Concepts for Fire Protection of Passenger Rail Transportation Vehicles: Past, Present, and Future*

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Recent advances in passenger rail transportation, fire test methods, and hazard analysis necessitate re-examination of requirements for fire safety. Several studies have indicated nearly random ability of current bench-scale tests to predict actual fire behavior. Fire safety in any application, including transportation, requires a multi-faceted approach. The effects of vehicle design, material selection, detection and suppression systems, and emergency egress and their interaction, on the overall fire safety of the passenger trains must all be considered. The strengths and weaknesses of current methods for measuring the fire performance of rail transportation systems are evaluated. A systems approach to fire safety which addresses typical passenger train fire scenarios is analyzed. A rationale is presented for the direction in which most fire science-oriented organizations in the world are clearly headed – the use of fire hazard and fire risk assessment methods supported by measurement methods based on heat release rate.

INTRODUCTION

New alternative technologies have been developed which can be used to increase intercity passenger train operating speeds. These technologies include steel-wheel-on-rail and magnetic levitation (maglev) systems. Fire safety is an area of particular interest for these technologies, as well as for conventional intercity and commuter trains. While the historical fire record has been very good with few serious passenger train fires, minor incidents have occurred which could have developed into potential life-threatening events.

Recent advances in fire test methods and hazard analysis techniques necessitate re-examination of fire safety requirements for passenger trains. Several studies have indicated almost random ability of current bench-scale materials tests to predict fire safety in actual use. Fire safety in any application, including transportation systems, requires a multi-faceted systems approach. The effects of vehicle design, material selection, detection and suppression systems, and emergency egress and their interaction, on the overall fire safety of the passenger trains must all be considered.

The Federal Railroad Safety Act of 1970, Section 202(e), gives the Federal Railroad Administration (FRA) jurisdiction over 'all forms of non-highway ground transportation that run on rails or electromagnetic guideways, including... any high-speed ground transportation systems that connect metropolitan areas...'. This authority thus covers conventional rail as well as new technology applications.

To address US passenger train fire safety, the FRA has issued guidelines for the flammability and smoke emission characteristics for materials used in passenger rail equipment.[1] These evolved from earlier versions.[2,3] The guidelines are similar to Federal Transit Administration (FTA) recommendations for rail transit vehicles,[4] but also include vehicle material tests and performance criteria for components such as mattresses and wall coverings. While the primary focus of these guidelines is material fire performance, the importance of vehicle design is recognized through requirements for separation between passengers and fire sources and acceptance criteria for structural fire testing based upon the time required for passenger evacuation from the train.

Amtrak has issued 'Specification for Flammability, Smoke Emissions and Toxicity', Specification No. 352, for its passenger cars.[5] This specification describes test requirements and criteria for flammability and smoke emission which are nearly identical to the FRA guidelines (with the addition of toxicity testing). In addition, the Amtrak specification requires that several other factors, (e.g. quantity of material present, configuration and proximity to other combustibles) be considered in combination with the material test data to develop a fire-hazard assessment for use in selecting materials on the basis of function, safety, and cost. Moreover, the Amtrak specification requires testing of an assembly to provide information about the actual behavior of materials in a 'real world' vehicle fire.

The majority of the flame spread and smoke emission tests and performance criteria for vehicle interior materials contained in the National Fire Protection Association 'Standard for Fixed Guideway Transit System' (NFPA 130),[6] intended for application to rail transit vehicles, are identical to the FRA guidelines and the Amtrak specification. However, NFPA also includes fire protection requirements in several other vehicle area, such as ventilation, electrical fire safety, etc. In addition, NFPA 130 includes requirements for trainways (i.e. right-of-ways) and stations, as part of a systems approach. A fire risk assessment is required to evaluate smoke emission, ease of ignition, and the rate of heat and smoke release, in addition to fire-propagation resistance. NFPA 130 indicates that a hazard load analysis and the use of

materials with appropriate properties are two means which can be used to perform the fire risk assessment. NFPA 130 encourages the use of tests which evaluate materials in certain subassemblies and the use of full-scale tests. Finally, NFPA 130 provides requirements for stations, trainways, vehicle storage and maintenance areas, emergency procedures, and communications.

Background

Interest in improving the fire safety of passenger train vehicles is not new. From 1906 to 1928, the Pennsylvania Railroad undertook an ambitious program to replace their wooden passenger car fleet with all-steel passanger train cars due to a concern for safety and fire prevention.[7] A total of 5501 all-steel passenger train cars including baggage, mail, express, and dining cars were involved, representing an investment of approximately $100 million. Emphasis on passenger comfort and aesthetic appeal have led to the increased use of synthetic materials.[8] Plastic use in rail car interiors started in the early 1950s.[9,10] Over the years, concern has been raised over the flammability and impact on fire hazard of these materials in the end-use configuration, even though they may be acceptable in bench-scale tests.[11]

While nonmetallic materials have traditionally been used in seat cushioning and upholstery, their use in other system components such as coverings for floors, walls and ceilings; window glazing and window or door gasketing; and nonstructural storage compartments have increased the fire load within the vehicles. In addition to the flammability characteristics of the interior furnishing materials, the size and design of the vehicle are all factors in determining the ultimate hazard to passengers and crew as a result of a fire.

In addition to interior furnishing materials, limited ventilation and difficult egress compound the potential fire hazard in intercity and commuter rail cars. Ventilation in a typical car is typically $17 \, m^3 \, min^{-1}$ (600 cfm) of fresh makeup air. Exhaust is through leakage and, thus, during evacuation, through the same exits used by escaping passengers.

Specific requirements for the flammability of materials in rail transportation vehicles first appeared in 1966.[9] These rail car specifications dictated 'flame tests' for seat foam materials before the material use would be approved for the original Metroliner passenger rail cars. The National Academy of Sciences[12] provided general guidelines in 1979 for the use of flammable materials in rail transit vehicles. These guidelines recommended the use of only those polymeric materials that, by testing and comparison, are judged to be the most fire retardant and that have the lowest smoke and toxic gas emission rates. Further, they suggest these be used sparingly, consistent with comfort and serviceability.

Fires in passenger trains are rare, but can lead to serious disasters. The 1983 Amtrak fire in Gibson, California, led to two passenger deaths, two serious passenger injuries, and numerous passenger and crew being treated for smoke inhalation.[13] Damage was estimated at $1 190 300. The National Transportation Safety Board (NTSB) report identified several areas of concern as a result of its investigation of the fire. These included the role

of materials in fire involvement, fire detection, interior arrangement (i.e. narrow hallways, door operation), intra-train communications equipment, crew training in ventilation control, emergency lighting, rescue personnel emergency access, and passenger evacuation. Although the materials used for the interior trim of the cars in the train were considered to be the best products available at that time for fire retardancy and flammability, the use of certain materials was recognized as a potentially dangerous situation requiring correction. The FRA fire safety guidelines were issued to address the flammable material concerns raised by the NTSB. Many of the other issues mentioned by the NTSB have been addressed by subsequent passenger car specifications. The recommendations of the NTSB report also provide a starting point for this report by pointing out important areas of concern in fire safety of passenger-guided ground transportation vehicles. These areas are reflected in the organization of the report section's discussing current approaches to fire safety.

Fire-related losses in rail transportation are not limited to vehicles. The King's Cross fire in the London subway system[14,15] demonstrated the need for fire safety considerations in the design of railway stations. The fire involved an escalator shaft, ticket hall, along with passageways leading to the streets and mainline concourse above. As a result of the fire, there were 30 fatalitites and numerous injuries. New British regulations governing sub-surface railway stations are under development as a result of the fire.

Literature surveys

Preliminary to starting work on this study, prior studies of fire safety requirements which may be applied to passenger rail transportation systems were reviewed. Rakaczky[16] examined the available literature on fire and flammability characteristics of materials which could be used in passenger rail transportation vehicles. With the exception of some documents published by the FTA, limited information was available for materials that related specifically to passenger rail vehicles. Much of the literature reviewed related more to other transportation applications (primarily aircraft) than to rail transportation. Key in the Rakaczky study, however, was a prevailing concern of many researchers of the ability of bench-scale tests in predicting real-scale burning behavior. Hathway and Litant[17] provided an assessment of the state-of-the-art of fire safety efforts in transportation systems in 1979. Without annotation, they provide a bibliography of literature from 1970 to 1979. Peacock and Braun[18] studied the fire behavior of Amtrak passenger cars for the FRA. They provide a review of material testing requirements and a comparison of bench- and real-scale testing of vehicle interior materials. Recently, Schirmer Engineering Corporation studied the fire safety of railroad tunnels and stations in New York City, including the impact of passenger trail flammability requirements on the fire load in tunnels and stations.[19]

Of particular interest are two safety-related studies recently completed for the FRA. The first study by the Volpe Center presents the results of a review to determine the suitability of German safety requirements for applica-

tion to maglev train systems proposed for US application.[20] That report provides a starting point for the review of the systems approach to fire safety design discussed in this paper. The Volpe Center report raises a number of questions related to maglev system fire safety design. Part of the intent of this report is to address these questions. A second study compares international safety requirements which may be applicable to maglev systems proposed for US operations[21] and provides an overview of numerous areas which may be applicable to maglev system design, including fire safety. Although the discussion of fire testing issues and impact of different test methodologies is minimal, the report provides a detailed review of the overall transportation system and the interrelationships among safety-related components of the system.

