*** POOR QUALITY ***

SAMPE Journal, Vol. 33, No. 4, 23-31, 1997

Introd[illegible]

[illegible] ma-terials [illegible] ponent is a high stre[illegible] ement and the [illegible] organic resin binder. [illegible] comprise the majority [illegible] and consist primarily [illegible] families which include epoxy, [illegible] de, phenolic, cyanate ester, [illegible] and vinylester. High temperature engineering thermoplastics are used as composite resins and resin modifiers in military applications, but their use in transportation applications is limited. Reinforcing fibers include glass, aramid, carbon, quartz, and boron, either alone or as hybrids in the form of fabrics, unidirectional tapes, bundles (tows), or chopped to various lengths.

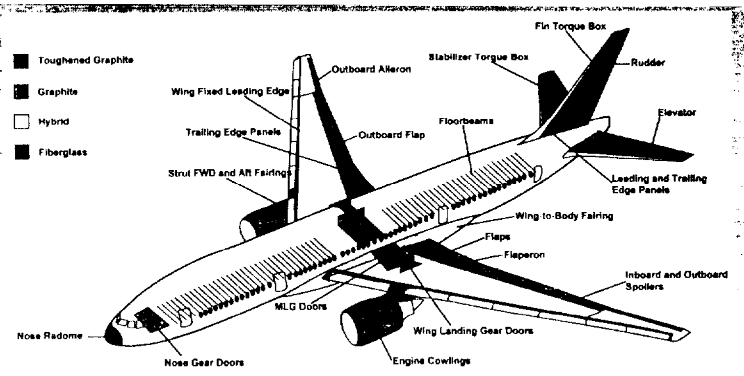

Figure 1. Advanced materials use in Boeing 777.

A Review of Fire Test Methods and Criteria for Composites

Usman Sorathia, Naval Surface Warfare Center, Carderock Division; Richard Lyon, Federal Aviation Administration; Thomas Ohlemiller, National Institute of Standards & Technology; and Lt. Andrew Grenier, US Coast Guard

Composite components and structures are fabricated by impregnating the fibrous reinforcement with liquid resin using various processes including vacuum assisted resin transfer molding, infusion of preforms in a closed cavity mold, filament winding, pultrusion, lamination of pre-impregnated fiber mats, fabrics, or tapes, etc. Fiber reinforced polymer composites can be engineered to provide strength, stiffness, weight, and assembly advantages over conventional monolithic materials but they also pose fire safety concerns due to the combustibility of the organic polymer constituents.

Structural composites for naval, commercial marine, and infrastructure applications are typically glass reinforced with polyester, vinyl ester, or epoxy resins. For civilian and military aircraft and space applications, these are typically composed of graphite reinforcement with a variety of matrices whose choice is dependent upon environmental and temperature exposure of the component or the weapon system platform. Some of these applications include empennages in the F-15, F-16 and F-22; secondary wing structures of the B1-B, portions of the fuselage of the F-22 and B-2; wing components of the F-22, and various engine components in all the aircraft. Some of the thermosetting matrices employed include standard epoxies and higher use temperature polyimides in the forms of the PMR resins and AFR-700B. Space applications for graphite composites include control surfaces of missiles, some engine components and rocket motor cases. Matrices employed in space components typically consist of thermosetting epoxies and cyanate ester resins as well as thermoplastic compositions of homopolymers and copolymers of polyimides, polyphenylene sulfides, polyaryleneether sulfides and sulfones, polyetherketones and polyetheretherketones. In order to take advantage of improved high tensile strength and modulus of elasticity, some space components of rocket motor cases and rigid tubular structures of the proposed space station have been fabricated from liquid crystalline aromatic heterocyclic rigid-rod materials. These polymers represent an improvement in materials processing technology since the polymers are biaxially oriented in the melt during the extrusion process and exhibit twice the crush resistance when compared to uniaxially oriented extruded tubes.

Weight savings and resulting fuel efficiency are driving the use of advanced light weight materials by airframe manufacturers and other civil transportation industries. FAA is evaluating advanced thermoplastics and composite materials for aircraft interiors, airframe, skins, and other structural applications. Boeing projections for the structural weight fraction of polymer composites in subsonic commercial airplanes show increases in use from about seven percent currently to about 20 percent over the next fifteen years. Usage of advanced materials in Boeing 777 is shown in Figure 1.

Current seaborne applications of composite materials in the US Navy include sonar [illegible] windows, and coastal minehunter MHC-51 hulls [illegible] five to 10 years, the US Navy has also been [illegible] materials for

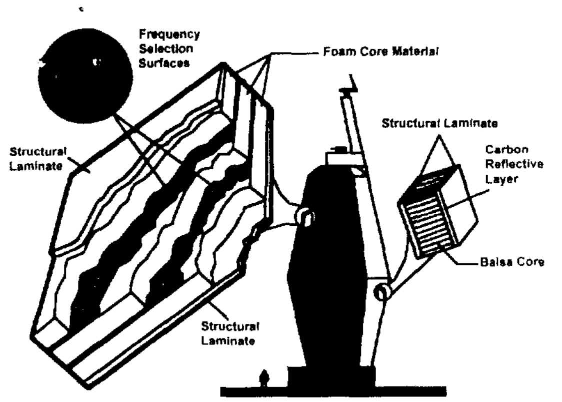

Figure 2. Advanced Enclosed Mast/Sensor (AEM/S) System).

both primary and secondary load-bearing structures such as foundations, deckhouses, and hulls; machinery components such as piping, valves, centrifugal pumps and heat exchangers; and auxiliary or support items such as gratings, stanchions, ventilation ducts and screens (4). A recent notable large composite application is Advanced Enclosed Mast/Sensor (AEM/S) System which has been installed on USS RADFORD as shown in Figure 2. The AEM/S System is a high payoff Advanced Technology Demonstration (ATD) to develop the Navy's next generation of masts and topside design concepts with reduced signatures and improved sensor performance.

