and temperatures ($800 \pm 200^\circ\text{C}$) measured inside of open aircraft cabin doorways in full-scale tests simulating a burning jet fuel spill[7-10] require that essentially non-combustible aircraft cabin materials be developed to prevent ignition, flame spread, smoke, and toxic gas generation under postcrash fire conditions. The importance of incident heat flux on combustion and flame spread has only recently been recognized as an effect which is absent from traditional flammability tests such as the Bunsen burner and oxygen index.

The ignition of a combustible material is the initial step in a fire. A material can ignite by being uniformly heated to an autoignition temperature or by piloted ignition of thermally generated combustible vapors. A higher surface temperature is needed for autoignition since the solid material itself is the ignition source. Actual fires start when the external radiant energy reaches the critical heat flux for autoignition or a localized ignition source (flame or spark) is present. The ignition of a material is considered to consist of three stages: (1) a thermal induction period corresponding to unsteady-state heating by an external source during which the decomposition

temperature front moves through the material causing pyrolysis, (2) a diffusion induction period when volatiles are produced at the receding surface and diffuse into the oxidant (air), and (3) a chemical induction period when the fuel vapors and oxygen react exothermically producing heat (flame)[5].

The generation of combustible vapors in a fire is given by the mass loss rate, \dot{m} , [11]

$$\dot{m} = \frac{(\dot{Q}_{external} + \dot{Q}_{flame} - \dot{Q}_{reradiation})}{\Delta H_g} = \frac{\dot{Q}_{net}}{\Delta H_g} \quad (1)$$

where \dot{Q}_{net} is the difference between the incident heat from an external heater and/or surface flame and the heat lost through reradiation to the surroundings, and ΔH_g is the heat of gasification. The heat of gasification is an operationally defined quantity which may vary during the burning process and relates the fuel gasification rate to the heat absorbed by the material without resorting to a detailed heat transfer and kinetics calculation. The average heat of gasification is determined experimentally from the slope of a plot of peak mass loss rate versus external radiant heat flux according to equation 1. The chemical heat release rate, \dot{Q}_c is the product of the heat of combustion, ΔH_c , the combustion efficiency, ϵ , and the mass loss rate,

$$\dot{Q}_c = \dot{m} \epsilon \Delta H_c = \frac{\epsilon \Delta H_c \dot{Q}_{net}}{\Delta H_g} \quad (2)$$

The chemical heat of combustion, ΔH_c , is the energy liberated during the cleavage of primary chemical bonds in the material and the formation of new chemical bonds during combustion while the heat of gasification depends on the heat capacity, thermal stability, and decomposition temperature of the polymer. For a given thickness of material the ratio $\Delta H_c/\Delta H_g$ in equation 2 is thought to be a characteristic property which depends on the atomic composition of the material and its additives[12]. Since ΔH_c is a thermodynamic quantity it can be calculated from the atomic composition of the material using tabulated values for heats of formation. Using polymethylmethacrylate (PMMA) as an example with atomic composition, $C_5H_8O_2$, the complete combustion to gaseous products under well ventilated fire conditions proceeds as



PMMA has a repeat unit molecular weight of 0.10 kg/mol and heat of formation of -307 kJ/mol, for the (hypothetical) gaseous polymer at 300 K from tabulated group contributions[13]. Heats of formation of gaseous combustion products at 300 K are $O_2 = 0$, $CO_2 = -395$, $H_2O = -229$, $CO = -138$, $C(\text{solid}) = 62$, and $C_2H_4 = 64$ kJ/mol. The calculated heat of complete combustion ($\epsilon \equiv 1.0$) is $\Delta H_c = H_{products} - H_{reactants} = -25.8$ kJ/g in agreement with tabulated values of -26.2 kJ/g measured in an oxygen bomb calorimeter[14]. Polymer molecules which contain little or no hydrogen to react with air and form water have lower heat release in fire tests, perhaps because of the low heat of formation of CO_2 compared to H_2O on a mass basis.

Polytetrafluoroethylene (PTFE) is an example of a polymeric material containing no hydrogen atoms, and this fluoropolymer will only burn in pure oxygen as per[15]



However if hydrogen-containing materials such as polyethylene are present with PTFE, the combination will burn readily in air to form hydrogen fluoride and carbon dioxide

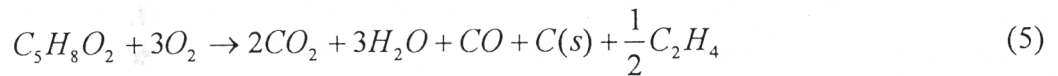


Subtracting the heat of combustion for the pure hydrocarbon



from the heat of combustion of the PTFE+hydrocarbon mixture gives the net heat of combustion for PTFE in the mixture as $\Delta H_c = [(-1872 \text{ kJ/mol}) - (-1265 \text{ kJ/mol})] = -607 \text{ kJ/mol}$. Comparison with the heat of combustion of isolated PTFE (equation 4a), shows that 2.3 times as much heat is released per mole when PTFE is burned in the presence of a hydrogen source such as the polyethylene. These calculations highlight the importance of antagonistic material combinations with regard to fire behavior.