SYSTEMS APPROACHES TO FIRE SAFETY

Although the primary focus of this paper is material testing, it is important to recognize that many other factors can have a significant effect on overall fire safety. Fire safety for any application, including transportation, requires a multi-faceted approach. The underlying goals embodied in the guidelines and standards of various countries provide for public safety from fires. Litant[22] recognized the need for a systems approach to fire safety in rail transportation including vehicle design, material selection, detection, and suppression as components of the system approach.

The *goals for fire protection* are universal; only the means chosen to achieve them vary. These goals can be simply stated in the following list:[23]

(1) *Prevent the fire or retard its growth and spread*
  - Control fire properties of combustible items.
  - Provide adequate compartmentation.
  - Provide for suppression of the fire.
(2) *Protect occupants from the fire effects*
  - Provide timely notification of the emergency.
  - Protect escape routes.
  - Provide areas of refuge where necessary and possible.
(3) *Minimize the impact of fire*
  - Provide separation by tenant, occupancy, or maximum area.
  - Maintain the structural integrity of property.
  - Provide for continued operation of shared properties.
(4) *Support fire service operations*
  - Provide for identification of fire location.
  - Provide reliable communication with areas of refuge.
  - Provide for fire department access, control, communication, and water supply.

To *prevent the fire or retard its growth and spread*, material and product performance testing is used to set limits on the fire properties of items which represent the major fuels in the system. Vehicle design and compartmentation requirements along with limits on the rate of fire growth perform the function of limiting fire spread. Extinguishing systems, manual or automatic, can also be

used to control the fire. *To protect occupants from the fire effects*, detection and alarm systems notify the passengers to take appropriate actions. These systems also notify designated employees or the public fire service to begin fire fighting operations and to assist occupants. Training of personnel to react appropriately to fire incidents and system design to facilitate passenger evacuation can play an equally important part in timely passenger evacuation and fire suppression. Structural fire endurance testing of floors and partitions provide compartmentation of the fire and are intended to *minimize the impact of the fire*. Overall system design, personnel training, extinguishing equipment, and communication systems *support fire service operations*.

This section presents the overall approaches to passenger train fire safety in light of these overall goals. These goals are highlighted in italics to indicate the link between the requirements and these goals. It will be seen that although material selection plays an important role, additional areas are addressed to varying degrees in each of the approaches which are important to the overall fire safety of the passenger train system.

United States

The majority of fire safety requirements for US passenger trains consist of material fire performance test criteria designed to *prevent the fire or retard its growth and spread*. Based on test methods which evaluate fire properties of individual materials, the FRA guidelines and similar requirements for other rail applications form a prescriptive set of design specifications for material selection.

The US approach is not limited to material fire performance, however. The FRA guidelines and other requirements include specifications for fire endurance sufficient to allow passenger evacuation. The FRA currently requires that each passenger car have at least four emergency windows. Both of these requirements provide measures to *protect occupants from the fire effects*. In addition, the fire endurance requirements *minimize the impact of fire*. NFPA 130[6] includes requirements for fire detection, emergency communication, emergency lighting, emergency egress, fire extinguishers, and shutdown of the vehicle ventilation system. The NFPA standard also contains requirements for stations, train-ways, vehicle storage and maintenance areas, emergency procedures, and communications which *support fire service operations*. Fire safe design for electrical wire and cable are addressed in both Amtrak and NFPA documents.

France

The goal of the French approach to *preventing the fire or retarding its growth and spread* is similar to its US counterparts, in that materials used in each application area are treated individually. However, the French specification is a complex system based on several classification indices, each derived from multiple test results. The French standards then classify the materials on the perceived risk to occupants. The intent is to provide indices which are indicative of the risk to occupants from individual materials. However, risk results from the entire

system's reaction to a fire event. Risk inherent in individual materials may be offset by other design features. Thus, risk should be viewed for the overall system, not just individual components of the system.

In addition to material fire performance requirements, the French approach includes perscriptive requirements for fire detection in engine compartments and fire extinguishers. Fire alarm and emergency egress (via door and window design) provisions *protect occupants from the fire effects*. The French documents reviewed include only requirements for compartmentation via fire barriers in ceiling spaces to *minimize the impact of fire*. Minimal requirements are included for fire endurance.

Germany

The German Federal Railways 'Railroad Construction and Traffic Regulations' (EBO) provides general safety and operational procedures for railroad operation in Germany.[24] No information is included covering fire safety. The primary German standards covering rail car fire protection are included in DIN 5510, 'Preventive Railway Fire Protection in Railway Vehicles', published by the German Standard Institute (DIN).[25] These standards are utilized for multiple rail applications from streetcars[26] to maglev systems.[27] The German requirements address fire protection with more emphasis on efforts to *minimize the impact of fire* than in the US or France. For streetcars, the older requirements for streetcars include material selection, and particularly operating procedures. The more recently developed requirements for maglev systems carries more stringent requirements and assigns class four fire protection requirements to maglev trains in accordance with DIN 5510. Class four is the highest level of protection and is applied to trains that cannot be evacuated everywhere along the track (such as tunnels or elevated sections). The maglev specification requires that the system must be designed to maintain a safe hover long enough for the vehicle to reach a safe evacuation point—with vehicle, structural integrity, and electrical system design requirements to provide such capability. Fire endurance requirements are extensive in DIN 5510, with application to all structural components, including floors, walls, and ceilings.

DIN 5510 requires that the supporting structures, fittings, and linings of passenger cars be selected and arranged to prevent or delay danger to passengers, crew, and rescue personnel caused by the development, propagation, and spread of fire. A series of test to evaluate material performance are used to prove compliance with these requirements. These measures provide a means to *prevent the fire or retard its growth and spread.*

Additional requirements for electrical wire and cable, batteries, lighting, heating, air conditioning shutdown, automatic fire alarms, and fire extinguishers *protect occupants from the fire effects* and *support fire service operations*. DIN 5510 and the requirements for maglev systems also include requirements for emergency egress and emergency rescue planning.

Other countries

The International Union of Railways Code, 'Regulations relating to fire protection and fire-fighting measures in passenger-carrying railway vehicles or assimilated vehicles used on international services' (UIC 564-2),[28] covers passenger-carrying railway vehicle design for international service in Europe. There is considerable overlap between this code and the French standards. UIC Code 564-2 includes as a general guideline for vehicle design: 'The coach design and interior fittings must above all prevent the spread of fire'. To meet this goal, a set of material test methods is included similar in intent and implementation to the French standards, covering vehicle design (to reduce potential ignition), compartmentation (to prevent spread of fire from one vehicle to another), electrical systems, fire detection in engine compartments, fire extinguishers, fire alarms, and emergency egress (via door and window design).

Young[29] discusses the British standard 'Code of practice for Fire Precautions in the Design and Construction of Railway Passenger Rolling Stock' (BS 6853),[30] which defines two categories of vehicle use:

- Trains which require higher resistance to fire (underground, sleeping cars, unmanned operating trains)
- All other vehicles.

The British standard includes provision for material selection, compartmentation (particularly in sleeping cars), electrical equipment, cooking equipment, emergency lighting, and emergency egress.

Requirements in other countries take similar approaches to implementing the fire safety goals discussed above. The Mass Rapid Transit system in Singapore[31] was constructed in the 1980s following NFPA 130 for the station, trainway, and vehicle design. Compartmentation in stations and vehicles, ventilation systems, emergency egress provisions, and vehicle design were all considered in the overall design of the system. In Japan[32] a combination of bench-scale material screening tests and real-scale proof-testing is used to evaluate overall fire protection levels for passenger rail cars.