Composite materials have been used in the marine industry for over 50 years, and their use is increasing as their burning behavior is better understood and regulations evolve to reflect current technology. The current applications include widespread use in the hulls of yachts, pleasure craft, and racing boats to certain specialized applications such as life boats, pipe, deck grating, and various other components. Composites are also common in small commercial fishing vessels and passenger vessels. Interest in the use of composite materials for larger vessels has been increasing in recent years, primarily for high speed craft. Their corrosion resistance, low maintenance, and ease of repair make them attractive alternatives to the traditional shipbuilding materials: steel and aluminum.

In infrastructure applications, fiber reinforced organic matrix based composites are very attractive materials of construction due to their strength, relatively light weight which facilitates on-site handling, and anticipated long term weather resistance. The Federal government has budgeted $78 billion over the next 20 years for major infrastructure rehabilitation since nearly 200,000 bridges and highways in the US are deficient or obsolete. Composites are being considered for various infrastructure uses such as building reinforcement to enhance earthquake resistance, highway overpass reinforcement and repair, as well as foot and highway bridge construction. In such applications, the composites may take a variety of forms. In reinforcement and structural repair applications, for example, the composite might be a thin flat sheet, composed of carbon fibers and epoxy resin, held to the repaired surface (typically concrete) by an adhesive. In bridge and pier construction, the physical form of the composite structural elements is highly variable with the specific design, encompassing pultruded beams, honeycomb deck structures and filament wound tubes. The resins are limited by cost considerations to high volume, low cost polymer types.

The inherent chemical nature and complexity of polymer matrix composite materials do not lend themselves to easy analytical prediction of their behavior when exposed to a high heat flux from a fire source. Composites exhibit anisotropic heat transfer. They selectively burn, produce smoke, release heat, chemically degrade, produce char, and delaminate. Fire requirements for flammable components consist of a pass/fail rating in one or more fire tests. Polymers and composites are the passive component of an overall fire protection strategy which includes fire detection, suppression, containment, and egress.

Assessment of the fire hazard of combustible composites and plastics has evolved over the past three decades to include measurement of flammability characteristics such as ignitability, flame spread, combustibility, rate of heat release, and smoke and gas production during exposure to heat or fire. While gas phase and aerosol combustion have been studied extensively (1-2) because of their commercial importance (e.g., furnaces, internal combustion engines, etc.), very little is known about the solid-state chemical kinetic processes of flaming combustion which generate the gaseous fuel. In particular, the material property or combination of properties which governs the flammability of polymers and composites is not readily quantified for complex, commercial polymers.

The lack of fundamental knowledge on polymer and composite flammability has not hindered the application of these materials for surface, marine, and air transportation all of which have increased greatly owing to the availability of standardized fire performance tests, and material properties such as high strength and modulus, chemical and corrosion resistance, durability, and low density.

The purpose of this paper is to summarize the major application areas in which composite materials are serious contenders to replace traditional materials of construction and finish, with a focus on the fire requirements that this entails. Nearly all of the test methods and related criteria were developed before the advent of composites.

Composites and Fire Threat

A significant concern in any application of organic matrix based composites in occupied spaces is the possibility that an accidental (or deliberate) fire may impinge on the structure. This is potentially problematical for two reasons. First, heat weakens the polymer binder. Thermoplastic binders begin to creep and then to flow as the impinging flames raise their local temperature past the glass transition temperature. Thermoset binders degrade to a char or gasify or both. The functioning of the binder is thus diminished and the composite loses strength. If the structure is one in which the composite forms only a reinforcing or repair role, the consequences of a local, heat-induced composite failure are not likely to be serious; time is available to repair the damaged material. However, if the affected composite component is part of a primary critical

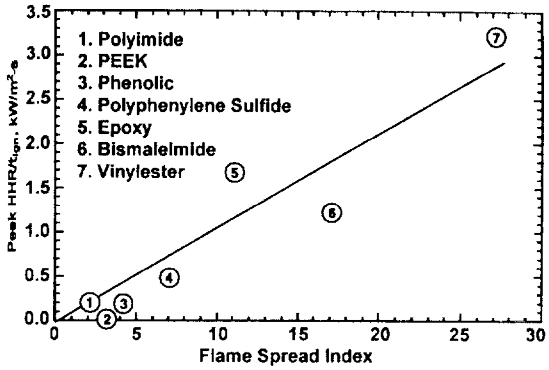

Figure 3. Peak heat release rate/time to ignition versus the flame spread index for various composites.

structure such as the wing of an aircraft, the structure may collapse.

The second aspect of the problem can greatly magnify the first. The binder may ignite and support the spread of flame on the composite surface and also release heat and generate potentially toxic smoke. Thus the localized, external fire may cause a larger structural fire involving the composite which now becomes the fuel for the growing fire. In confined or enclosed spaces such as ships and aircraft, the growing fire could lead to a flashover condition in which all combustible materials within the enclosure begin to burn. In open spaces such as bridges, a growing fire clearly increases the chance of structural collapse. Again, the consequences are less threatening when the composite merely serves a reinforcing role as opposed to being a primary structure. For earthquake reinforcement, the problem is somewhat more complex. Fires accompany earthquakes but they tend to lag the initial shock. If a quake induced fire did destroy the composite reinforcement on a structure, the structure might readily survive the initial quake only to fall victim to an after shock occurring after the fire.