Under poorly ventilated conditions the transport of oxygen into the combustion zone becomes limiting and chemical oxidation is incomplete—producing carbon monoxide, soot, and unburned hydrocarbons. For PMMA an incomplete combustion reaction might be[12]



The heat of combustion for this reaction is $\Delta H_c = -12.1 \text{ kJ/g}$ compared to -25.8 kJ/g for complete combustion, yielding a combustion efficiency $\epsilon = (-12.1 \text{ kJ/g})/(-25.8 \text{ kJ/g}) = 0.47$ for this reaction. Oxygen-depleted cabin environments in full-scale aircraft fire tests are associated with poor ventilation and/or rapid fire growth at flashover. Although the heat release is lower in poorly ventilated conditions the primary nonthermal fire hazards—carbon monoxide poisoning and smoke obscuration—become significant[16].

For a thermally thin material the time to ignition, t_{ign} , at a net incident heat flux, \dot{Q}_{net} , is [17]

$$t_{ign} = \frac{\rho C_p b (T_{ign} - T_o)}{\dot{Q}_{net}} \quad (6)$$

with, ρ , C_p , T_o , T_{ign} , and b , the density, heat capacity, initial (ambient) temperature, ignition temperature, and thickness of the material, respectively. The piloted ignition temperature of a polymer is close to its thermal decomposition temperature in most cases because of the large gaseous fuel generation rate at that temperature. The decomposition temperature of the material

depends on the bond strength of the weakest chemical bond in the constituent molecules[13]. The energy required to break chemical bonds between carbon and other atoms in typical polymeric materials increases in the order: C-I (209 kJ/mol), C-Br (280), C-H (339), C-Cl (397); C-Si (435), C-P(515), C-F (536), C=C (720), C-N (770), C≡C (962), C-O (1075) [18]. These bond energies explain why chlorinated and brominated hydrocarbon polymers and flame retardants have low decomposition and ignition temperatures (< 300°C) and poor thermal stability compared to highly conjugated/fused aromatic systems (-C=C-, -C≡C-, char) and fluorine-, nitrogen-, and oxygen-containing compounds.

If the specimen thickness is such that the time for ignition is less than the thermal penetration time, i.e., $t_{ign} < b^2\rho C_p/k$, for a thermal conductivity, k , then the specimen is considered thermally thick. Under these conditions temperature gradients exist within the material at ignition and the ignition time is[17]

$$t_{ign} = \pi k \rho C_p \left[\frac{T_{ign} - T_o}{2\dot{Q}_{net}} \right]^2 \quad (7)$$

Fire propagation in thermally thick materials is normally associated with the upward or concurrent flame spread rate, dy/dt (m/sec)[19], which for a vertical orientation is

$$Flame\ spread\ rate = \frac{dy}{dt} = \frac{\delta_f}{k\rho C_p} \left[\frac{\chi_r \dot{Q}_c}{T_{ign} - T_o} \right] \quad (8)$$

where δ_f is the flame height and χ_r is the radiant fraction of the chemical heat release rate, \dot{Q}_c . Flame spread rate determines the rate of accumulation of fire hazards—heat, smoke, and toxic gases. If the vertical flame height per unit width, w , is[20,21]

$$\delta_f = 5 \left[\frac{\dot{Q}_c w}{(C_p T_o \rho)_{air} \sqrt{g}} \right]^{2/3} \quad (9)$$

with g the gravitational constant, then

$$Flame\ spread\ rate = \frac{1}{k\rho C_p} \left[\frac{\Phi \chi_r}{T_{ign} - T_o} \right]^2 \dot{Q}_c^{8/3} \quad (10)$$

for

$$\Phi = \left[\frac{11w}{(C_p T_o \rho)_{air} \sqrt{g}} \right]^{1/3} \quad (11)$$

Equation 10 is a scaling relationship between buoyancy-assisted linear flame spread rate on a vertical surface in an aircraft cabin fire and tailorable material properties related to heat transfer (k , ρ , C_p , χ_r), atomic composition (ΔH_c), and thermal stability (T_{ign}). The magnitude of energy required to generate combustible vapors from a material, approximated by the heat of gasification, depends on the thermal stability of the material. While the theoretical heat of combustion depends only on the initial and final (combusted) state, the heat release rate which governs ignitability and fire growth is a superposition of several kinetically determined rate processes which occur during a real fire. These kinetic processes—mass loss rate, oxygen diffusion, and heat conduction—can change the path of the combustion process. The propensity for ignition and flame propagation of thermally thick aircraft materials can be minimized through a reduction in the chemical heat of combustion of the materials or an increase in their decomposition temperature ($\approx T_{ign}$), thermal conductivity, and heat capacity. An increase in density is unacceptable for economic reasons without a commensurate increase in performance.

