

DEVELOPMENT OF A HAZARD-BASED METHOD FOR EVALUATING THE FIRE SAFETY OF PASSENGER TRAINS

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ABSTRACT

The fire safety of U.S. passenger rail trains currently is addressed through small-scale flammability and smoke emission tests and performance criteria promulgated by the Federal Railroad Administration (FRA). The FRA approach relies heavily on test methods applied to the primary combustible materials of rail vehicle components. As building fire safety regulations move toward performance codes, there has been interest in the application of fire hazard assessment to rail vehicles using modeling techniques. Accordingly, with FRA funding, the National Institute of Standards and Technology (NIST) and the Volpe National Transportation Systems Center (Volpe Center) have been working on such an alternative approach. This effort included a systematic study of the fire performance characteristics of current rail car materials. First, the heat release and smoke production of actual materials in use were characterized in the Cone Calorimeter. Next, full-scale assembly tests of components such as seats and interior panels constructed of these same materials were conducted in a furniture calorimeter. Full-scale tests of rail cars incorporating the tested components are planned. The predictive accuracy of fire hazard modeling techniques will be assessed against the full-scale test results and the model's utility in evaluating alternative fire safety improvements, such as automatic suppression or smoke exhaust will be demonstrated. The paper provides an overview of five years of work and the findings to date. It is expected that this work could lead to the recognition of fire hazard-based methods as an alternative the current prescriptive requirements.

CURRENT FRA REQUIREMENTS

As part of the passenger rail equipment rulemaking process required by Congress, the FRA has proposed that passenger train materials be required to meet certain flammability and smoke emission test methods and performance criteria¹. These proposed requirements are based on guidelines for intercity and commuter rail cars which FRA first issued in 1984 and revised in 1989^{2,3}. The 1984 FRA guidelines were identical to Urban Mass Transportation Administration (UMTA), now Federal Transit Administration (FTA) recommended practices for rail transit vehicles, also issued in 1984⁴. The FRA issued revised guidelines in 1989 that used terms and categories to more closely reflect passenger train design and furnishings; smoke emission performance criteria for floor coverings and elastomers were also included.

Based primarily on small-scale test methods which demonstrate fire characteristics of individual materials, the FRA requirements form a prescriptive set of design specifications which historically have been used to evaluate transportation vehicle material fire performance. This approach provides a screening device to allow interested parties to identify particularly hazardous materials and to select preferred combinations of individual components; material suppliers can independently evaluate the fire safety performance of their own materials.

TYPICAL RAIL CAR MATERIALS

Passenger rail cars are constructed primarily of stainless steel; some newer designs incorporate aluminum components. Due to the typically longer distances traveled, the furnishing of conventional passenger train cars is more complex than the furnishing provided in a rail transit vehicle (e.g., subway, light rail). Most intercity and many commuter rail cars are equipped with upholstered seats. Multilevel cars have stairways which allow passengers to move from one level to another. Intercity passenger trains may consist of coach cars, cafe/lounge cars, dining cars, and sleeping cars. In addition, cooking equipment, heat and air conditioning systems, AC and DC power equipment, and lavatories are included in various passenger car designs.

Intercity passenger rail cars typically have interior walls, ceilings, and floors partially covered with carpeting or fabric glued to a perforated sheet metal base material. The underside of the overhead luggage storage rack is covered either with the same carpeting or rigid PVC/acrylic. In some configurations, the carpeting on walls has been replaced with fiberglass-reinforced polymer (FRP) material. Polycarbonate windows are usually used. Fabric drapes are used at windows in many cars. Elastomeric materials are used for gasketing at door edges, around windows and between cars. Polymeric materials are also used in hidden spaces (nonpassenger-accessible space), such as cable and wiring, pipe wrap, ventilation and air ducting. The majority of rail car floors are constructed of plywood/metal (plymetal panels). Fiberglass insulation is used in the floors, sidewall, end wall, and air ducts in the cars. The floor covering consists of carpet and resilient matting.