Compared to many flammable materials, composites have a built-in advantage that helps resist the worst consequences (extensive fire involvement). This is a result of their (usually) inert fiber content of as high as 70 percent by weight in some cases. The fibers displace polymer resin, making less fuel available to the fire. When the outermost layers of a composite lose their resin due to heat induced gasification, they act as an insulating layer, slowing heat penetration into and evolution of gases from the depth of the composite.

Fire Growth and Test Methods

Interior applications of composites in earth-based structures are likely to come under existing building or construction code requirements. Most frequently this means a requirement for some specified level of performance in the ASTM E-84 tunnel test. Here, the test sample is mounted on the horizontal ceiling of a channel down which a strong gas burner flame is blown. Any flame spread here is in the same direction as the gas flame movement so that, while it is not an upward flame spread test, it is a forward flame spread test. The test has been shown to rank "well-behaved" materials in the same order as the fire behavior measured in full scale enclosures (5). The term "well-behaved" here means essentially materials which behave like wood in a fire (i.e. materials which char and stay in place on the top of the tunnel for the majority of the test time). Correctly ranking the order of fire behavior of materials in a given type of full-scale test is a minimum requirement for a test method. An ideal test method would provide engineering data that could be used to predict other conditions and scenarios.

The tunnel test has been shown to be potentially misleading in its predictions of fire growth hazards of non charring materials such as polymer foam slabs and of textile-covered wall surfaces (5). At present, there does not seem to have been any assessment of the correlation between the results of this test and full scale fires for any composite materials used as compartment surfacing. Given the difficulties with textile wall coverings and the basic similarity between these and such composites as thin layers of carbon-epoxy adhesively bonded to a surface as a structural reinforcement, there is reason to be cautious.

Another bench scale measurement of flame spread is ASTM E162. The procedure in ASTM E 162 involves the measurement of a flame spread index (Is) which is a product of rate of energy released and average flame spread velocity in the downward direction. Although these quantities change with time as the material burns, the index is formulated to be a constant in order to provide a common scale for ranking different materials.

The difficulty with textile materials in the E-84 test has led to adoption of a room corner type of test for such materials. This is essentially a full-scale test. That might well be appropriate for thin composite layers, though the question of generalization of the results to other configurations and conditions is still not clear.

As noted, for most applications of composites, fire growth potential should be the first issue addressed and overcome for habitable environments. Rather surprisingly, this issue has received relatively little attention, except for a limited number of compartment fire growth studies (6). Much of the sparse work on fire spread on the surface of a composite has employed tests for lateral or downward flame spread (7-8). These are relatively slow modes of fire growth and they differ mechanistically from upward flame spread, which tends to be much faster. Good performance in the lateral/downward mode does not necessarily imply good performance in upward spread. The converse, however, is likely to hold true, i.e., resistance to upward spread should carry over to yield resistance to lateral or downward spread.

At present, there are no small scale tests for upward flame spread potential. The closest pertinent test is full-scale and it involves both lateral and concurrent flame spread (an analog of upward flame spread), This is ISO 9705 which has been recommended for interior surface materials (including composites) in high speed craft (9). This is a full room test and can be quite expensive for assessing composites. As an enclosure test, it may be unnecessarily severe for composites which are utilized in open spaces, such as in bridges or piers. However, for enclosed spaces such as deckhouse on a ship, this test is quite appropriate. The enclosure provides an enhanced heat feedback effect, due to accumulating hot smoke which is not present in an open fire exposure.

Ideally, expensive large scale tests would be unnecessary; one would be able to predict susceptibility to fire growth by upward flame spread from appropriate tests on small samples of the composite of interest. This prediction requires a verified flame spread model or, at least, a well-tested empirical correlation. NIST has conducted limited testing of three available models for upward fire growth on a single, isolated flat wall against experimental data for a vinyl ester/glass composite (10). None of the models was capable of highly quantitative predictions of the observed behavior but all were sufficiently so as to provide a clear, semi-quantitative indication of a substantial potential for fire growth on this composite.

In actual use, composite structures exposed to fire will most likely be more susceptible to fire growth than a flat wall due to radiative interchange with other nearby surfaces. Therefore, composite structures should not be assumed to be flat since this could lead to an overly optimistic assessment of fire growth potential. Models for fire growth in a corner are in a more tentative state than those for single, flat vertical surfaces. A predictive computer program which is said to correctly assess the behavior of wall materials in ISO 9705 on the basis of small-scale test results is available from SP in Sweden. Another fire growth model developed by Quintiere at the University of Maryland has been validated for common building materials and has been used for prediction of fire growth in marine composites (11).

Suppression of fire growth potential calls for measures which either preclude the heat from an external fire getting to the surface of a composite or which dampen the inherent response of the resin to this heat. At one extreme is total fire insulation of the composite (12). This has been suggested as a solution for both the hazard of fire involvement and for the threat of structural collapse. A sufficiently thick layer (e.g., 5 cm) of fiber insulation can keep the temperature of the composite below its ignition temperature (reducing hazard of fire involvement) and also below its glass transition temperature for periods of 30 minutes or more (reducing threat of structural collapse).

Flame retarded resins are potential solution to fire growth problems but they only lessen the flammability of a composite. This translates into resistance to a bigger external fire source before fire growth ensues (13). In unpublished NIST tests, brominated vinyl ester/glass composites exhibited essentially unchanged ignition behavior but required somewhat stronger external heat fluxes to sustain full height flame spread (1.2 m); the increase was from 3-5 kW/m^2 to approximately 10 kW/m^2. Whether this is sufficient depends on the use of the composite and the ignition sources it is likely to experience. Choice of a strongly charring resin such as a phenolic can provide greater benefits if other properties are compatible with the application.