FIRE HAZARDS OF AIRCRAFT 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 forming a distinct, hot, smoky layer just below the ceiling which deepens as the fire continues to burn. The availability of air influences the products of combustion as well as the intensity of a fire (e.g., equations 3–5), and as oxygen is depleted during combustion the fraction of carbon monoxide in the smoke increases appreciably. 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. Burning panels fall and ignite seats causing total involvement of the interior. 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, exceeding individual and combined tolerance limits[22] at that time. Consequently the time required to reach flashover is a measure of the time available for escape from an aircraft cabin fire.

If flashover corresponds to a critical combustible gas concentration or critical heat release rate in the cabin, the time to flashover in a cabin fire will be the time necessary to involve a critical surface area of material with a particular mass loss rate and heat release rate per unit area[23]. For steady-state fire propagation the rate of surface involvement in the fire (linear growth rate per unit width) divided by the critical area is the reciprocal time to flashover, which according to equation 10 depends on the 8/3 power of either the mass loss rate or the chemical heat release rate. Figure 1 shows FAA data for chemical heat release rate of interior cabin materials plotted according to equation 10 as $\dot{Q}_c^{8/3}$ versus reciprocal time to flashover measured in full-scale aircraft cabin fire tests. Heat release rate data are one-minute averages calculated from oxygen

consumption for an irradiance of 50 kW/m². 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 was adhesively bonded a 50- μ m-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[24]. Incident heat fluxes of 50 ± 10 kW/m² were measured near the bottom and center of the open door exposed to the kerosene pan fire[10].

The solid line in figure 1 is the best linear fit of the data and, assuming similar material properties for all of the composites, indicates approximate scaling as per equation 10. Similar correlation was observed for heat release data of panel materials obtained at 35-kW/m² irradiance and by plotting peak heat release rate or integrated heat release values at 0.5-, 1-, 2-, 3- or 5-minutes test duration. The advanced aircraft panel materials, PEEK-polyimide/glass, barely ignited at 35-kW/m² irradiance and exhibited a ten-fold reduction in chemical heat release rate at 50-kW/m² irradiance compared to conventional materials—which increased the time to flashover (escape time) in the full-scale fire tests from about 4 minutes to greater than ten minutes (no flashover was observed).

Time to flashover in building fires[25,26] and aircraft cabin fires[10] have been successfully correlated with a material parameter, $\dot{Q}_c^{peak} / t_{ign}$, called the *propensity-for-flashover* parameter[27] which ratios the peak value of the chemical heat release rate of the material, \dot{Q}_c^{peak} , with its time to ignition, t_{ign} , in an attempt to normalize for sample thickness in ranking materials for fire hazard potential. Figure 2 shows the correlation of $\dot{Q}_c^{peak} / t_{ign}$ measured at 50-kW/m² irradiance with measured time to flashover of panel materials in full-scale cabin fire tests. The solid line is a best-fit second-order polynomial.

Other correlations of time to flashover of materials in aircraft cabin fires include the time to reach a heat release rate of one megawatt in a room-corner fire test of the same materials, which has been proposed as a basis for simplified zone modeling of cabin flashover[23].

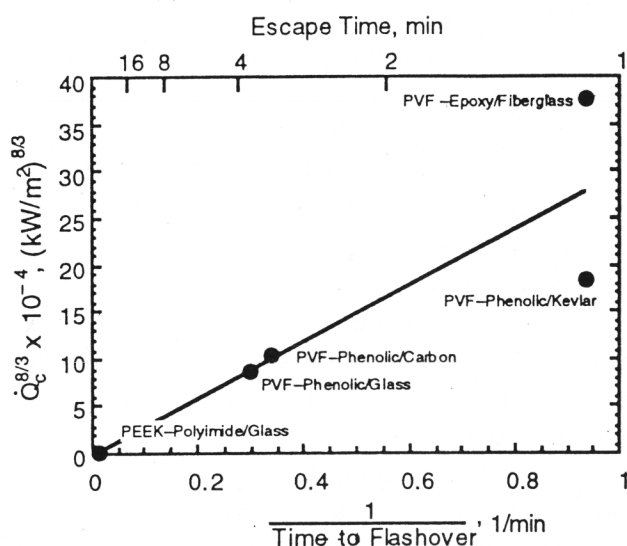


Figure 1. $\dot{Q}_c^{8/3}$ of decorative panels versus reciprocal time to flashover in full-scale aircraft cabin fire tests.