Coach cars contain rows of upholstered seats, windows and overhead luggage storage space. Coach seats consist of fabric-covered foam cushions installed on steel seat frames with plastic seat shrouds, back shells, and food trays. Seat support diaphragms provide flexible support for the seat bottom. Certain coaches used for longer distances are equipped with padded arm and leg rests, and foot rests, as well as curtains which cover the windows. The seats in first class sections are similar to coach seats described above but plush fabric upholstery installed over thicker foam cushions provides a higher level of comfort.

For trains using a single level car configuration, cafe/lounge car interior furnishings are similar to the coach cars. The cafe/lounge cars have a minimal food service area and reduced seat density and may be equipped with tables. Dining cars contain an extensive separate food preparation area, laminated tables and walls, and vinyl upholstered seats. Dining tables are phenolic laminate over plymetal. Seat assemblies are constructed similar to the coach cars.

Sleeping cars contain a series of individual rooms arranged along a corridor plus luggage storage space. Seat configuration in the individual rooms is somewhat different than coach seat configuration, but comparable materials are used in the seat assemblies. The seats convert to beds with fabric-covered foam mattresses; pillows, cotton sheets, and wool blankets provided. Fabric curtains line the doors to provide privacy. Partitions between sleeping compartments and hallways are constructed of plymetal panels.

Materials selected for evaluation were provided by Amtrak which provides U. S. intercity rail passenger service. The Amtrak fleet consists of several generations of passenger rail cars. These include cars which provide coach or first class seating, food service, or overnight sleeping accommodations. Selected materials reflecting a broad cross section of Amtrak passenger train interior finishing materials (representing the bulk of the fire load found in most passenger rail cars) were tested in the Cone Calorimeter. Table 1 lists the materials selected and tested.

Table 1. Selected Passenger Train Materials Evaluated in The Study

Category	Sample No.*	Material Description (Components)
Seat and Bed Assemblies	1a, 1b, 1c, 1d	Seat cushion, (foam, interliner, fabric/PVC cover)
	2a, 2b, 2c	Seat cushion, (foam, interliner, fabric cover)
	3	Graphite-filled foam
	4	Seat support diaphragm, chloroprene elastomer
	5	Seat support diaphragm, FR cotton muslin
	6	Seat shroud, PVC/acrylic
	7	Armrest pad, coach seat (foam on metal support)
	8	Seat footrest cover, chloroprene elastomer
	9	Seat track cover, chloroprene elastomer
	10a, 10b, 10c	Mattress (foam, interliner, ticking)
	11a, 11b, 11c	Bed pad (foam, interliner, ticking)
Wall and Window Surfaces	12	Wall finishing, wool carpet
	13	Wall finishing, wool fabric
	14	Space divider, polycarbonate
	15	Wall material, FRP/PVC
	16	Wall panel, FRP
	17	Window glazing, polycarbonate
	18	Window mask, FRP
Curtains, Drapes, And Fabrics	19	Privacy door curtain and window drape, wool/nylon
	20	Window drape, polyester
	21	Blanket, wool fabric
	22	Blanket, modacrylic fabric
	23a, 23b	Pillow, cotton fabric/polyester filler
Floor Coverings	24	Carpet, nylon
	25	Rubber mat, styrene butadiene
Misc	26	Cafe/lounge/diner table, phenolic/wood laminate
	27	Air duct, neoprene
	28	Pipe wrap insulation foam
	29	Window gasketing, chloroprene elastomer
	30	Door gasketing, chloroprene elastomer

* – letters indicate individual component materials in an assembly.