As noted previously, intumescent coatings are an established fire protection technology for non-composite applications. Limited work has been done on their ability to protect composites (12,14). These studies looked at the ability of various coatings, including certain intumescents, to delay ignition, lower the rate of heat release (ASTM E1354), suppress lateral flame spread (ASTM E1317), and extend the duration of fire resistance of composites in a standard temperature-time exposure (ISO 834) which does not call for mechanical loading of the test specimen. These studies revealed that only a limited minority of commercial coatings have the needed ability to remain in place during intense heat exposures characteristic of large fires.

Smoke Generation and Test Methods

The smoke density chamber test ASTM E 662 is widely used for characterization of smoke density of materials as it relates to vision obscuration due to incomplete combustion products. The test is conducted in a closed chamber of fixed volume and the light attenuation is recorded over a known optical path length. A sample is subjected to a radiant heat flux of 25 kW/m^2, under piloted ignition and non-flaming (smoldering) mode and the corresponding light transmission provides specific optical density (Ds). Visibility through smoke is inversely related to specific optical density. The maximum optical density (Dm) over the duration of the test is used to identify materials with relatively high smoke production. Combustion gas generation is defined as the gases evolved from materials during the process of combustion. The most common of gases evolved during combustion are carbon monoxide and carbon dioxide along with HCL, HCN, and others depending upon the chemistry of the matrix resin of a given composite material. The smoke toxicity is currently best obtained with animal exposure methods for purposes of predicting the fire hazard of different materials or by smoke analysis in combination with an empirical model (15).

Heat Release and Test Methods

In recent years, developments in fire research and understanding of fire dynamics have highlighted the importance of heat release rate (HRR) as the primary fire hazard indicator. Fire hazard under a given set of conditions of fuel load, geometric configurations, and ventilation conditions can be expressed in terms of heat release rate and the fire hazard analysis should include the relevant fire response parameter(s) of a material. The assessment of potential fire hazard based on heat release rate measurements extends to composite materials also. The rate of heat release, especially the peak amount, is the primary characteristic determining the size, growth, and suppression requirements of a fire environment.

Two heat release test methods adopted by ASTM have found their way in government and commercial acceptance criteria. These are ASTM E1354 (oxygen consumption Cone Calorimeter) and ASTM E906 (Ohio State University). ASTM E-1354 measures the response of a small sample of material exposed to controlled levels of radiant heating and is used to determine the heat release rates, ignitability, mass loss rates, effective heat of combustion, and visible smoke development. Specific thermal insults of 25, 50, 75, and 100 kW/m^2 are required. These thermal insults correspond to a small Class A fire, a large trash can fire, a significant fire, and an oil pool fire. ASTM E-1354 utilizes the oxygen consumption principle in which the heat release rate is computed from the measurements of mass flow rate and oxygen depletion in the gas flow. ASTM E906 is based on thermopile method where the temperature rise is used to determine the heat release of materials. The thermopile method uses the heat release of materials at a radiant heat flux of 35 kW/m^2.

While the heat release rate history is more complex for composite materials during a test, an acceptance criteria analogous to current regulatory standards by FAA and US Navy can be derived with sufficient testing and analysis. For example, Figure 3 shows a good correlation between flame spread index (ASTM E162) and the peak heat release rate divided by the time-to-ignition (tign) measured in a fire calorimeter according to ASTM E 1354 for a number of glass or carbon-fabric reinforced crossply laminates. Heat release measurements can also serve as input in fire growth models to describe a variety of potential fire scenarios.

Fire Requirements and Regulations

Nearly all fire tests have been designed to represent some realistic set of fire conditions by simulating an expected fire scenario or by reproducing the heat exposure conditions. The current regime of fire tests mandated for regulatory purposes provide numerical results for ranking of materials based on experience and intuition gained over the past thirty years. The majority of guidelines developed by regulatory agencies focus on material and product performance testing designed to control flame spread and ignitability of combustible materials. The diverse applications of composites for both military and civilian sectors discussed here involve different fire safety concerns owing to the individual geometry and configuration of an enclosure, fire load, fire scenario, mission requirements, ease of escape, and the extent of potential human and property loss. The following sections separately discuss the fire requirements for use of composites in infrastructure (highways and bridges), ground transportation (cars, trucks, and buses), air transportation (small and large), commercial marine transportation (cargo and passenger vessels), and military applications.

Infrastructure and Fire Regulations

The use of composites in transportation infrastructure such as bridge and highway repair and seismic retrofit is expected to be a growing market. Advantages of advanced composites for new construction include tailorable mechanical properties, high strength to weight ratios, and chemical inertness which significantly exceed those of conventional engineering materials such as concrete and steel. The California Transportation Department (CALTRANS) is spending several billion dollars for repair of bridges and highway structures. Candidate repair systems include continuous fiber reinforced polymer composites of carbon and glass with epoxy and polyester resins. There are currently no requirements for flammability or fire endurance of infrastructure materials due to the fact that these are exterior applications.