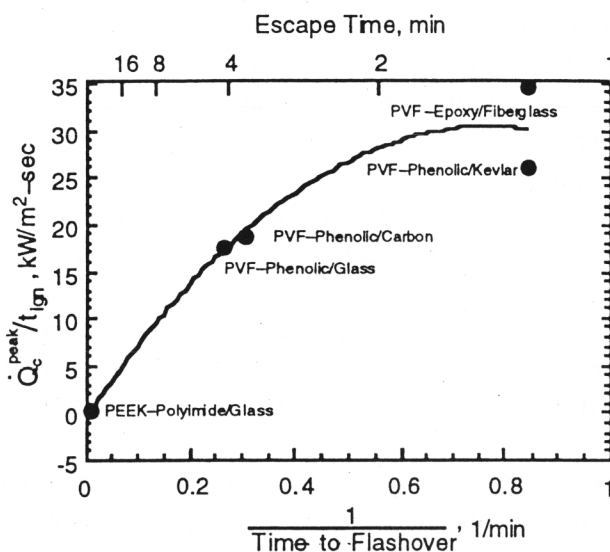


Figure 2. $\dot{Q}_c^{peak} / t_{ign}$ of decorative panels versus reciprocal time to flashover in full-scale aircraft cabin fire tests.

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, advanced materials for use in aircraft must be ultralightweight. 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[28]. No advanced materials will be used in aircraft no matter how desirable its properties if processing and manufacture cannot be performed efficiently and economically.

Current installed costs for aircraft materials average \$300/lb, of which over sixty percent is manufacturing cost including processing and fabrication. Less than twenty percent of product cost is attributable to design, development, and analysis in a successful aircraft program. The remaining twenty 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[29].

As the design and analysis tools for fiber-reinforced structural composites mature over the next decade and production becomes more efficient, aircraft manufacturers will utilize 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 advanced subsonic and supersonic aircraft. Boeing projections for the structural weight fraction of polymer composites in subsonic commercial airplanes show increases from about seven percent currently to about twenty percent over the next fifteen years. The fireworthiness of these structural composites in ramp, in-flight, 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[30] 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[31] and a lack of knowledge concerning the structural performance of these materials during and after fire exposure. Fiber composites utilizing high-temperature resins such as poly(ether ether ketone) (PEEK), polyimide, or phenolic are more resistant to ignition at realistic fire heat fluxes[32] but suffer from poor 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. The current ban on the production of ozone-depleting Halon[®] 1211 and Halon[®]1301 fire extinguishing agents currently used for extinguishing cabin, cargo compartment, and engine fires may result in the use of less effective agents and the need for enhanced fire-hardening.

Postcrash fire-hardening of cabin materials may be necessary if a proposed double-deck wide-body 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 wide-body 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 depletors indicates a need 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[33].

A single "master" 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. Advantages of the master 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 master 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[34]. Fire-safe thermoplastic polymers have advantages over thermosets as a master 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 several times lower cost, better impact resistance, and ability to use existing processing machinery and technology. The master polymer concept is analogous to the master aircraft aluminum alloy which has processing-dependent properties and obviates the need for a large inventory of different alloys and materials forms[28].

FIRE-SAFE MATERIALS RESEARCH

The Fire-Safe 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. Consistent with the FAA Fire Research Program goal of eliminating fire as a cause of death in aircraft accidents over the next ten to fifteen years, the Fire-Safe Materials effort has the following objectives: (1) discover the fundamental relationships between the composition and structure of materials and their behavior in fires, (2) use this knowledge to identify and design new materials and material combinations which provide an "order-of-magnitude" improvement in fireworthiness, and (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 new materials for aircraft use be successful.

Due to the severe consequences of aircraft cabin fires and the lack of knowledge concerning the relationship between material composition and bench- and full-scale fire test performance the current program has set extremely conservative preliminary materials fire performance guidelines in an effort to achieve an "order-of-magnitude" improvement in aircraft cabin fireworthiness. As fire modeling and probabilistic risk assessment tools improve over the course of the program and more full-scale test data become available to better relate bench-scale fire test data to ignition and flame spread in aircraft, fire performance guidelines may be relaxed consistent with maintaining a totally fire-resistant aircraft cabin as demonstrated in full-scale performance tests.