Individual component materials are listed in order in parentheses following the material description

Note: All foam except Sample 3 is the identical type

COMPARISON OF CONE CALORIMETER TEST DATA WITH EXISTING FRA TEST DATA

Heat release rate (HRR) and fire hazard analysis are the primary focus of this current study of passenger train fire safety. HRR is the key indicator of real-scale fire performance of a material or construction, including ignition, flammability⁵, and smoke emission⁶ properties. HRR data are necessary

to conduct fire hazard analyses and can also be used to predict real-scale fire behavior. Although passenger rail car materials have historically been tested according to test methods and performance criteria which are not directly related to HRR, there have been very few serious fires involving materials which meet the FRA requirements. In this section, the Cone Calorimeter test data are compared to test data obtained from Amtrak for FRA-cited test methods. Although the primary use of the HRR data is as input to a fire hazard analysis, this comparison is also intended to provide a better understanding of the relationships and limitations of Cone Calorimeter test data relative to FRA-cited test method data. A detailed report is available ⁷.

FRA-Cited Test Method Data

Several FRA-cited test methods include measures of material flammability in terms of flame spread (ASTM E 162, D 3675, and E 648) or ignition/burn resistance (FAA 25.853 (a) and ASTM C 542). ASTM E 162 and D 3675 measure downward flame spread on a near vertically mounted specimen (the specimen is tilted 30° from the vertical with the bottom of the specimen further away from the radiant panel than the top of the specimen). FAR 25.853 (a) and ASTM C 542 are small burner tests which measure a material's resistance to ignition and burning for a small sample of material. ASTM E 648 measures lateral flame spread on a horizontally-mounted specimen. Since ASTM E 648 was designed to measure fire performance of flooring materials, it is the only test method that attempts to replicate end-use conditions. Material flammability and smoke emission test data were obtained for thirty materials from manufacturers and/or suppliers. Additional data from related studies were also reviewed. Data from these related studies ^{8, 9, 10} show performance similar to the current tests.

Of the materials currently in use, only the space divider does not meet the FRA flammability performance criterion; as a window glazing, the same material meets the FRA performance criterion. ASTM E 648 was used to evaluate two floor covering materials: nylon carpet and resilient rubber floor mat. The test data indicated that both met the FRA performance criteria. The FAR 25.853 (a) burn length test data available for 4 of the 10 materials indicated they met the FRA performance criteria. Flame time was available for only 3 of the 10 materials which also passed the criterion.

Available ASTM E 662 test data showed that the majority of samples met FRA smoke emission criteria. Exceptions such as seat support diaphragm, armrest pad, footrest pad, seat track cover, window and door gasketing) represent a small portion of the fire load in a typical vehicle interior. Amtrak is currently considering replacement materials with better fire performance.

It is unclear whether the contribution from all these materials would be significant. However, the issue cannot be adequately assessed through small-scale tests alone. Again, part of the purpose of the current research effort to apply fire hazard analysis to passenger trains is to allow quantitative evaluation of the contribution of an individual material or combination of materials to the overall fire hazard in a passenger rail car.

Cone Calorimeter Test Method Data

The individual material data obtained from the Cone Calorimeter tests are shown in Table 2. All Cone Calorimeter tests in this study were conducted at a heat flux exposure of 50 kW/m². This level represents a severe fire exposure consistent with actual train fire tests. With the high performance level typical of currently used materials, levels higher than 50 kW/m² are unlikely. A spark ignitor was used

Table 2. Cone Calorimeter Test Data for Selected Passenger Train Materials

Sample Number*	Time to Ignition(s)	Peak HRR(kW/m ²)	SEA 180s Average(m ² /kg)
1a, 1b, 1c, 1d	14, 5, 11, 7	80, 30, 420, 360	30, 300, 225, 770
2a, 2b, 2c	14, 5, 8	80, 30, 265	30, 300, 400
3	7	65	40
4	31	295	1400
5	7	190	490
6	28	110	490
7	54	610	780
8	45	400	960
9	26	190	1100
10a, 10b, 10c, 11a, 11b, 11c	9, 5, 7	80, 25, 150	40, 70, 70
12	30	655	510
13	21	745	260
14	105	270	1000
15	23	120	1000
16	18	270	530
17	115	330	1000
18	53	210	n.a.
19	13	310	380
20	20	175	810
21	11	170	560
22	17	18	n.a.
23	24	340	570
24	10	245	350
25	35	300	1400
26	44	250	80
27	30	140	810
28	7	95	700
29	33	210	1100
30	38	200	1200