There is a lack of consensus on appropriate tests for fire growth potential on composites to be used in exterior infrastructure applications, probably because likely fire-exposure conditions are not well-defined. A composite bridge, for example, may be exposed to fire on its road surface due to an accident that causes a gasoline spill. The road surface will likely be a non-composite substance designed to provide wear resistance. Any fire threat to the composite materials below the road deck could depend strongly on where the burning gasoline flows, how long it burns and the details of the bridge support structure. Such a bridge is also vulnerable to debris, brush, woodland or arson fires at the base of its abutments (or elsewhere, depending on design and scale). Here the main form of the fire threat is most likely upward flame spread, normally the fastest mode of fire growth. Good fire growth control in this configuration should also lead to good behavior in the variety of more complex configurations that may ensue from a fuel spill, for example, on the bridge deck or other structural surfaces. Such fires involve lateral or downward flame spread which generally is weaker and slower. Thus, any test should contain a dominant element of forward or upward flame spread. NIST has used a 2.4 m open corner test to study the effects of exposure fire size (30 to 140 kW) on the potential for upward flame spread on composites. The results confirm a strong sensitivity to initiating fire size, as implied by models for the simpler, flat wall configuration. NIST also used a 3.05 m open corner with a larger width, 250 kW burner to examine the ability of intumescent coatings to control upward fire growth (16).

Given the unresolved state of testing of composites for exterior applications, work is needed to provide a basis for a consensus. First, some statistical data are needed on likely fire exposures in the various infrastructure applications of composites. This may well lead to various categories of threat depending on the nature and location of the composite structure. Interior testing of composites could benefit from similar data. Next, some assessment program is needed on the intensity and physical extent that such fire exposures entail; this means measurement of the imposed heat flux patterns, and their durations, which a composite structure must endure. It is impossible to devise test methods which represent all applications and fire exposures. Consensus is thus needed on the most appropriate structural configuration, fire size and duration to accurately assess the likely behavior of a composite system in real applications. Fire growth modeling, which aids in generalizing such inherently limited test results, is an essential element in any such program.

Ground Transportation and Fire Regulations

Over 400,000 motor vehicle fires occur yearly in the US, claiming over 700 lives and causing nearly 3,000 civilian injuries (17). Most of these fires originate in the engine compartment or as a result of impact, with cigarette ignition of interior materials being a minor cause of vehicle fires. The first and only US requirement for interior materials and components used in cars, trucks, and buses was developed by the National Highway Transportation Safety Administration (NHTSA) and established as Motor Vehicle Safety Standard (FMVSS) 302 (18). This requirement is directed at reducing the hazards of interior fires caused by smoking and matches. A Bunsen burner flame test is used to measure the rate of flame spread on a 254 mm (10 in) horizontal specimen. The test procedure has been adopted by the automotive industry in several other countries and incorporated as an International

Organization for Standardization (ISO) Standard 3795. FMVSS 302 is not a severe fire test due to the relative ease and speed of passenger egress from a motor vehicle in the cigarette ignition scenario.

Fire safety requirements specific to passenger rail car interiors are mandated by the Federal Railroad Administration (FRA), the regulatory agency responsible for US passenger train safety. The FRA guidelines (19) for the flammability and smoke properties of materials apply to passenger cars in intercity and Amtrak trains. Similar guidelines have been issued by the Federal Transit Administration (FTA), formerly known as the Urban Mass Transportation Administration (UMTA) (20), for materials used in light rail, subway cars, and urban mass transit buses. The strategy for fire safety incorporated in these

Table I. Summary of Fire Requirements for Composite Materials in the United States

Sector	Component	Property	Test Procedure	Criteria
Infrastructure	Fire Requirements Not Yet Well Defined			
Surface (Cars, Trucks, and Buses)	Panels	Flame Spread	FMVSS 302	Rate of Flame Spread, 4 in/min
Surface Mass Transit Vehicles (Buses, Light Rails, and Passenger Trains)	Seat Materials	Flame Resistance	FAR 25.853	Flame Time ≤ 10s Burn Length ≤ 6 in
	Panel, Partition, Wall, Ceiling	Flame Spread	ASTM E162	Flame Spread Index ≤ 35
	Floor Structure	Fire Endurance	ASTM E119	Nominal Evacuation Time ≥ 15 min
	Seat, Panels, Walls, Partitions, Ceiling, Floor	Smoke Emission	ASTM E662	Ds (1.5) ≤ 100 Ds (4.0) ≤ 20
	All Materials	Toxicity	NBSIR-82-2532	As Appropriate
Air (Commercial Aviation Aircraft)	Cabin and Cargo Compartment Materials: Seat, Panel, Liner, Ducting	Flame resistance -Vertical -Horizontal -45 degree	 FAR 25.853 (a-b) FAR 25.853 (b2-b3) FAR 25.855	Flame Time: 15s Flame Time of Drippings: 3s Burn Length: 6 and 8 in. Rate of Flame Spread: - Class b-2: 2.5 in/min - Class b-3: 4 in/min
	Cargo Compartment Liners, Seats	Fire Endurance	FAR 25.855 FAR 25.853	No Flame Penetration of Liner. Peak Temperature 102 mm Above Specimen: ≤ 204°C; Mass Loss and Flame Spread Criteria for Seats.
	All Large Area Cabin Interior Materials	Smoke Emission	FAR 25.853 (a-1)	Ds (4.0) ≤ 200
		Heat Release Rate	FAR 25.853 (a-1) ASTM E906	Peak HRR in 5 min: 65 kW/m2 Total HRR in 2 min: 65 kW-min m^2
Marine (Life Boats, Rescue Boats, and Small Passenger Vessels)	Main Structure, Hull	Resin/Laminate Flammability (Fire Retardancy)	MIL-R-21607 or ASTM E-84	Resin Qualified Under MIL-R-21607 or Laminate Tested to ASTM E84, Flame Spread Index ≤ 100
Marine (High Speed Craft, Fire Restricting Materials)	Bulkheads, Wall and Ceiling Linings (Surface Materials)	Heat Release Rate, Surface Flammability, Smoke Production	ISO 9705 Room/Corner Test	-Ave HRR ≤ 100 kW -Max HRR ≤ 500 kW -Ave Smoke Prod. ≤ 1.4 m^2/s -Max Smoke Prod. ≤ 8.3 m^2/s -Flame Spread ≤ 0.5 m From Floor -No Flaming Drops or Debris
Marine (High Speed Craft, Fire Restricting Materials)	Furniture Frames, Case Furniture, Other Components	Ignitability, Heat Release, Smoke Production	ISO 5660 Cone Calorimeter	Criteria are Currently Under Development
Military US Navy Submarines	Structural Composites Inside The Pressure Hull	Heat Release, Smoke, etc	MIL-STD-2031(SH)	- Flame Spread Index ≤ 20 - Max Smoke Dm ≤ 200 - 25 kW/m^2 : PHR ≤ 50 kW/m^2 Tign ≥ 300s -50 kW/m^2 : PHR ≤ 65 kW/m^2 Tign ≥ 150s -75 kW/m^2 : PHR ≤ 100 kW/m^2 Tign ≥ 90s 100 kW/m^2 : PHR ≤ 150 kW/m^2 Tign ≥ 60s