Preliminary FAA aircraft materials fire performance guidelines parallel some of the acceptance criteria for composite materials used in submarines recently published by the Navy[35,36]. The FAA guidelines have no relationship to any current or proposed regulatory activity. Rather, these fire performance guidelines should serve as a long-term goal for aircraft materials fire performance. The interim FAA materials fire performance guidelines adopt the Naval

requirements for smoke and smoke toxicity, but add a full-scale test requirement and extend the ignitability and heat-release guidelines to require essentially noncombustible behavior of all cabin materials.

TEST: IGNITABILITY

OBJECTIVE: To reduce the propensity for ignition of cabin materials in a postcrash jet fuel fire.

REQUIREMENT: No piloted ignition of 1.6-mm-thick materials when tested in a vertical orientation at 50-kW/m² irradiance in accordance with ASTM E-1354. Incident heat fluxes of 50 ± 10 kW/m² (corresponding to an equilibrium surface temperature of about 650°C) are measured near the bottom and center of open doors in passenger aircraft exposed to external jet fuel fires[8–10]. Organic polymers which are thermally stable to temperatures of 650°C are in fact nonignitable when tested at 50-kW/m² irradiance[37].

TEST: HEAT RELEASE

OBJECTIVE: To delay cabin flashover in a postcrash jet fuel fire.

REQUIREMENT: Maximum heat release rate less than 50 kW/m² for 1.6-mm-thick materials tested in a vertical orientation at an irradiance level of 75 kW/m² in accordance with ASTM E-1354. Heat fluxes measured above open doors in passenger aircraft exposed to external fuel fires are 75 ± 50 kW/m², depending on fire size and wind conditions[8–10]. Correlation of time-to-flashover data from full-scale aircraft cabin fire tests with both $\dot{Q}_c^{8/3}$ (figure 1) and the flashover parameter $\dot{Q}_c^{peak} / t_{ign}$ (figure 2) indicate that the maximum heat release rate must be less than about 40–50 kW/m² to delay flashover of thermally stable ($T_{decomp} \approx 650^\circ\text{C}$) cabin materials for fifteen minutes in a postcrash fuel fire scenario.

TEST: FULL-SCALE AIRCRAFT CABIN FIRE TESTS

OBJECTIVE: Performance criteria for fire-safe materials systems. Demonstrate survivable aircraft cabin conditions for 15 minutes in postcrash fuel fires.

REQUIREMENT: No flashover or incapacitation from combustion gases for at least 15 minutes in full-scale aircraft cabin fire tests by the FAA under quiescent wind conditions. The complex geometry and multicomponent materials systems of passenger aircraft cabin interiors makes empirical testing of realistic configurations necessary. Full-scale aircraft cabin fire tests by the FAA have resulted in the successful adoption of many materials fire safety improvements in commercial aircraft.

These fire performance guidelines will be met by synthesizing new materials characterizing and modeling their thermochemical and thermophysical behavior in fires at the atomic, micro, and macroscopic levels and applying this knowledge to the design of new materials with better thermal

MODELING.

Computational and theoretical models of the chemical and mechanical behavior of materials exposed to fire and severe thermal environments will be developed. Atomistic computational modeling of homogenous materials using molecular dynamics simulations will be used to study solid-state thermal decomposition, thermoxidation, char formation, and gasification (fuel production) rate in relation to inter- and intra-molecular bond strength(s), bond strength distributions, molecular mobility/reptation, diffusion of gases and small molecules, and the role of morphological features on these processes. Atomistic computational modeling of thermally induced reactions of metal-containing polymers and metal-polymer mixtures will help elucidate the mechanistic processes responsible for the anomalous high-efficiency and synergistic activity of antimony-oxide flame-retardants and help design replacements for these potentially toxic heavy metal compounds. Computational studies of surface catalytic effects on thermal and thermoxidative degradation and char formation processes at internal material interfaces will be performed to assess and design effective additives, blends, and surface treatments for fibers and particulate additives in an effort to explore the limits of reduced flammability using existing materials. Theoretical analytical models will be formulated to describe and predict reaction kinetics, phase behavior, and miscibility of fire-resistant polymer blends and fire-retardant additives.

Determining the fire hazard of polymers and polymer composite materials in airframes, skins, and cabins requires accurate engineering models which capture the essential physics, chemistry of and mechanical impact of heat transfer, gasification, heat release, flame spread, smoke generation, and char formation for use in field fire models of postcrash scenarios. Mechanistic analytic models for thermal degradation, pyrolysis, and char formation are necessary to gain a physical understanding of the relationship between these quantities and to connect the molecular modeling with engineering fire models.