Summary of overall system fire safety

The trend toward a systems approach to fire safety is evident in nearly every country of the world. This trend is driven largely by the realization that the interactions among various system components can create mitigating or extenuating conditions not evident when examining the performance of the individual component. Further, it is sometimes more cost effective to compensate for the performance shortfalls of one component rather than to attempt to correct it. The traditional method of evaluating overall system safety by conducting real-scale tests is effective, but costly. Less costly (and less effective) is to test real-scale assemblies of major components of a system (for example, an entire seat assembly). In recent years, the evolution of predictive models as resulted in the development of fire hazard and fire risk evaluations which attempt to synthesize the interactions of the complete system into a computational model.

This systems approach is evident in all the fire safety requirements reviewed for this paper. It is demonstrated by requirements for assembly testing in addition to the traditional component testing with bench-scale apparatus. In addition, fire hazard analyses are utilized to

evaluate the fire load including the quantity and configuration of the combustible materials present.

Alarm systems and extinguishers, along with provision for emergency shutdown of ventilation systems are being specified in order to extend the time available for safe egress. Provision of emergency exits along with emergency plans for rescue by external forces provide an additional level of safety in case of failure of other provisions to limit the size of the fire incident.

Disastrous fires are often the result of a series of failures which allow the fire to develop. Fire safety requires a multi-level approach in which all of the components of system safety are treated in a systematic manner, such that a potential failure is countered by a safety feature. While material performance testing is important, it provides only one facet of the overall approach to effective fire safety for the traveling public.

US REQUIREMENTS

Within the general context of the system safety goals discussed in the previous section, the US fire safety requirements address specific criteria deemed necessary to meet these goals. Individual, prescriptive requirements are included for a range of components of the overall system.

There is considerable overlap of requirements for rail transportation vehicles. For example, the FRA, Amtrak, FTA, and NFPA documents contain similar requirements covering the fire safety of materials used in passenger vehicles. The German requirements include test methods used by the US Federal Aviation Administration. A report to the Office of the Secretary of Transportation recognized the potential for similar requirements in multiple modes of transportation.[33] The review in the report included fire protection and control, material controls, engine components, structural components, procedures, and buildings. Numerous areas were identified for potential cooperation and common requirements between different transportation modes. To date, the overlap is primarily limited to material controls. Similar requirements in multiple rail transportation sectors are evident in the review below. In this paper, the detailed review will be limited to the US requirements, and will concentrate on material testing requirements. A more detailed report including requirements in France and Germany is available.[34]

The FRA flammability and smoke emission guidelines for passenger train cars[3] are summarized in Table 1. The Amtrak[5] and NFPA[6] requirements are nearly identical to the FRA guidelines, with differences noted in the table and discussed in the sections covering the individual test methods. The requirements are based in large part on two bench-scale test methods – ASTM E 162, 'Surface Flammability of Materials Using a Radiant Energy Source'[35] (with a variant, ASTM E 3675 for cellular materials[36]) and ASTM E 662, 'Specific Optical Density of Smoke Generated by Solid Materials'.[37] Several additional standards are specified for individual material applications. With one exception, the test methods are bench-scale tests designed to study aspects of a material's

fire behavior in a fixed configuration and exposure. All these requirements are reviewed and discussed below.

Flame spread—ASTM E 162 and ASTM D 3675

The ASTM E 162, illustrated in Fig. 1, was developed by the National Bureau of Standards in 1955.[35,38] An almost identical method, ASTM D-3675, is used for cellular materials such as seat cushioning. This method measures flame spread and rate of energy release under a varying radiant flux from about 40 to 3 kW m^{-2}. The flame spread factor, F_s, calculated from the flame spread velocity, and the heat evolution factor, Q, determined by measuring the temperature in an exhaust duct, are combined to yield a flammability index, I_s, defined as:

$$I_s = F_s \times Q$$

The higher the index, the greater the flammability. The test instrument is calibrated to an arbitrary scale with red oak assigned as I_s of 100.

The criteria for this test method range from $I_s \leqslant 25$ for cushions, mattresses, floor coverings and insulation to $I_s \leqslant 100$ for window and light diffuser panels. With exceptions, these values are comparable to those typically found in building construction. The criteria for window and light diffuser panels of $I_s \leqslant 100$ is less restrictive than that for wall panels even though the exposure during a fire is identical. Small differences in the criteria such as the requirement of $I_s \leqslant 25$ for insulation in the FRA and FTA guidelines and $I_s \leqslant 35$ in the Amtrak specification would have little effect on fire safety. Actual acceptance criteria for any particular application are not included as part of the tests method.

Some published test results are available for the ASTM E 162 test in transportation applications. Williamson[39] tested six different candidate lining materials for rapid transit vehicles. Test results ranged from a low of $I_s = 2$ to a high of $I_s = 59$. The comparability of the bench-scale tests with large-scale tests was seen to depend on the size of the ignition source in large-scale tests. However, the data were considered by Williamson to be too sparse to comment on an overall correlation potential for E-162. Other work by McGuire[40] for fires on corridor wall, floor, and ceiling materials initiated by a room fire strongly suggest that combustible walls are more critical than, perhaps ceilings, and definitely floors, in terms of fire growth potential. For these elements alone, $I_s = 35$ for walls led to extensive spread, while an $I_s > 130$ for a ceiling and an $I_s > 435$ for a floor appears necessary for extensive spread. Peacock and Braun[18] show similar results for materials in rail vehicle interiors, where wall carpeting and carpet lining beneath luggage racks appeared critical to large fire development, even with most of the materials in the mock-up of the vehicle interior meeting the FRA guidelines. Unfortunately, for the one test which does not fit the expected pattern of fire growth based on bench-scale test results, complete bench-scale test measurements, including ASTM E-162, were not available for the wall carpeting. Nelson et al.[41] and Bridgman and Nelson[42] report on over 350 large-scale fire tests conducted to study the performance of materials in real world environments and the relationship of bench-scale test criteria to improvements in fire safety.

Table 1. US Flammability and smoke emission requirements for passenger rail vehicles

Category	Function of material	Flammability		Smoke emission	
		Test procedure	Performance criteria	Test procedure	Performance criteria
Passenger seats sleeping and dining car components	Cushions, mattresses	ASTM D-3675	$I_s \leqslant 25$	ASTM E-662	$D_s(1.5) \leqslant 100$; $D_s(4.0) \leqslant 175$[a]
	Seat frames, mattress frames	ASTM E-162	$I_s \leqslant 35$	ASTM E-662	$D_s(1.5) \leqslant 100$; $D_s(4.0) \leqslant 200$
	Seat and toilet shroud, food trays	ASTM E-162	$I_s \leqslant 35$	ASTM E-662	$D_s(1.5) \leqslant 100$; $D_s(4.0) \leqslant 200$
	Seat upholstery, mattress ticking and covers, curtains	FAR 25.853 (vertical)	Flame time $\leqslant 10$ s Burn length $\leqslant 6$ in	ASTM E-662	$D_s(4.0) \leqslant 250$ coated $D_s(4.0) \leqslant 100$ uncoated
Panels	Wall, ceiling, partition, tables and shelves, windscreen,	ASTM E-162	$I_s \leqslant 35$	ASTM E-662	$D_s(1.5) \leqslant 100$; $D_s(4.0) \leqslant 200$
	HVAC ducting	ASTM E-119	As appropriate[a]	ASTM E-662	
	Window, light diffuser	ASTM E-162	$I_s \leqslant 100$	ASTM E-662	
Flooring	Structural	ASTM E-119	Nominal evacuation time, at least 15 min	ASTM E-662	$D_s(1.5) \leqslant 100$; $D_s(4.0) \leqslant 200$
	Covering	ASTM E-648	C.R.E $\geqslant 5$ kW $^{-2}$	ASTM E-662	
		ASTM E-162[d]	$I_s \leqslant 25$	ASTM E-662	
Insulation	Thermal, acoustic	ASTM E-162	$I_s \leqslant 25$[e]	ASTM E-662	$D_s(4.0) \leqslant 100$
Elastomers	Window gaskets, door nosing, diaphragms, roof mat	ASTM C-542	Pass	ASTM E-662	$D_s(1.5) \leqslant 100$; $D_s(4.0) \leqslant 200$
Exterior plastic components	End cap roof housings	ASTM-162	$I_s \leqslant 35$	ASTM E-662	$D_s(1.5) \leqslant 100$; $D_s(4.0) \leqslant 200$
Component box covers	Interior, exterior boxes	ASTM E-162	$I_s \leqslant 35$	ASTM E-662	$D_s(1.5) \leqslant 100$; $D_s(4.0) \leqslant 200$

[a] UMTA and NFPA 130 requirement is $D_s(1.5) \leqslant 100$; $D_s(4.0) \leqslant 200$.
[b] "May use test criteria for floors or criteria appropriate to the physical locations and magnitude of the major ignition, energy, or fuel loading sources."
[c] Amtrak requirement is C.R.F. $\geqslant 6$ kW m^{-2}.
[d] NFPA 130 only.
[e] Amtrak requirement is $I_s \leqslant 35$.