requirements reflects a two pronged approach: control flammability of materials used, and compartmentalize the fire source away from the occupants. This approach was designed to address the three most common scenarios encountered in rail transit fires: a) undercar fires, b) wayside ignition fires, and c) compartment fires. FRA guidelines, summarized in Table I, consist of prescribed limits for selection of materials based on ignition resistance, flame spread, smoke density, and fire endurance tests to ensure the structural integrity of passenger cars. Identical guidelines comprise the National Fire Protection Association (NFPA) Standard for Fixed Guideway Systems (NFPA 130). The FRA criteria for the amount of smoke generated at 1.5 and 4.0 minutes into exposure are Ds = 100 and 200 respectively.

Amtrak has expanded on the FRA guidelines by stipulating that exterior and interior rail car components be tested as complete assemblies, i.e. in a finished product form, rather than as separate materials. Amended Amtrak specifications require a toxicological screening of all new materials using the NBS test method for determination of acute inhalation toxicity due to combustion products. In addition, a fire hazard analysis is required to take into account the complete fire load, configuration, and structural design in combination with the material test data providing a systematic approach to the evaluation of material performance.

Air Transportation and Fire Regulations

Flammability requirements for materials used in commercial aircraft cabins have become highly stringent following new regulations based on heat release measurements enacted in 1990. The baseline performance requirements stipulated in Federal Aviation Regulations (FAR) resulted from full-scale fire tests carried out at the FAA Technical Center in Atlantic City, NJ. These tests simulated a post-crash external fuel fire penetrating an intact fuselage. The test results indicated that occupant survival is possible until the burning interior cabin materials cause the cabin to flashover (21). Therefore, it was deemed essential to control the heat release contribution of cabin materials used in large area applications such as sidewalls, ceiling, stowage bins, and partitions. Subsequent testing showed that heat release rate measured in bench-scale fire tests correlated with cabin flashover time. The Federal Aviation Administration (FAA) incorporated limits on the total heat release, heat release rate and smoke emission from materials used in aircraft cabins are contained in FAR 25.853 and are shown in Table I. Recognizing the growing emphasis on fire safety of aircraft interior materials, the Suppliers of Advanced Composite Materials Association (SACMA) organized a Flammability Task Force in 1990 to address these new fire regulations (22).

The FAA heat release standard requires all cabin materials to be tested in a modified Ohio State University heat release test apparatus as described in ASTM E 906. The materials are required to have less than 65 kW/m^2-min total heat release over two minutes and a peak heat release rate of 65 kW/m^2 over the five minute duration of the test. The regulations also limit the smoke density of large area interior materials to Ds ≤ 200 at four minutes using ASTM E 662. Other bench-scale tests are required for ignition resistance and flame propagation using a Bunsen burner with 12 and 60 seconds exposure. Bunsen burner tests are also required for interior cabin materials. An oil burner exposure test is required for aircraft seating since 1987, and for cargo liners since 1991. The specified acceptance criteria are reported in Table I.

Commercial Marine Transportation and Fire Regulations

US regulations for commercial shipping are found in the Code of Federal Regulations (CFR), Title 46, which covers nearly every aspect of design and construction of small and large passenger vessels, cargo vessels, tank vessels, mobile offshore drilling units, and shipbuilding materials. CFR Title 46 currently limits the use of composites to small passenger vessels, life boats and various minor components. For most vessels, regulations require main structure to be steel or equivalent non-combustible material, and most of the ship interior and outfit to be non-combustible. The breakpoint for this is certain small passenger vessels (23) which can be built completely of composite materials provided that the Coast Guard approved fire-retardant resins (MIL-R-21607) are used. There are provisions to allow a general purpose resin to be used in lieu of fire retardant resins, such as installing fire rated boundaries surrounding galleys, limiting ignition sources, fire detection and extinguishing systems in certain spaces, machinery space boundaries lined with non-combustible materials, and restrictions on furnishings (46 CFR 177.410).

The International Maritime Organization (IMO), a specialized agency of the United Nations, is responsible for maintaining the "International Convention for the Safety of Life at Sea" (SOLAS). Enforcement of the IMO conventions and standards is the responsibility of the flag state; the IMO has no direct enforcement mechanism. Two significant recent IMO efforts affecting the use of composites and fire testing in general are the adoption of: 1) the High Speed Craft Code; and 2) the Fire Test Procedures (FTP) Code (24). The adoption of the FTP code makes the use of IMO test procedures mandatory for materials and products used for vessels engaged in international voyages. Before the FTP code, each country could use its own national standards, or the IMO recommendations.