Sophisticated thermostructural models will be developed for fire exposed composites which can account for strength degradation. Theoretical mechanics models of time- and temperature-dependent buckling and creep of viscoelastic polymers and anisotropic polymer composites are necessary to assess the structural capability of fire-exposed airframes, empennage, and secondary structures such as floor beams. Theoretical mechanics models will be developed to provide guidance for toughening and durability modification of typically brittle high-temperature polymers used as resins and adhesives, and to identify novel high strength micro- and macro-structures for ultralightweight foams and cores. The modeling effort is expected to yield:

- Validated computational methodologies for molecular design of fire resistant polymers.
- Mechanistic models for pyrolysis and char formation of aircraft materials.
- Engineering models for ignition, combustion, heat release, heat transfer, and flame spread of materials for use in risk assessment (structural response codes and fire field models).

- Theoretical and engineering models for load-bearing capability of polymers and composites during and after fire exposure.

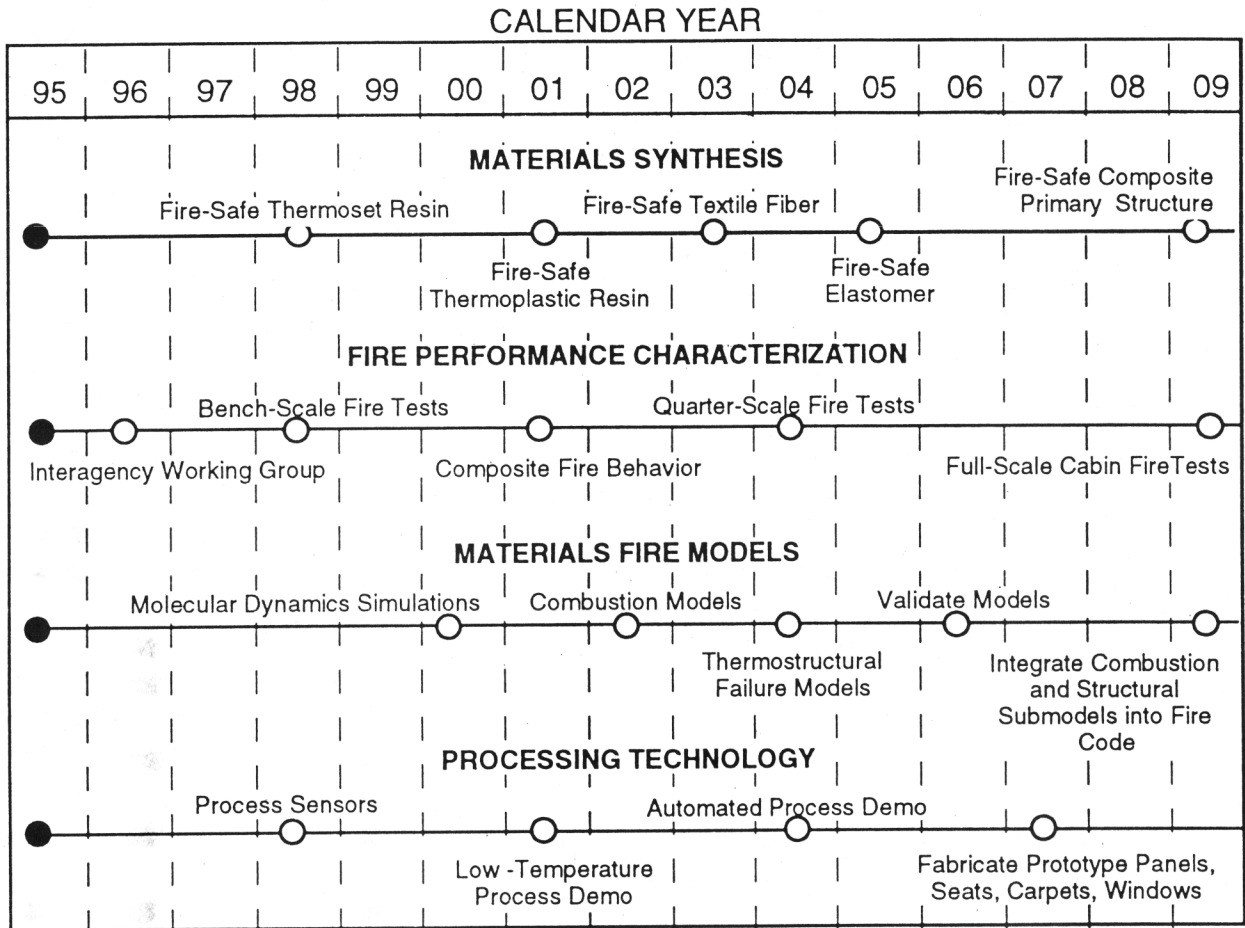
PROCESSING.