These reports detail a number of factors associated with ASTM E-162 which affect test results:

- Thermocouple and baffle placement within the thermocouple stack
- Thermocouple grounding
- Position of the thermocouple stack with respect to the hood canopy exhaust duct
- Drafts with the room housing the apparatus
- Air supply to the radiant panel, gas supply
- Position, condition, and length of the pilot flame,
- Time to warm-up
- Location of the calibrating radiation pyrometer
- Radiometer calibration
- Calibration frequency
- Standard specimens.

They conclude that ASTM E 162 is reasonably predictive of large-scale test behavior and maintain that vehicles which comply with the FTA guidelines have less potential fire involvement, potentially longer times for evacuation, and less eventual fire damage than earlier constructions. However, large-scale testing must play an important role in determining the performance of a system of diverse materials in a vehicle interior. This system
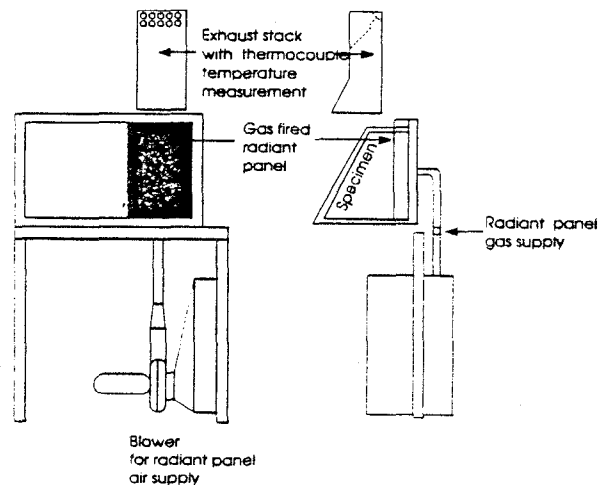

Figure 1. The ASTM E-162 test for surface flammability of materials using a radiant heat energy source.

approach is in contrast to the test selection criteria used in the development of the flammability guidelines for rail transit vehicle interiors.[4,3] In the current FTA guidelines, test methods are specifically directed at the evaluation of
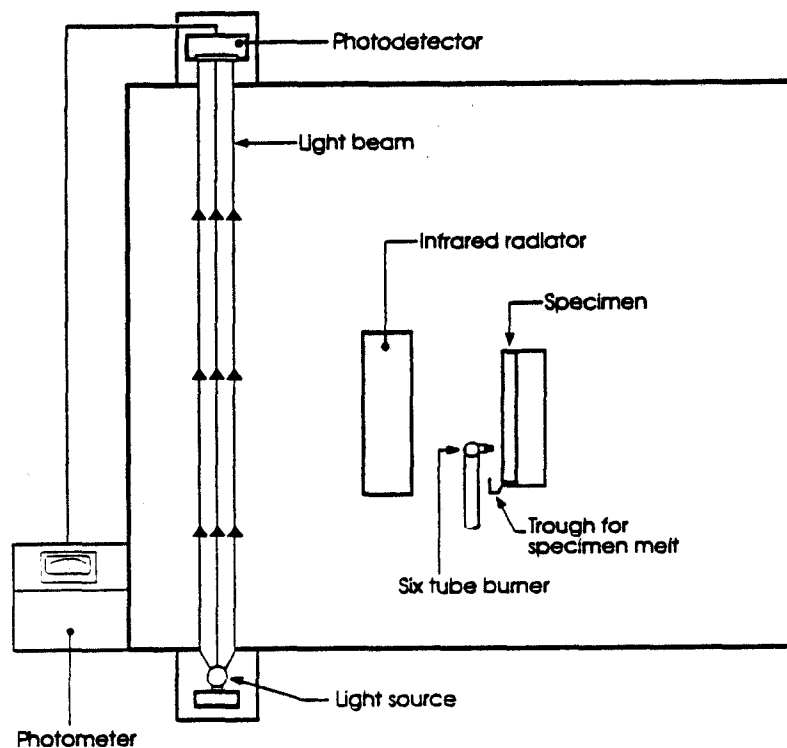
Figure 2. The ASTM E-662 test for specific optical density of smoke generated by solid materials.

the performance of individual component materials. While this allows the component supplier to determine the adequacy of their products without having to be concerned with other suppliers and products, synergistic effects of material combinations cannot be evaluated.

Other comparisons of ASTM E 162 with real-scale fires and other bench-scale tests show similarly mixed results. On the positive side, Bieniarz[44] and Fang[45] show a 'reasonably predictive' capability of the test. However, in a study of bench-scale tests used to evaluate aircraft cabin interior materials, Nicholas[46] concludes that there were practically no test methods that correlated ignitability, flame spread, or heat release for fabrics and panels. Two test methods, ASTM E 162 and the OSU rate of heat release apparatus[47] showed good correlations for heat release as an indicator of fire hazard. Other researchers have proposed that heat release rate, rather than flame spread, are more important predictors of fire hazard. Like Nicholas, Quintiere[48] concludes that rate of heat release measured in a laboratory-scale test apparatus seems to be the most significant parameter in correlating full-sale data on room temperature or time to flashover. For rail transit vehicle applications, Bonneres and Allender[49] repeat this theme, promoting heat release rate testing. In fact, heat release rate has been advanced to be the single most important predictor of fire hazard.[50]

The Smoke Density Chamber—ASTM E 662

The Smoke Density Chamber (ASTM E 662)[37] is used widely in testing of transportation-related materials. Il-

lustrated in Fig. 2, it measures smoke generation from small, solid specimens exposed to a radiant flux level of 25 kW m^{-2} in a flaming (piloted ignition) or nonflaming mode. The smoke produced by the burning specimen in the chamber is measured by a light source – photometer combination. The attenuation of the light beam by the smoke is a measure of the optical density or 'quantity of smoke' that a material will generate under the given conditions of the test. Two measures are typically reported. D_s is an instantaneous measure of the optical density at a particular instant in time. The maximum optical density, D_m, is used primarily in ranking the relative smoke production of a material and in identifying likely sources of severe smoke production. The criteria for this test method are typically D_s at $1\frac{1}{2}$ min $\leqslant 100$ and D_s at 4 min $\leqslant 200$. Small differences in criteria such as D_s at 4 min $\leqslant 175$ for cushions and matresses contained in the FRA guidelines would appear to have little effect on fire safety. Like the small differences in requirements for ASTM E 162, the differences are likely driven by perceived product acceptability rather than real differences in fire safety. Other criteria including the omission of a requirement at $1\frac{1}{2}$ min for HVAC ducting are likely due to the inability of an otherwise acceptable product to meet the criteria.

Hirschler provides an excellent critique of bench-scale smoke measurement. He divides test methods used to measure smoke obscuration accompanying a fire into five broad categories:

● Static bench-scale smoke obscuration tests on materials

- Dynamic bench-scale smoke obscuration tests on materials
- Traditional large-scale smoke obscuration tests on products
- Full-scale tests measuring heat release and smoke release
- Bench-scale tests measuring heat release and smoke release

The Smoke Density Chamber (ASTM E 662) is an example of the static bench-scale test. Many researchers have concluded that tests like the Smoke Density Chamber *do not* do an adequate job of representing the smoke emissions to be expected in real-scale fires.[51-55] The problems cited include:[51]

- Results do not correlate with full-scale tests.
- Vertical orientation leads to melt and drip.
- Time dependency of results cannot be established.
- No means of weighing sample during test.
- Maximum incident radiant flux is 25 kW m^{-2}.
- Fire self-extinguishes if oxygen level goes below 14%.
- Composites often give misleading results.
- Wall losses are significant.
- Soot gets deposited on optics.
- Light source is polychromatic.
- Rational units of $m^2 \text{ kg}^{-1}$ are not available.

Christian and Waterman[56,57] conclude that no single smoke rating number should be expected to define relative smoke hazards of materials in all situations. No suitable correlation was found between bench-scale smoke density tests and real-scale fires.[58] They suggest a combination of results from tests under widely differing exposure conditions to account for the effects of material location, fire intensity, and other factors for materials in a totally involved fire.

Dynamic bench-scale smoke obscuration tests measure smoke along with another fire property (typically heat release rate). Implicit in this technique is the recognition that smoke is actually a result of the fire and not a property unto itself. Many large-scale tests for smoke obscuration have been devised for any number of specific situations. These include the ASTM E 84 test and a modified version of the ASTM E 648 test utilized for carpets in rail transit applications. These are often intended for a specific purposes other than smoke measurement and have been adapted for smoke measurement to varying degrees of success.