n.a. = data not available* letters indicate individual component materials in an assembly. Note: All foam except sample 3 is the same type

to ignite the pyrolysis gases. All specimens were wrapped in aluminum foil on all sides except for the exposed surface. A metal frame was used and where necessary a wire grid was added to prevent expanding samples from entering into the cone heater. Included in table 2 are ignition time, peak HRR, and average specific extinction area (SEA) for the first 180 s of each test. More extensive data are available ⁷.

Times to ignition varied from 5 s for the cotton interliner used in the seat assemblies to 115 s for the window glazing. In general, seat and bedding materials and curtain and fabric materials exhibited the shortest times to ignition, typical of thin materials. Wall and window surfaces, as well as window and door gaskets, had the longest times to ignition, typical of thicker materials.

Peak HRR varied over an order of magnitude from 65 kW/m² for the graphite foam to 745 kW/m² for the wall fabric. The majority of the 34 individual sample materials tested had peak HRR between 100 and 600 kW/m²:

- 6 materials had peak HRR below 100 kW/m² – including all the seat and mattress foams;
- 25 materials had peak HRR between 100 and 600 kW/m²; and,
- 3 materials had peak HRR over 600 kW/m² – usually thin materials.

Since the seat foam is one of the largest single combustible materials in a rail car, the low HRR results are particularly important.

SEA data showed a larger distribution for the 180 s average, σ (m²/kg), as compared to the peak HRR. Peak σ varied from 30 m²/kg for a seating foam to 1400 m²/kg for a seat support diaphragm and a rubber floor covering material.

Several materials showed elevated HRR and smoke values over an extended period of time. Although the peak HRR of these materials fall into an intermediate range, the extended duration of the HRR curve makes these materials important for study in future fire hazard analysis efforts.

For component assemblies of materials, the time to ignition was controlled by the exposed layer of material. The peak HRR for assemblies was generally between the highest and lowest peak HRR for individual component materials making up the assembly. Smoke data was greatly reduced compared to individual component materials with 180 s average σ varying from 30 m²/kg for a mattress assembly to 560 m²/kg for a pillow.

Cone Calorimeter data from the 1984 FRA/Amtrak study ⁸, 1990 NHTSA school bus study ⁹, and 1996 MARC rail car study ¹¹ shows material performance similar to the materials tested for this study. In addition, the NHTSA and MARC data includes tests conducted at a range of incident fluxes which showed an expected increase in peak HRR as incident heat flux increased.

Impact of Small-Scale Test Data on Current Passenger Train Design

For the majority of materials, the relative ranking from "best" to "worst" was similar in both test methods. While the materials tested represent a range of those currently used in passenger trains, many other material combinations are possible in actual use. Accordingly, the comparisons are intended only to show that the Cone Calorimeter test method provides an approach to screen passenger rail car interior materials similar to that provided by the FRA-cited test methods. However, new materials and designs are better judged through a systems approach which considers the impact of material and design choices on the overall fire safety of the system. The use of HRR data in a hazard analysis applied to passenger trains could provide such an overall system evaluation.

ASSEMBLY TESTING

The outstanding fire safety record of rail transportation shows that current requirements have been successful in preventing small ignition sources from causing major fires. To provide data for fire hazard analysis, selected assemblies from Amtrak trains were tested in the furniture calorimeter. All of the assemblies tested were extremely resistant to ignition. The assemblies tested require an initial fire source ranging from 25 kW to 200 kW to ignite. Some of the materials do not contribute to the fire even with these ignition sources.