Fabrication processes for advanced fire-safe materials must be fully reproducible, verifiable, and able to maintain tight tolerances in order to replace existing materials in passenger aircraft. Research will focus on processing to reliably provide novel materials with uniformly improved properties at lower cost is of interest. On-line remote process monitoring for continuous processing via reactive extrusion and pultrusion offers economies when coupled with chemometric or neural network techniques for intelligent processing. Relationships between processing, fire performance, and mechanical performance will be investigated for reactive extrusions and processing-generated microstructures. Chemorheology of fire-safe thermoset reactions, low temperature processing routes to high temperature materials, electromagnetic processing (ultrasonics, microwave, e-beam, etc.), rheology of ternary blends, process sensors, and recycling concepts for noncombustible materials will be considered. Processing-generated microstructures with superior fire resistance and innovative processing routes to high-strength, ultralow density core materials and materials systems are the type technologies that may be produced. The processing effort is expected to yield:

- On-line process monitoring and control technology for high-volume, economical, tight tolerance production of polymers and composites.
- Low-temperature routes to high-temperature capable materials.
- Novel processing-generated microstructures and ultralow density core materials.

Formal collaboration between materials researchers and fire scientists in academia, government, and industry is essential. Installation of new materials in aircraft will require close cooperation between researchers, materials manufacturers, and the aircraft industries to develop a supplier base, manufacturing technology, and cost and performance requirements for new materials. The FAA anticipates sponsoring an industrial research program in parallel to the academic research program as part of the Fire-Safe Materials effort to encourage the development of pre-competitive industrial technology for fire-safe materials and to leverage core technologies and commercial production capabilities of key chemical and materials producers. A preliminary timeline identifying major programmatic milestones is given in table 2.

TABLE 2. FIRE-SAFE AIRCRAFT MATERIALS PROGRAM MILESTONES



REFERENCES

1. "Special Study: U.S. Air Carrier Accidents Involving Fire, 1965-1974 and Factors Affecting the Statistics," National Transportation Safety Board, Report NTSB-AAS-77-1, February 17, 1977.
2. Fire & Smoke: Understanding the Hazards, National Research Council Committee on Fire Toxicology, National Academy Press, Washington, D.C., 1986, Chapter 1.
3. Federal Register, October 26, 1984, p. 43191.
4. R.G. Hill, "The Future of Aircraft Cabin Fire Safety," Proceedings of the International Conference for the Promotion of Advanced Fire-Resistant Aircraft Materials, Atlantic City, New Jersey, February 9-11, 1993, p. 365.
5. National Materials Advisory Board, "Fire Safety Aspects of Polymeric Material, Volume 6, Aircraft: Civil and Military," Publication NMAB 318-6, Washington, D.C., 1977, p.68.
6. V. Babruskas and J.F. Krasny, "Prediction of Upholstered Chair Heat Release Rates from Bench Scale Measurements," Fire Safety: Science and Engineering, T.Z Harmathy, ed. ASTM Special Technical Publication 882, Phila., PA 1985, pp.269-284.
7. T.I. Eklund, "Pool Fire Radiation Through a Door in a Simulated Aircraft Fuselage," FAA-RD-78-135 (December 1978).
8. L.J. Brown, "Cabin Hazards From a Large External Fuel Fire Adjacent to an Aircraft Fuselage," FAA-RD-79-65 (August 1979).
9. R.G. Hill, G.R. Johnson, and C.P. Sarkos, "Postcrash Fuel Fire Hazard Measurements in a Widebody Aircraft Cabin," FAA-NA-79-42 (December 1979).
10. J.G. Quintiere, V. Babrauskas, L. Cooper, M. Harkleroad, K. Steckler, and A. Tewarson, "The Role of Aircraft Panel Materials in Cabin Fires and Their Properties," DOT/FAA/CT-84/30 (June 1985).
11. D.P. Macchione and A. Tewarson, "Flammability Characteristics of Fiber-Reinforced Composite Materials," in Fire and Polymers: Hazards Identification and Prevention, G.L. Nelson ed., ACS Symposium Series 425, American Chemical Society (1990).
12. A. Tewarson, "Flammability Parameters of Materials: Ignition, Combustion, and Flame Spread," Proceedings of the International Conference for the Promotion of Advanced Fire Resistant Aircraft Materials, Atlantic City, New Jersey, Feb. 9-11, 1993, p. 263.
13. D.W. Van krevelen, Properties of Polymers, Elsevier Scientific, NY, 1976.