Like the tests for flammability, it has been proposed that smoke can be best measured in a dynamic test which best stimulates actual end-use burning behavior.[51] Tests in large- and bench-scale which measure heat and smoke release fill this niche. Requirements for a bench-scale test to measure smoke have been proposed:[51]

- Measure fire properties in such a way that they can be used for purposes other than simple rankings or pass/fail criteria.
- Measure smoke obscuration together with those fire properties of considerable fire hazard interest, principally the rate of heat release.
- Utilize tests which have proven to give results that are representative of the corresponding property in real-scale.
- Allow for calculations to compensate for complete

sample consumption, characteristic of bench-scale tests.

The only tests in existence which fulfil these requirements are those based on heat release rate calorimetry. Hirschler[51] concludes that the best way to measure smoke obscuration in a meaningful way for real-scale fires is to use a bench-scale heat release rate test such as the Cone Calorimeter[59] (or the OSU calorimeter[47]) with compensation for incomplete burning of materials in a bench-scale test. He finds good correlation with real-scale fires for a range of materials.

Floor covering—ASTM E-648

The Flooring Radiant Panel test or 'Standard Test Method for Critical Radiant Flux of Floor Covering Systems Using a Radiant Heat Energy Source' (ASTM E 648) exposes a specimen placed horizontally to a radiant energy source that varies across a 1 m length from a maximum of 11 kW m^{-2} down to 1 kW m^{-2} (Fig. 3).[60] After ignition by a small line burner at the high radiant flux end, the distance at which the burning floor material self-extinguishes is determined. This point defines the critical radiant flux (CRF) necessary to support continued flame spread. The higher the CRF, the better is the fire performance of the floor covering.

Lawson[61] recently reviewed the development, precision, and appropriate use of the Flooring Radiant Panel. With exceptions, he notes that the precision of the test method is considered equivalent to other fire test methods and has generally reduced losses with fires involving carpeting, where the flooring materials are classified by this test methods. Carpeting taken from several large fatal fires in which the carpeting was determined to be the means of fire spread was found to have very low CRFs when tested according to this method — less than 1 kW m^{-2}.[62] The best performing floor covering would have CRF's greater than 11 kW m^{-2}. An acceptance criterion of 4.5 kW m^{-2} for egress ways in non-sprinklered public occupancies is currently in use.[63,64] The limit for rail transit vehicles of 5 kW m^{-2} cited in NFPA 130 is a somewhat more stringent criterion. It is important to note that these test criteria essentially limit the carpeting such that it will not spread fire from a small ignition source or become involved early in a growing fire. For fully involved fires, fluxes in excess of 20 kW m^{-2} can be developed. In these extremes, carpeting may become involved.

In transportation vehicles, carpeting is also routinely used for wall and ceiling covering. For such applications, the results of the horizontally oriented Flooring Radiant Panel test would have little meaning. The additional requirement to test floor covering materials under ASTM E 162 is included to address vertically oriented applications. In the US the acceptance criterion for carpeting is identical to other wall and ceiling coverings.

Fire endurance test—ASTM E 119

Standard test methods for determining the resistance of floor, partitions, and walls to sustained fire exposure have been available since 1903.[65,66] The test method
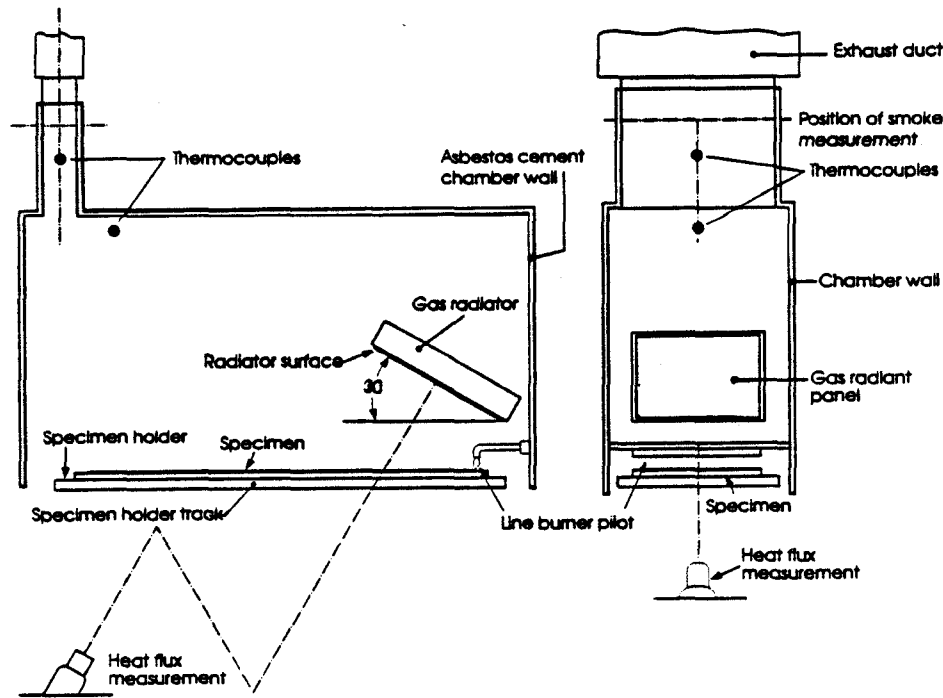
Figure 3. The ASTM E-648 flooring radiant panel test.

specified in the FRA guidelines, ASTM E 119 – 'Fire Tests of Building Construction and Material's has been widely used for determining the structural integrity of construction for a wide variety of applications.[67] While numerous minor changes have been made in the last 80 years, the time–temperature curve, the basic test apparatus, and some of the criteria have remained unchanged since its introduction as a standard test method, then numbered C19, in 1918.[68] The complete construction, stressed with weights or hydraulic jacks to simulate the mechanical loads of actual use, in subjected to heating in a furnace with a prescribed temperature–time curve. Measurement of temperature, heat transmission, and structural integrity are used to judge acceptability. Typical test criteria which cause failure of an assembly include:

● Failure to support load
● Temperature increase on the unexposed surface 139°C (250°F) above ambient
● Transmission of heat or flame sufficient to ignite cotton waste
● Excess temperature (as specified) on structural steel members
● Failure when impacted by high-pressure fire hose streams (for walls and partitions).

The larger scale of these test methods seems to have led to fewer questions concerning their ability to predict end-use fire behavior. Although it is recognized that the actual time to failure of an assembly may be different (either a shorter or a longer time),[69] relative rankings for different assemblies should be indicative of relative actual performance. For short exposure times, this uncertainty could be significant factor in actual fire performance. For fire endurance testing of building materials, test dura-

tions of 1 to 4 h are typical – significantly longer than the 15 min minimum specified in the guidelines. The actual acceptance criteria specified in the FRA guidelines depends upon the evacuation time of a vehicle and could be longer than this minimum. The effect on fire endurance of openings in the assembly is also addressed in the FRA requirements with a specification that 'penetrations (ducts, etc.) should be designed against acting as conduits for fire and smoke'. Details of such a design are left to the system designer.