The SOLAS regulations are very similar to US domestic regulations in that they require steel or non-combustible vessel construction. In order for composites to be used in ship construction (other than for high speed craft), they must be considered "equivalent to steel" as determined by "interim" guidelines by the IMO's Maritime Safety Committee (25). These guidelines include the following criteria:

- Non-combustible (IMO FTP Code, Part I)
- Fire resistant compartment boundaries (IMO FTP Code Part 3)
- Low smoke/toxicity (IMO FTP Code, Part 2)
- Determination of structural properties and critical temperature of the composite, in accordance with given guidelines.

SOLAS classifies materials as non-combustible if they do not ignite or evolve combustible gases when heated to 750°C in a vertical cylindrical chamber (ISO 1182). For determining the flammability of surface finishes, the IMO specifies lateral flame spread apparatus (ASTM E1317). Some IMO requirements for fire safety are summarized in Table I. The US Coast Guard (USCG) is responsible for enforcing compliance with SOLAS requirements for all US ships engaged on international voyages, and for foreign ships entering US ports.

The most promising new regulatory effort in recent years was the adoption of the IMO's High Speed Craft (HSC) Code (26). This Code is intended to be a stand-alone document, with a philosophy based on the management and reduction of risk as well as the traditional philosophy of passive fire protection. It encompasses all aspects of the design, construction, and operation of high speed passenger or cargo craft, and is intended to be used in its entirety. As with nearly all maritime regulations, the Code does not specifically allow or restrict composite materials. It uses performance based criteria, and introduces a new regulatory class of material: "fire-restricting materials", defined as having low flame spread characteristics, limited rate of heat release, and limited smoke and toxic products emission. Table I lists the related fire test standards for fire restricting materials (27). The definition of this new class of construction materials represents an improvement in the standards and incorporates modern fire test methods.

Research has been instrumental in influencing the development of maritime regulations. Continued research in the near term will focus on :

- Defining acceptable criteria for qualifying fire-restricting materials for high speed craft using modern bench scale fire test methods; and
- Developing a method for predicting critical temperatures in composite laminates that can be used for designing fire resistant ship structures. The USCG is presently involved in research in both of these areas with industry cooperation.

Military Use of Composites and Fire Regulations

The use of composites in high technology military applications represents the largest market for advanced materials. The new acquisition reform is leading the military to develop performance based standards using commercially available test methods. In some cases, waivers may be granted due to mission requirements if materials cannot meet fire requirements.

The use of composites inside Naval submarines is now covered by MIL-STD-2031 (SH), "Fire and Toxicity Test Methods and Qualification Procedure for Composite Material Systems Used in Hull, Machinery, and Structural Applications Inside Naval Submarines" (28). This military standard contains test methods and requirements for flammability characteristics such as flame spread index, specific optical density, heat release and ignitability, oxygen-temperature index, combustion gas generation, long term out gassing, etc. Two guiding criteria (29) were established for the use of composite systems aboard Navy vessels. The first is that the composite system will not be the fire source, i.e., it will be sufficiently fire resistant not to be a source of spontaneous combustion. The second is that ignition of the composite system will be delayed until the crew can respond to the primary fire source, i.e., the composite system will not result in rapid spreading of the fire.

Both the USAF and US Army have military standards regulating the use of composites in military aircraft and fighting vehicles. However, these standards are application specific and designed for specific components.

Future Outlook

The use of composite materials in public transportation will continue to increase as materials and manufacturing costs decline due to the advantages of light weight and corrosion resistance. Changes for the next decade in composite materials include developing a better understanding of the fire response of these materials in terms of solid-state combustion processes and the physical and chemical properties which govern flammability. Improved models for fire growth in realistic configurations will guide the search for improved fire performance from composites. Research into flammability mechanisms will allow rational development of low-cost, fire-safe polymers and composites for transportation use and provide fire protection engineers with the tools to design fire safe passenger cabins for public transportation.

Development of advanced fire resistant polymers and composites is an integral part of the fire research efforts at the Federal Aviation Administration, Department of Defense, National Aeronautics and Space Administration, and many other civilian agencies. The long-term goal of these research efforts is to eliminate burning materials and resulting fire growth as a cause of death in public structures, commercial aviation, public surface and marine transportation, and military vessels. These research efforts are also likely to result in the development of predictive methodologies for fire hazard evaluation and structural fire endurance of composite assemblies.

Acknowledgments

The authors wish to acknowledge the technical contributions and consultations with E.C. Fischer, A.G. Morton, J. Benson (NSWCCD); James Kelly (ONR); S. Gandhi (FAA); R.G. Gann (NIST); M. Unroe (USAF); B. Sokolis (US Army); and L. Nash, C. Myskowski (USCG).

References

1. A. Linan and F.A. Williams, "Fundamental Aspects of Combustion," Oxford University Press, New York, 1993.
2. R.A. Strehlow, "Combustion Fundamentals," McGraw Hill, New York, 1984.
3. J.E. Gagorik, J.A. Corrado, and R.W. Kornbau, " An Overview of Composite Developments for Naval Surface Combatants," *Proc Int'l SAMPE Symposium*, **36**, (1991).
4. I. Caplan, "Marine Composites—Learning Lessons Along The Way," *1st Int'l Workshop on Composite Materials for Offshore Operations*, University of Houston, TX, Oct 1993.
5. M. Janssens, "Modeling the E-84 Tunnel Test for Wood Products," *Proc of Fire and Materials*, Interscience Communications Ltd, London, **1**, 33 (1992).
6. P. Hovde and A. Hansen, *Proc of Fire and Materials*, Interscience Communications Ltd, London, **3**, 139 (1994).
7. R. Morchat and J. Hiltz, *Proc Int'l SAMPE Tech Conf*. **24**, 153 (1992).
8. A. Gibson and J. Hume, "Plastics, Rubber and Composites Processing and Applications," **23**, 175 (1995).
9. Anon, "Fire and Flammability Bulletin," April, 1995, p. 2.
10. T. Ohlemiller and T. Cleary, "Upward Flame Spread on Composite Materials", Chapter 28 in *Fire and Polymers II—Materials and Tests for Hazard Prevention*, (G.L. Nelson, ed.) American Chemical Society, Washington, DC, 1995, pp 422-434.