14. Polymer Handbook, 2nd edition, J. Brandrup, E.H. Immergut, Eds., Wiley-Interscience, NY 1975, V-56.
15. C. Huggett, "Estimation of Rate of Heat Release by Means of Oxygen Consumption Measurements," *Fire and Materials*, **4** (2), pp 61-65 (1980).
16. C.P. Sarkos and R.G. Hill, "Evaluation of Aircraft Interior Panels Under Full-Scale Cabin Fire Conditions," *Proc. AIAA 23rd Aerospace Sciences Mtg.*, Reno, NV, Jan. 14-17, 1985.
17. P.H. Thomas, "On Concurrent Upward Surface Spread of Flame," *Fire Safety J.*, **22**, pp 89-99 (1994).
18. *CRC Handbook of Chemistry and Physics*, CRC Press, Boca Raton, FL, 1980.
19. J.G. Quintiere and M.T. Harkelroad, in "New Concepts for Measuring Flame Spread Properties," *Fire Safety: Science and Engineering*, T.Z. Harmathy, ed. ASTM Special Technical Publication 882, Phila., PA 1985, pp. 239-267.
20. M.A. Delichatsios, "Modeling Aircraft Cabin Fires," NBS-GCR-84-473, September 1984.
21. T.I. Eklund, "A Vortex Model for Wall Flame Height," DOT/FAA/CT-85/17, Sept. 1985.
22. C.P. Sarkos and R.G. Hill, "Effectiveness of Seat Cushion Blocking Layer Materials Against Cabin Fires," SAE Technical Paper 821484, Aerospace Congress and Exposition, Anaheim, CA October 25-28, 1992.
23. J.G. Quintiere, G. Haynes, and B.T. Rhodes, "Applications of a Model to Predict Flame Spread Over Interior Finish Materials in a Compartment," *Proceedings of the International Conference for the Promotion of Advanced Fire Resistant Aircraft Materials*, Atlantic City, New Jersey, February 9-11, 1993, p. 207.
24. R.G. Hill, T.I. Eklund, and C.P. Sarkos, "Aircraft Interior Panel Test Criteria Derived from Full-Scale Fire Tests," DOT/FAA/CT-85/23, September 1985.
25. U. Wickstrom and U. Goransson, *J. Testing Evaluation*, **15** (6), p 364 (1987).
26. M.M. Hirschler and R.A. Poletti, *J. Coated Fabrics*, **94**, p 19 (1989).
27. V. Babrauskas, "Bench-Scale Methods for Prediction of Full-Scale fire Behavior of Furnishings and Wall Linings," Technical Report 84-10, Society of Fire Protection Engineers, Boston (1984).

28. Materials Research Agenda for the Automotive and Aircraft Industries, National Materials Advisory Board, Commission on Engineering and Technical Systems, National Research Council, NMAB-468, National Academy Press, Washington D.C., 1993.
29. P.S. Guard and J.M. Peterson, "Future Material Development Trends for Commercial Airplane Interiors," Proceedings of the International Conference for the Promotion of Advanced Fire Resistant Aircraft Materials, Atlantic City, New Jersey, Feb. 9-11, 1993, p. 313.
30. J.A. Milke and A.J. Vizzini, "Thermal Response of Fire-Exposed Composites," J. Comp. Techn. & Res., **13** (3) pp 145-151 (1991).
31. U. Sorathia, T. Dapp, and J. Kerr, "Flammability Characteristics of Composites for Shipboard and Submarine Internal Applications," Proc. 36th Int'l SAMPE Symposium, **36** (2), pp 1868-1877 (1991).
32. U. Sorathia, C.M. Rollhauser, and W.A. Hughes, "Improved Fire Safety of Composites for Naval Applications," Fire and Matls., **16** pp 119-125 (1992).
33. D.S. Malin, "Cone Corrosimeter Testing of Fire Retardant and other Polymeric Materials for Wire and Cable Applications," Proceedings of the Nineteenth International Conference on Fire Safety, San Francisco, CA, pp 10-14, 1994.
34. R.G. Diehl, "Applications of Continuous Fiber Reinforced Thermoplastics in Aircraft Interiors," Proceedings of the International Conference for the Promotion of Advanced Fire Resistant Aircraft Materials, Atlantic City, New Jersey, Feb. 9-11, 1993 p. 93.
35. R.A. De Marco, "Composite Applications at Sea: Fire-Related Issues," Proc. 36th Int'l SAMPE Symposium, **36** (2), pp 1928-1937 (1991).
36. MIL-STD-2031(SH), "Fire and Toxicity Test Methods and Qualification Procedure for Composite Materials Systems Used in Hull, Machinery, and Structural Applications Inside Naval Submarines," February 1991.
37. P.K. Kim, P. Pierini, and R. Wessling, "Thermal and Flammability Properties of Poly(p-phenylenebenzobisoxazole)," J. Fire Science, **11** (4) pp 296-307 (1993).