Bench-scale 'Bunsen Burner' tests

Bench-scale Bunsen burner type tests, wherein a sample of a material is exposed to a small flame from an alcohol or gas burner, have been frequently used and misused to test the flammability of materials since the 1930s.[70] During the 1950s and 1960s there was increased reliance on testing the flammability of materials by means of Bunsen burner type tests. This dependence has decreased in recent years following action by the Federal Trade Commission. In passenger-guided ground transportation, the primary use of these types of tests is in the Federal Aviation Regulation FAR-25.853, Appendix F (Fig. 4). This standard, used in the current context to assess the acceptability of seat upholstery, mattress ticking and covers, and curtains, defines both a test procedure and acceptance criteria for small-scale fire performance of compartment interior materials used in transport category airplanes.[71] It is based on Federal Test Method Standard No. 191, Method 5903.[72] The test procedure is a vertical test with a 3.9 cm (1.5 in) flame applied either for 12 s or for 60 s (determined by the end-use of the material) to the lower degree of a 5 cm (2 in) wide,
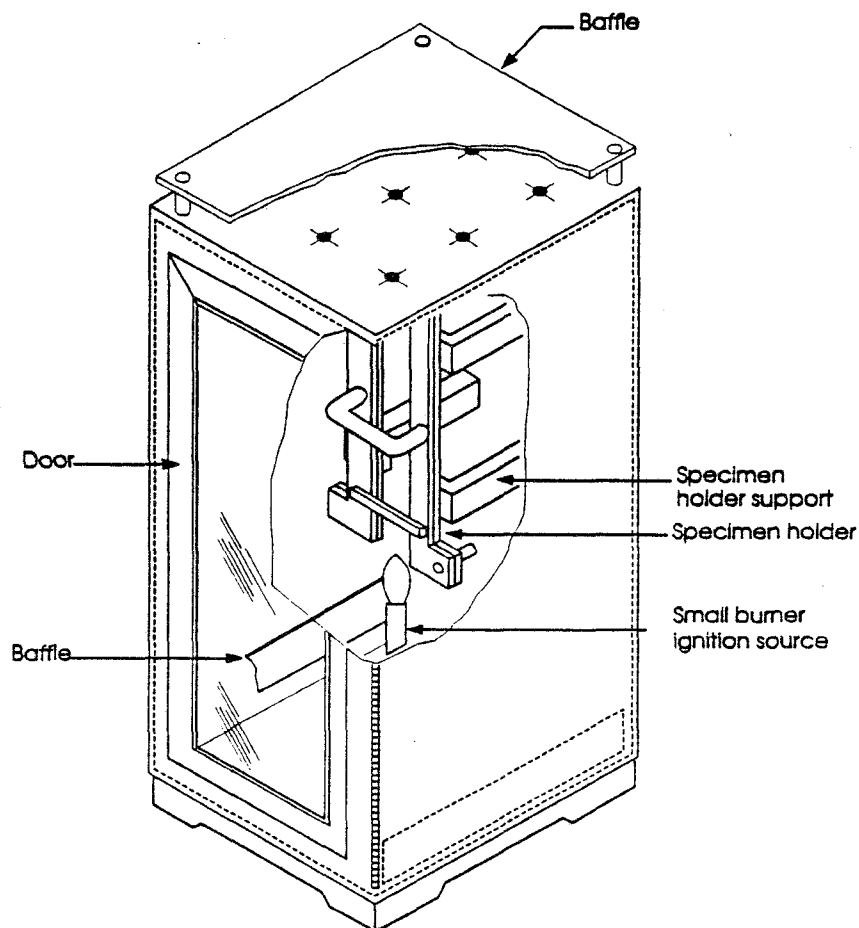
Figure 4. The FAR-25.853 vertical Bunsen burner test.

30.5 cm (12 in) long specimen. The test records the flame time, burn length, and flaming time of dripping material. For elastomers (defined in the FRA guidelines as window gaskets, door nosing, diaphragms, and roof mat), a similar test, ASTM C-542, 'Standard Specification for Lock Strip Gaskets', is used. The test consists of a 46 cm (18 in) long specimen suspended over a Bunsen burner flame for 15 min.

Considerable evidence questions the usefulness of these tests. Tustin[73] studied the correlations between the Bunsen burner test and fires in a full-scale airplane fuse large interior. Burn length in the Bunsen burner tests showed poor correlation to the full-scale test results. In contrast, bench-scale rate of heat release apparatus provided acceptable correlations to the large-scale test with some corrections to the bench-scale test data. Sarkos *et al.*[74] reaffirm this finding with comparisons between bench-scale test results and an intermediate-scale test of interior partition panels. Although these types of tests may provide an indication of the resistance of a material to ignition, they cannot be used to predict the performance of materials that exhibit high burning rates when subjected to external heating conditions. Neither the Bunsen burner test or the ASTM E 162 radiant panel test correctly predicted the rank order of interior panels in the intermediate-scale tests. Sarkos et al. recommend a rate of heat release apparatus (the OSU apparatus[47]),

with exposure conditions appropriate for the fire scenarios of interest, as an improved test method. This method now supplements the vertical Bunsen burner test in airplane requirements. There is little correlation between these tests and real situations, nor is there an accepted level of the index which could be considered hazardous. In particular, early BART system vehicle fires have gone to flashover, despite passing the similar ASTM D-1692 Bunsen burner test.[75,76] Later designs have improved the fire performance of the vehicles considerably. Material selection consistent with the FTA guidelines and full scale mockup testing indicated minimal fire propagation of the improved designs.[77]

MATERIAL REQUIREMENTS BASED ON HEAT RELEASE RATE TESTING

In the majority of fire cases, the most crucial question that can be asked by the person responsible for fire protection is: 'How big is the fire?' Put in quantitative terms, this translates to: 'What is the heat release rate (HRR) of this fire?' Recently the National Institute of Standards and Technology (NIST) examined the pivotal nature of heat release rate measurements in detail.[50] Not

only is heat release rate seen as the key indicator of real-scale fire performance of a material or construction, HRR is, in fact, the single most important variable in characterizing the 'flammability' of products and their consequent fire hazard. Examples of typical fire histories illustrate that even though fire deaths are primarily caused by toxic gases, HRR is the best predicator of fire hazard. Conversely,the relative toxicity of combustion gases plays a smaller role. The delays in ignition time, as measured by various Bunsen burner type tests, also have only a minor effect on the development of fire hazard.

There are at least two approaches to utilizing HRR data in material selection for any application:

- Use the heat release rate with appropriate limiting criteria for the selection of materials and constructions for the application. This is similar to the traditional approach of using the results of test methods to guide the selection of individual materials for an application. The key limitation to this approach is the inability to judge a material in the context in which it is used and in conjunction with other materials in a given application.
- Use the heat release rate in a hazard analysis of the actual application. This removes the limitations of the traditional approach above. However, it requires consideration of how materials are combined in an application and thus is more difficult for individual material suppliers to judge the adequacy of their product to the application.

Both these approaches are appropriate for passenger trains.

Correlation methods for prediction

A detailed discussion of fire scenarios for passenger trains is presented in reference 34. In this section, it is sufficient to note the most important fire scenarios in passenger train vehicles:

(1) Fires originating outside the passenger compartment
(2) Fires originating on or under a passenger seat due to arson
(3) Fires spreading from either of the above fires to adjacent seats or to the interior lining of the vehicle.

For category (1), large-scale fire endurance tests such as ASTM E 119 provide a measure of protection by reducing the risk of a fire penetrating the interior of a vehicle. To address the latter two categories, available correlations based on heat release rate measurements are available. Two areas of the vehicle are primarily involved in fires in categories (2) and (3) – upholstered seating and interior linings. Correlations for these applications are described below.

Upholstered seating. Babrauskas and Krasny[78] and Ames and Rogers[79] studied the burning behavior of upholstered furniture. The latter study included testing of seating to the BS 5852 Part II seating mock-up test included as a requirement for British conventional rail vehicles. These studies included non- or slightly fire-retarded seating assemblies. More highly fire-retarded seating materials are already in use in passenger train vehicles. Such seating materials are the subject of an extensive investigation carried out jointly by NIST and the California Bureau of Home Furnishings (BHF).[80] Furniture sold for use in institutional occupancies in the state of California must pass the California Technical Bulletin 133 test (T.B. 133).[81] Other states have also begun to adopt this test. The T.B. 133 fire test is conducted in a room 3.7 m by 3.0 m by 2.4 m high, lined with gypsum board. Alternatively, the test can be conducted in the ASTM Standard Room (2.4 m by 3.6 m by 2.4 m high) or under a large calorimeter. The furniture is located on a weighing platform in the rear corner farthest from the doorway. The ignition source is a specially-designed, T-shaped gas burner placed at the back of the seat. Temperatures, CO concentration, smoke opacity, and mass loss are measured durign the test. For the purpose of this investigation, instrumentation was added to measure the heat release rate by oxygen consumption.

Ten sets of chairs were tested at NIST and at BHF. These were of plain, rectilinear construction with wood frames. Only the type of fabric, type of foam and the presence or absence of a fiberglass interliner were varied between the chairs. The fabrics included wool, nylon, polyolefin and PVC vinyl. The foams examined were a fire-retardant treated polyurethane that passed the California Bulletin 117 bunsen burner and cigarette tests and a more highly FR melamine-treated polyurethane. The chosen combinations provided a very large range of fire performance. The total heat release rates were measured in the NIST furniture calorimeter, the ASTM room fire test, and the room fire test specified in T.B. 133. The ASTM room refers to the proposed ASTM room fire test, which is conducted in a 2.4 m by 3.6 m by 2.4 m high room, lined with calcium silicate board. The newspaper ignition source specified in T.B. 133 and a propane burner used to simulate it[82] were each used to ignite these chairs. The het release rate per unit area and the heat of combustion were measured in the Cone calorimeter for each of the ten combinations of materials.