These tests represent a range of materials used in intercity passenger trains and are consistent with those tested in the Cone Calorimeter. The tests were arranged in six groups:

- Ten trash bag tests, with six taken from an actual Amtrak overnight train and four filled with newspaper to match the HRR of the trash-filled bags with a more repeatable filling. These newspaper-filled trash bags were used as an ignition source for the seating and bedding tests described below.
- Four coach seat assembly tests to study the burning behavior of entire seating assemblies to varying ignition sources. The assemblies were placed next to a noncombustible wall representative of an Amtrak coach car wall and overhead luggage rack.
- Three bedding assembly tests in a compartment sized to be representative of an economy room on an overnight train. Although the construction materials for the bedding assemblies are similar to the seating assemblies, the geometry of the compartments is significantly different from that in a coach car.
- Four wall and ceiling carpet tests. In some configurations, wall and ceiling carpet comprise a significant fraction of the surface area in a car. The extent to which the carpeting supports the spread of fire is a controlling factor in fire spread from a seat assembly to the upper walls and luggage rack.
- Six window drape and door privacy curtain tests. Like the carpet, drapes and curtains can be a path for fire spread to the upper walls and luggage rack.
- Two window assembly tests, including window glazing and window masks from Amtrak coach cars. The window assemblies comprise a significant fraction of the wall surface area in a car.

Assembly Test Results

Peak HRR values were measured during each of the 29 tests conducted. For the assemblies tested, the peak HRR ranged from 27 kW for a coach seat assembly (including the TB 133 burner) to 918 kW for a sleeping compartment assembly (including both lower and upper berths, bedding, window drapes, and a trash bag ignition source).

Implications of Test Results on Current Passenger Train Design

Clearly, it takes a significant ignition source for any of the items tested to become involved in a fire. All of the assemblies tested were exposed to an initial ignition source ranging from 17 kW to 200 kW. Some of the materials do not contribute to the fire even with these ignition sources. For example, the seat cushions do not produce a significant HRR even with the severity of the near 200 kW newspaper-filled trash bag ignition source. For the seat assemblies, the HRR results largely from burning of carpeting attached to the rear of the assemblies.

Conversely, if a severe ignition source exists, some of the materials can contribute to further fire growth. The wall carpeting and window glazing, though difficult to ignite, produce high HRR values once ignited. This is consistent with earlier NBS real-scale mockup tests conducted on Amtrak coach interior materials⁸. In these earlier tests, the wall covering (carpeting or window mask) adjacent to the seating were seen as important to the growth of fire in the tests. Also like the earlier NBS tests, the effect of geometry can be significant. In the bed tests, the small enclosed geometry of the sleeping compartment allowed a much larger HRR for the bed assembly tests than for the seat assembly tests, even though the materials are similar.

FIRE HAZARD ANALYSIS

Traditionally, techniques for hazard analysis¹² typically involve a four step process for the evaluation of hazard of a product or products in a specific scenario: 1) defining the context, 2) defining the scenario, 3) calculating the hazard, and 4) evaluating the consequences. For the analysis of passenger trains, this process limits the evaluation to the contribution of specific products without providing an overall assessment of the performance of the entire system.

Therefore, the procedure outlined above was extended for this project to better reflect the minimum appropriate performance of the overall system while maintaining an evaluation of a specific design as compared to that required minimum performance level. For such a systems-based analysis, the process is also conducted in four steps:

- 1) Defining the application,
- 2) Calculating the fire performance of the application,
- 3) Defining specific fire scenarios for the application, and
- 4) Evaluating the suitability of the proposed system design.

Steps 1 and 4 are largely judgmental and depend on the expertise of the user. Step 2, which involves extensive use of computer software, requires considerable expertise in fire safety practice. The heart of fire hazard analysis, Step 2 is a sequence of procedures implemented in computer software to calculate the development of hazardous conditions over time, calculate the time needed by occupants to escape under those conditions, and estimate the resulting effects on the occupants based on tenability criteria. In addition to evaluating the hazard resulting from specific products used in the design, this new procedure used in this report determines the worst case fire which allows the overall system to meet chosen design criteria. Step 3 defines the specific fires which are likely to occur in the application. Step 4 compares the results of Steps 2 and 3, evaluates the appropriateness of the calculations performed, and determines whether the proposed design meets the design goals established in Step 1.