11. A.T. Grenier, "Fire Characteristics of Cored Composite Materials for Marine Use," Master's Thesis, Worcester Polytechnic Inst, May 1996.
12. A. Grand, "Fire Evaluation of Coatings for Glass-Reinforced Polymeric Composites," *Proc of Fire and Materials*, Interscience Communications Ltd., London, **2**, 144 (1993).
13. T. Ohlemiller, T. Cleary, and J. Shields, *Proc Int'l SAMPE Symposium*, **41**, 734 (1996).
14. U. Sorathia and C. Beck, "Fire Protection of Glass/Vinyl Ester Composites for Structural Applications," *Proc Int'l SAMPE Symposium*, **41**, (1996).
15. V. Babrauskas, B. Levin, R. Gann, M. Paabo, R. Harris, R. Peacock, and S. Yusa, "Toxic Potency Measurement for Fire Hazard Analysis," National Institute of Standards and Technology Special Publication 827, December 1991.
16. T. Ohlemiller and J. Shields, "The Effect of Surface Coatings on Fire Growth Over Composite Material," National Institute of Standards and Technology NISTIR 5940, December 1996.
17. C.J. Conley, "US Vehicle Fire Trends and Patterns Through 1992," NFPA Report, National Fire Protection Assoc. Quincy, MA, Oct. 1994.
18. Title 49- Transportation 571-302. Standard 302: Flammability of Interior Materials, Federal Register, 36:232, 1972.
19. Federal Railroad Administration, Guidelines for Selecting Materials to Improve Their Fire Safety Characteristics, Fed Register, 49:162, 1984.
20. Urban Mass Transportation Administration. Recommended Fire Safety Practices for Rail Transit Materials Selection, Fed Register, 49:158, 1984.
21. C.P. Sarkos and R.G. Hill, "Heat Exposure and Burning Behavior of Cabin Materials During an Aircraft Post-Crash Fuel Fire," National Materials Advisory Board, National Research Council, NMAB Report 477-2, National Academy Press, 25, 1995.
22. D.A. Nollen, *J Fire Sci*, **8**, 227 (1990).
23. Code of Federal Regulations, Title 46, Shipping, Chapter 1, Part 175 -185, Subchapter T, Small Passenger Vessels (Under 100 Gross Tons), 46 CFR § 175-185.
24. IMO Resolution MSC.61(67), "International Code for the Application of Fire Test Procedures," Int'l Maritime Org. London, Dec 1996.
25. IMO, MSC Circular 732, "Interim Guidelines on the Test Procedure for Demonstrating the Equivalence of Composite Materials to Steel Under the Provisions of the 1974 SOLAS Convention," June 1996.
26. *The International Code of Safety for High Speed Craft*, Int'l Maritime Org., Maritime Safety Committee, Adopted as Chapter 10 to SOLAS, May 1994.
27. IMO Resolution MSC.40(64), "Standard for Qualifying Marine Materials for High Speed Craft as Fire-Restricting Materials," Int'l Maritime Org, London, Dec 1994.
28. MIL-STD-2031(SH), "Fire and Toxicity Test Methods And Qualification Procedure For Composite Material Systems Used in Hull, Machinery, and Structural Applications Inside Naval Submarines," Feb 1991.
29. R.A. DeMarco, "Composite Applications at Sea: Fire Related Issues," *Int'l SAMPE Symposium*, **36**, (1991).

The Interagency Working Group On Fire and Materials (IWGFM)

This paper is presented under the auspices of Interagency Working Group on Fire and Materials.

Polymer research is producing new materials with exceptional properties, and products made with these materials may well replace conventional products where fire performance is a consideration. As this occurs, there are unique opportunities to improve the fire safety of the facilities in which they are used or to maintain a desired level of fire safety as other advantages accrue.

Many Federal agencies with fire performance responsibilities are affected by these advances in polymer and materials science. Government staff roles in the development of such materials include ascertaining their performance and the benefits or hazards that result, and providing the basis for procurement. Applications range from public safety to national security.

In 1993 Federal scientists and engineers from over 20 agencies formed a new Interagency Working Group on Fire and Materials. The mission of the Group is: *To implement a coordinated, long-range, national research effort to understand the fire and thermal behavior of materials and develop advanced materials with improved performance. The agencies participating in the Working Group have mutual interest in fire and materials and will support cooperative research through the sharing of information and resources with the ultimate goal of improving human survivability and protecting property in severe thermal environments.*

Within this mission, the IWGFM has five technical Thrust Areas. These include: Advanced Materials and Processing • Fire and Thermal Property Testing • Database for Materials Fire and Thermal Properties • Fire and Thermal Response Modeling • Health and Environmental Response

Every year, the IWGFM sponsors technical sessions on Fire Safety of Materials. If you have any questions or need more information, please contact Usman Sorathia (US Navy, IWGFM Secretary) at 301-227-5588 or Richard Lyon (FAA, IWGFM Chairman) at 609-485-6076. ♦