In general, the total heat release rate curves of upholstered seating have two major peaks, one representing the burning of the fabric and one the burning of the underlying foam or padding. For highly fire-retarded or institutional seating, the foam does not get involved and so there is only one peak. For one-fire-retarded seating, the foam becomes involved so quickly that the two peaks merge into one. For moderately fire-retardant seating, the two peaks are resolved and the separation between them can be quite large. In some cases the foam may smoulder for over an hour before it flames, producing the second peak long after the fabric burning has stopped. The actual heat release rate curves can exhibit additional peaks, due to other phenomena such as collapse.

Although limited to the chair designs and constructions used in the study, the real-scale burning behavior of the chairs could be predicted from bench-scale heat release rate measurements. Two simple correlations were seen comparing HRR measurements in the Cone calorimeter at an external flux of $35\,kW\,m^{-2}$ ($\dot{q}''_{bs}$) to the full-scale test results ($\dot{q}''_{fs}$). For highly fire-retarded chairs (including the first fabric peak of moderately fire-retarded chairs):

$$\dot{q}''_{fs} = 0.75\,\dot{q}''_{bs}$$

For chairs that are considerably flammable:

$$\dot{q}_{fs} = 4.7\,\dot{q}''_{bs}$$

For chairs of intermediate flammability, small changes in design or construction can lead to either of the two burning regimes embodied in the correlations. Thus, two *coveats* should be noted for the above correlations. The first correlation is dependent on the details of the ignition source and its location; the relation given applies only to the source used for California T.B. 133 testing. The second correlation is not a general predictive equation; it works only because the test chairs had nearly identical mass, frame, and style factors.

However, the simplicity of these successful correlations leads to a direct application of bench-scale heat release rate testing, particularly for application to seating of extremely limited flammability. For such highly fire-retarded seating, only the first correlation is used. This correlation combined with the State of California limit of 80 kW in full-scale testing for such seating, implies that a $\dot{q}''_{bs}$ value of less than 107 kW m^{-2} is required. For practical application of bench-scale Cone calorimeter results to establishing equivalency to the full-scale result, this could be rounded to 100 kW m^{-2}. It should be noted that these limits (80 kW in full-scale or 100 kW m^{-2} in bench-scale) provide a stringent criterion requiring highly fire-retarded seating assemblies.

It should be noted that although the implied level of risk in institutional occupancies to which the California T.B. 133 test criteria apply should be similar to that in passenger train vehicles, the actual acceptance criteria used must also depend on the current state-of-the-art in materials employed in a particular application. Widespread test results are not yet available for materials in current use in passenger trains. Thus, practical acceptance criteria could be the same or different from the limit recommended above.

Interior linings. At least two correlations are available for predicting the full-scale burning behavior of wall and ceiling lining materials. Wickström and Göransson[83-85] have shown from the results of the Cone Calorimeter that the full-scale room fire heat release rate curve (for the ISO 9705 room/corner test) can be calculated. Another similar correlation has been developed by Östman and Nussbaum.[86] They have succeeded in correlating time to flashover in the Room/Corner test with time-to-ignition and peak heat release rate measured in the Cone Calorimeter, and the density of the product. Both of these are described below, along with the Room/Corner test.

Following the ASTM disengagement from the development of a standard room fire test, activity was accelerated in the Nordic countries. Development was principally pursued in Sweden, at the Statens Provningsanstalt by Sundström.[87] The ISO method uses a room 2.4 by 3.6 m by 2.4 m high, with an 0.8 by 2.0 m doorway opening.[88,89] The specimen is mounted on the walls and ceiling and is ignited by a propane gas burner operated at two levels, 100 kW for the first 10 min and 300 kW thereafter. A classification scheme for wall and ceiling linings has been proposed by Sundström and Göransson[90] based on this test scenario. The proposed classification, based on time to flashover, is shown in Table 2.

Table 2. Proposed classification system for wall/ceiling lining materials tested in the Room/Corner test

Class	Time to flashover (min)	Peak HRR (kW)
A	$\geqslant 20$	$\leqslant 600$
B	$\geqslant 20$	No limit
C	$\geqslant 12$	No limit
D	$\geqslant 10$	No limit
E	$\geqslant 2$	No limit

In order to predict full-scale heat release rate from bench-scale measurements, an expression for the burning area, $A(t)$ is required. The step function nature of the ignition source in the Room/Corner test allows a simple empirical description of this burning area. Initially, the area in the corner behind the burner is ignited. The size of this area is assumed constant and the same for all products. The burning area is assumed to grow according to a given function of time. It will, however, start to grow only if an appropriate ignition criteria is reached. This is assumed to be a fictitious surface temperature which depends on ignitability as well as on heat release properties of the product. These parameters are obtained from the Cone Calorimeter. The resulting empirical correlation can then be expressed as

$$\dot{q}_{fs} = \frac{2A_0}{t_{ign}} \sum_{i=1}^{N} (t^i \dot{q}''^{N-i}_{bs} \Delta t)$$

where t_{ign} is the ignition time, A_0 is the area behind the burner and a is an empirical constant found to be 0.025 s^{-1}. The fictitious surface temperature criterion determines whether the fire will spread away from the vicinity of the burner. It is calculated from an empirical correlation and a calculated surface temperature assuming the material behaves as a semi-infinite solid.[91] Comparisons for 13 different wall and ceiling linings show reasonable agreement for all products, even though the products cover a wide range of fire behavior. No products are predicted to be in a wrong classification according to the system outlined in Table 2.

A simpler correlation has been proposed by Östman and Nussbaum.[86] They predict time-to-flashover in the Room/Corner test from ignition time and heat release measured in the Cone Calorimeter as:

$$t = \frac{2.76 \times 10^6 \, t_{ign} \sqrt{\rho}}{Q} - 46$$

where t is the predicted time-to-flashover in full-scale (s), t_{ign} is the time-to-ignition in the Cone Calorimeter at an irradiance level of 25 kW m^{-2} (s), ρ is the density of the material (kg m^{-3}), and Q is the heat release during the peak burning period (J m^{-2}). This function gave a quite good correlation between bench-scale and full-scale behavior (with a correlation coefficient of 0.963) and similar rankings for materials studied in bench- and full-scale.

Unfortunately, for surface linings, a simple acceptance criteria applicable to passenger trains is not immediately available as was proposed for seating. Again, test results of materials used in an application are required to establish appropriate acceptance criteria.

Smoke emission. The smoke emission of products is often viewed as a unique material property separate from other fire performance characteristics. In a study of 35 materials covering a wide range of fire behaviour, Hirschler[51] proposed five categories for material classification based on heat release rate, ignitability, propensity to flashover (expressed as the same ratio of time to ignition over heat release rate used by Östman and Nussbaum, above), and smoke emission (expressed as a 'smoke factor' – the product of the total smoke released and the peak heat release rate). The proposed classifications are shown in Table 3.

Of key importance in this classification scheme is that the better-performing materials in terms of HRR and smoke emission are mostly identical materials. In fact, five materials are in the top category in each of the four classifications. This suggests that smoke obscuration in full-scale fires is heavily dependent on fire performance and that those materials that have the best fire performance will also tend to generate less smoke.

Tests needed. Three types of tests are seen as necessary to evaluate the fire behaviour of materials used in passenger trains:

- The Cone Calorimeter, ASTM E 1354, can provide multiple measures of fire performance for materials and assemblies used in the construction of passenger train vehicles. These include ignitability; heat release rate; and release rates for smoke, toxic gases, and corrosive products.
- Standard fire endurance testing, such as specified in ASTM E 119, provides a measure of the ability of a given construction to prevent the spread of fire from one compartment to another or from the underside of a vehicle to the interior.
- Initial *reference* real-scale testing will always be needed for any product category. Bench-scale tests can then, if suitably validated against these real-scale fires, be used to provide for most of the needed product testing. Thus, the large-scale test will rarely be needed in actual practice. But, it must be available for those situations where the bench-scale test is not applicable. Babrauskas and Wickström[92] give further guidance on this point.

What is lacking in material testing. As noted above, appropriate acceptance criteria for application of HRR-based tests to passenger trains have not been developed. Widespread bench-scale heat release rate test results are not yet available for materials in current use in passenger trains. Actual acceptance criteria must consider not only the desired level of protection, but also the current state-of-the-art in materials design for the application. Some testing is still required to establish equivalent criteria for current materials.

Once these test results are available, some real-scale testing of materials will be required to establish or verify the predictive ability of the bench-scale tests. This will serve two purposes: (1) to provide a level of verification of the bench-scale testing, and (2) to minimize future real-scale testing needs for suppliers and manufacturers of passenger trains.