For the analysis, three different passenger car designs were considered: a single level coach car, a bi-level dining car, and a bi-level sleeping car. For each of these designs, data from the small-scale and assembly-scale testing of actual train car materials were used as input to computer fire models which predict the conditions within a train that result from a specified fire. Figure 1 illustrates the results of the analysis for the coach car. Each of the analyses shows that design features in addition to material controls can have an impact on the resulting fire safety of the overall design. These features include the geometry of the car, passive and active fire protection measures, emergency egress, and emergency procedures.

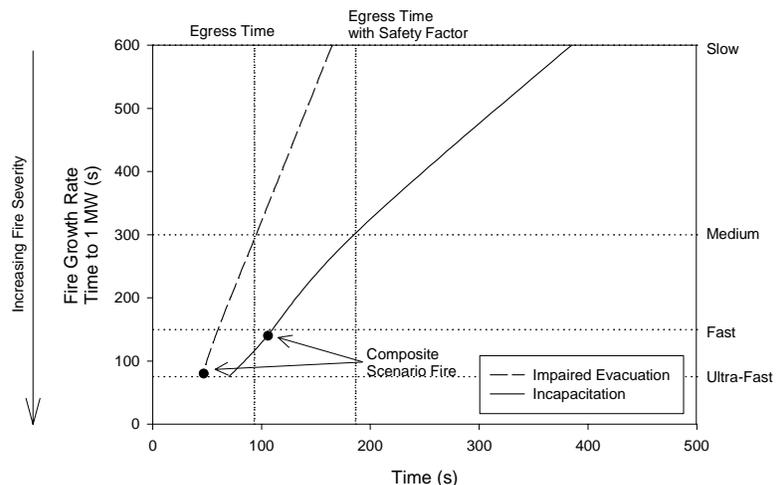


Figure 1. Calculated Fire Performance Graph for Baseline Fire Hazard Analysis of a Coach Car Including Safety and Available Egress Time for a Composite Scenario Fire.

Key Observations from the Fire Hazard Analysis

Fire hazard analysis can quantify the consequences of specific, interior fire scenarios on the safety of passengers and crew in typical intercity coach, sleeper, and dining cars. Such an analysis can provide information on:

- The largest fire that still provides sufficient time to insure that passengers and crew are safe from unreasonable risk of death or injury from interior fires. For example, materials or products exhibiting fire growth rates at or below a medium t-squared level would provide sufficient time for egress for the design fires considered in Figure 1.
- By comparing the largest design fire to specific fire scenarios involving materials used in the construction of passenger trains, the acceptability of the materials can be judged. For example, materials and products that comply with the current FRA requirements for fire performance exhibit fire growth rates below the medium t-squared level, and thus would be acceptable under the design criteria presented in Figure 1.

There are significant uncertainties worthy of note. These are the quantity, arrangement, and fire performance characteristics (ignitability and fire growth characteristics) of items brought aboard by passengers as baggage and the materials brought aboard as supplies such as the packaging materials associated with food and cleaning supplies. The latter was made clear by the burning behavior of the trash bags collected from an actual, overnight train. Further, Cone Calorimeter tests and assembly tests show that there are train car materials that can represent significant sources of heat as secondary fuels. The wall carpet and its adhesive, for example, resist ignition, but can produce a high HRR when exposed to a large fire insult.