Fire hazard analysis

Fire hazard analyses are gaining worldwide acceptance as means to establish the level of regulation needed to assure safe products without imposing unwarranted restrictions. In their efforts to harmonize regulations among the European nations, the EC Commission established the early goal that all fire tests selected should be consistent with fire hazard analysis procedures and provide the data needed by such techniques.[93] In Japan, the Building Research Institute of the Ministry of Construction (which promulgates the national building code and serves as the arbiter of its equivalency clauses) has formally established a fire hazard analysis procedure as one means of demonstrating the equivalency of new products and materials to their code requirements.[94] Australia is developing a similar system through its Warren Centre for Advanced Engineering (University of Sydney) and CSIRO Division of Building, Construction and Engineering.[95] Sweden, Norway, Denmark, Germany, France, and Singapore all have established the precedent of accepting new products, materials, or designs based on fire hazard or fire risk analysis calculations.

After preventing ignition, the primary goal of fire safety engineering is to limit the impact of the fire on a construction and its occupants. This has traditionally been addressed by placing a limit on the burning behavior of products in some standard test method which was intended to simulate a realistic threat. For example, the ASTM E-84[96] test evaluates the performance of interior finish products when exposed to a standard fire condition representative of a broad range of applications for these products. The results of these test methods can be misleading when applied to products without proper regard to their context of use, such as the testing of low density plastics in the E-84 test. In many cases, there is only a tenuous connection between the results of that test and the property that was being checked. This applies to various aspects of bench-scale tests including toxicity, flame spread, ease of ignition, and smoke emission.

Table 3. Classification of fire performance based on heat release rate, ignitability, propensity to flashover, and smoke emission

Peak heat release $\dot{q}''$ (kW m^{-2})	Ignitability, t_{ign} (s)	Propensity to flashover, $t_{ign}\dot{q}''$ (s m^2 kW^{-1})	Smoke factor, S (MW m^{-2})
$\dot{q}'' < 60$	$2.5 < \mathrm{Log}(t_{ign})$	$1 < \mathrm{Log}(t_{ign}/\dot{q}'')$	$1.5 > \mathrm{Log}(S)$
$60 < \dot{q}'' < 100$	$1.5 < \mathrm{Log}(t_{ign}) < 2.5$	$0 < \mathrm{Log}(t_{ign}/\dot{q}'') < 1$	$2 > \mathrm{Log}(S) > 1.5$
$100 < \dot{q}'' < 200$	$1 < \mathrm{Log}(t_{ign}) < 1.5$	$-1 < \mathrm{Log}(t_{ign}/\dot{q}'') < 0$	$2.5 > \mathrm{Log}(S) > 2$
$200 < \dot{q}'' < 300$	$0.5 < \mathrm{Log}(t_{ign}) < 1$	$-2 < \mathrm{Log}(t_{ign}/\dot{q}'') < -1$	$3 > \mathrm{Log}(S) > 2.5$
$\dot{q}'' > 300$	$\mathrm{Log}(t_{ign}) < 0.5$	$\mathrm{Log}(t_{ign}/\dot{q}'') < -2$	$\mathrm{Log}(S) > 3$

Source: Reference 51.

In general, it is difficult to substantiate the assertion that some critical property was measured in most bench-scale tests. However, the advent of modeling, developed mostly over the past decade, is having a profound impact on the ability to realistically evaluate the fire hazards of materials and products in their actual context of use. It is no longer necessary to totally depend on the stand-alone test methods for determining the degree of fire safety afforded by a component material. The interactions of multiple components with each other in the context of their application and use can be evaluated; interactions which are not considered in traditional test methods. Deficiencies of one component may be offset by the strengths of another, resulting in a safe combination. A good example of this is the use of blocking layers in aircraft seats[97] which protect the foam core for sufficient time to allow safe evacuation of the passengers. This allows retention of the benefits of light weight and comfort while still providing an appropriate level of safety.

It is the newly emerging technology of predictive fire modeling that enables evaluation of the combination of a material and the environment in which it is being used. A primary example of the application of this field is in assessing smoke toxicity from the burning of concealed combustibles[98] where the surroundings of the product affect its burning behavior as well as the movement of the smoke to where people might be harmed. Of even more importance, the model can keep track of the contribution of the smoke produced by other combustible items which may be involved. This relationship is a breakthrough, since only the total smoke toxicity can be measured in tests.

Ultimately, fire hazard analysis utilizing necessary data from bench-scale heat release rate measurements can provide a true assessment of the contribution of a material or assembly to the overall fire hazard for identified fire scenarios in passenger guided ground transportation. In addition, such analyses can include the effects of vehicle and system design, detection, suppression, and evacuation and any tradeoffs between multiple effects.

Quantitative hazard analysis techniques have the potential of providing significant cost savings. Alternative protection strategies can be studied within the hazard analysis framework to give the benefit-cost relation for each. In addition, measures are evaluated as a system with their many interactions, including the impact of both structure and contents. Providing these alternatives promote the design flexibility which reduces redundancies and cost without sacrificing safety. New technology can be evaluated before it is brought into practice, thus reducing the time lag currently required for code acceptance. Thus, quantitative hazard analysis is a powerful complement to existing codes and standards and a useful tool in evaluating improvements to them.

What is lacking in fire hazard analysis. Information by which to characterize the application environment is typically available through general statistical sources. However, there are two elements missing. The first is showing the ability to predict real-scale burning behavior for specific applications with results obtained from small scale tests combined with computational hazard analysis. Second, in order to carry out such an analysis completely, there is one computational piece missing, a predictive fire growth model which includes ignition, flame spread, and suppression. Barnett and Cappuccio[99,100] outline the additional research needs necessary to implement a hazard and risk analysis framework for rail transportation vehicles consistent with these two missing elements. They include three areas important for further study:

- Collection of small-scale test data for hazard analysis using methods such as the Cone Calorimeter, the furniture calorimeter, and the Radiant toxicity apparatus to collect fundamental flammability properties of the materials used in trains.
- Extension of existing compartment fire models for application to transit vehicle fires.
- Real-scale tests of actual trains.

Current models of fire growth rely on what is commonly called a specified fire. In such an application, one measures the heat release rate, smoke production, toxicity and so on with the test methods described above. Then these results are used to describe the fire which is used for the scenario calculations. In most cases, this is an acceptable solution. The heat release and species production are constrained by the available oxygen. In general, but not always, such an analysis will yield a conservative result. The reason is that the amount of pyrolysate available for burning is a coupled function of the heat generated, so often the mass flux from the fire will be different than expected from the tests performed in a free burn environment as is the case for the Cone Calorimeter and most other test apparaturs. Thus, the level of hazard can be bracketed. But to be able to extend the predictions to multiple products burning simultaneously or sequentially, such as an initial seating fire which ignites an adjacent wall panel, prediction of fire growth is essential.

Before such calculational tools are available to directly predict fire growth, estimates from correlations such as the Wikström and Göransson techniques for combustible wall panels or available correlations for upholstered seating must be used in place of a predictive pyrolysis model.

To date, hazard analysis techniques have focused on the products involved in fire. Other components of a system approach to fire safety are just beginning to be incorporated into predictive models. Until these are fully developed, the effects of vehicle design, fire detection, and suppression must be estimated from traditional design strategies. This is particularly important in transportation systems where fire detection can be important and innovative suppression systems (such as water mist[101]) are being considered.

CONCLUSION

Considerable advances in fire safety engineering have been made in the decade since the original development of the current US guidelines for passenger train material selection. Some requirements for system design, materials controls, detection, suppression, and emergency egress are included in the variety of requirements reviewed—with each applying to distinct subsets of passenger guided ground transportation. Better understand-

ing of the underlying phenomena governing fire initiation and growth have led to the development of a new generation of test methods which can better predict the real-scale burning behavior of materials and assemblies. At the same time, advances in fire and hazard modeling are leading a revolution in the analysis of a material's overall contribution to fire hazard in a particular application. Such an approach allows evaluation of factors in addition to material flammability and of tradeoffs in the fire-safe design of the entire fire safety system. These advances should be incorporated into future designs of passenger trains. To properly evaluate the fire safety of a system, motive power unit and passenger car design

and construction, material flammability, fire detection and suppression systems, communication systems, emergency evacuation, system operation, and personnel training must be considered.

Several independent sources support this new direction for rail transportation fire safety. Studies by Cappuccio and Barnett[99,100] on transit system analysis, Schirmer Engineering Corporation[19] on stations, tunnels, and vehicles for Amtrak, and Burdett, Ames, and Fardell[102] on the King's Cross subway station fire all promote new test methods coupled with mathematical modeling to assess potential hazards under real fire conditions.

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