Impact of Trade-Offs in Design

Presently, the focus of passenger train fire safety, and in fact in most transportation applications, is primarily passive fire protection: materials control and compartmentation. In buildings, modern fire safety techniques also depend heavily upon active systems: early detection, smoke management, and automatic suppression. While the use of active fire protection systems in passenger trains can provide contributions to rail fire safety, the impact of such systems cannot be judged in the context of the current prescriptive material requirements. Trade-offs in overall system design are best judged through a performance-based approach that considers the impact of material and design choices. This section discusses possible candidate active fire protection systems that may be useful in the design of passenger rail systems.

Detection systems are currently found only in sleeping car compartments and galley kitchens of passenger trains. In an occupied coach car, it is likely that a passenger will see a fire before an automatic system detects it. Detection systems, however, only notify someone of a problem. People must then take some action to mitigate that problem and/or commence evacuation procedures. Crew may be assigned to perform early suppression of fires, but this will require training and there are implications for worker safety under OSHA regulations¹³ where employees are expected to fight fires.

Smoke management may have beneficial effects on passenger train fire safety. Smoke management systems¹⁴ have been implemented in building fire safety strategies for many years. American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc. (ASHRAE) has published guidelines for the design of smoke control systems.¹⁵ Increases in available safe egress time can be achieved with automatic smoke and heat venting of the fire space.

Another design option that may have application to passenger rail is an automatic suppression system. In recent years, considerable research has been done on water mist systems. These use fine sprays of water to inhibit fire growth rather than to extinguish a fire. The Federal Aviation Administration ¹⁶, the U.S. Coast Guard ¹⁷, and the Navy ¹⁸ have performed significant testing into the feasibility of water mist systems for transportation vehicles. Such a system is a logical approach for mitigating fire hazard with a minimum of water.

APPLICATION TO FULL-SCALE TESTS

From the hazard analysis, the obvious question that arises is how good are the model predictions. The only widely-accepted method of verifying the model predictions is to test them against actual controlled experiments. Full-scale experiments are planned to examine the models predictions.

Two different types of tests will be conducted to evaluate the accuracy of the results of fire hazard analyses conducted: 1) a series of gas burner tests conducted to evaluate the accuracy of the fire performance curves for an actual train car geometry and 2) a smaller series of tests to evaluate fire spread and growth for actual train car furnishings exposed to a range of initial fire sources.

Gas Burner Tests – In the fire hazard analysis, the fire performance curves show the predicted response of the chosen car geometry to a range of typical fire growth rates and determine the available safe egress time from a car exposed to an arbitrary fire. These calculations are compared to the time necessary to evacuate passengers from the car to determine the largest fire growth rate and size that is allowable for the chosen car geometry. To evaluate the accuracy of the model calculations of the fire performance curves, a series of gas burner fires covering a range of fire size and growth rate should be used.

The experimental fire performance curve determined from temperature and gas concentration measurements made during the tests can then be compared against the predicted fire performance curve to determine any differences and their significance.

Fire Growth and Spread Tests – A smaller number of experiments should be conducted to study the fire growth and flame spread patterns in a realistic fire scenario. From the assembly tests, materials and products that comply with the current FRA requirements are difficult to ignite, requiring ignition source strengths of 2 to 10 times those used for similar materials and products found outside of the transportation environment. Still, it was also evident from the assembly tests that significant fires can develop with sufficiently severe ignition sources. For the fire growth and spread tests, initial ignition sources ranging from the TB 133 gas burner up to and including large trash bags could be used. These tests would allow us to compare the assembly tests conducted in the furniture calorimeter with actual fire growth in the car where the HRR may change due to the effects of the car geometry and proximity of materials to one another.

SUMMARY

This paper has presented an overview of research to demonstrate the use of heat release rate measurements and hazard analysis techniques when applied to passenger rail car fire safety. Such fire and hazard modeling allows evaluation of factors in addition to material flammability such as tradeoffs based on the fire-safe design of the entire fire safety system. The use of properly designed small-scale material tests and verified fire models for safety evaluation is consistent with ongoing efforts to develop performance-based fire codes in the U.S. and Europe.

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