EVALUATION OF PASSENGER TRAIN CAR MATERIALS IN THE CONE CALORIMETER

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ABSTRACT

Recent advances in fire test methods and hazard analysis techniques make it useful to re-examine passenger train fire safety requirements. The use of test methods based on heat release rate (HRR), incorporated with fire modeling and hazard analysis, could permit the assessment of potential hazards under realistic fire conditions. The results of research directed at the evaluation of passenger train car interior materials in the Cone Calorimeter are presented. These measurements provide data necessary for fire modeling as well as quantitative data that can be used to evaluate the performance of component materials and assemblies. The Cone Calorimeter test data were also compared with test data resulting from individual bench-test methods specified in the FRA fire safety guidelines. The majority of the tested materials which meet the current FRA guidelines show comparable performance in the Cone Calorimeter.

INTRODUCTION

Passenger train fires are rare, but can lead to serious consequences as was seen in recent U.S. accidents that occurred in Mobile, Alabama, and Silver Spring, Maryland. Other passenger train fires have recently occurred in the Channel tunnel and in Maidenhead, England.

Fire safety is an important element of overall system safety for conventional rail and new high-speed train technologies. A systems approach to passenger train fire safety requires that the effects of vehicle design, material selection, detection and suppression systems, and emergency egress, as well as their interaction, be considered.

Current Federal Railroad Administration (FRA) fire safety guidelines address the flammability and smoke characteristics of intercity and commuter passenger rail car materials[1]. The bench-scale tests and performance criteria cited in those guidelines provide a useful screening device to identify particularly hazardous materials. However, bench-scale fire tests do not account for material interaction and rail car component geometry, both of which impact on actual fire behavior.

A 1993 National Institute of Standards and Technology (NIST) study sponsored by the FRA, concluded that an alternative approach could provide a more credible and cost-effective means to predict real-world fire behavior[2]. This alternative approach employs fire hazard assessment techniques, based on fire modeling supported by measurement methods using ***heat release rate*** (HRR) data. An extensive effort sponsored by the European Railway Research Institute is also underway to relate bench-scale and real-scale fire performance using fire modeling[3].

To assess the feasibility of applying HRR test methods, fire modeling, and hazard analysis techniques to U.S. passenger rail cars, the U.S. Department of Transportation's Volpe National Transportation Systems Center developed a comprehensive three-phase fire safety research program to be conducted by NIST. This research program, sponsored by the FRA Office of Research and Dvelopment, is directed at investigating an alternative method of evaluating passenger train material fire performance. This paper presents the results of research evaluating the performance of typical passenger train car materials in the Cone Calorimeter.

BACKGROUND

In 1973, the Urban Mass Transportation Administration (UMTA) (now FTA) initiated an effort to evaluate and improve transit vehicle fire safety. As part of that effort, guideline specifications for flammability and smoke emission tests and performance criteria were developed. UMTA issued recommended practices for rail transit vehicle materials selection in 1984 based on those guidelines[4].

In 1984, the FRA issued passenger train fire safety guidelines containing tests and performance criteria identical to UMTA[5]. The FRA issued revised guidelines in 1989 that used terms and categories to more closely reflect passenger train design and furnishings and include smoke emission performance criteria for floor coverings and elastomers[1].

The individual test methods in these guidelines measure one or more of four different fire performance phenomena: ignition resistance, flame spread, smoke generation, and fire endurance. The requirements are based in large part on two bench-scale test methods that are designed to study aspects of a material's fire behavior in a fixed configuration and exposure.

In support of the FRA guideline development, the National Bureau of Standards (NBS, predecessor to NIST) completed a study of passenger train fire safety in 1984[6]. This study included a series of tests to assess the large-scale burning behavior of materials used for National Railroad Passenger Corporation (Amtrak) passenger rail car interior furnishings. Real-scale mock-up tests were conducted along with full seat assembly tests, as well as bench-scale laboratory tests on individual materials from the various components used for car interiors.

The NBS comparison of bench-scale measurement of flame spread, smoke emission, and HRR with large-scale test data showed that the bench-scale tests were able to adequately predict the effect of changes in materials within the same real-scale geometry. However, when the geometry of the full-scale test mockup was changed, the chosen bench-scale tests failed to predict the effect of these changes.

Considerable advances in fire safety engineering have been made since the completion of the 1984 NBS study and the original development of the existing FRA guidelines. Better understanding of the underlying phenomena governing fire initiation and growth has led to the development of HRR test methods which can be used to better predict the real-scale burning behavior of materials and assemblies[7]. Fire hazard modeling allows the analysis of a material's overall contribution to fire hazard in a particular application. The evaluation of a range of fire safety design parameters, including material flammability, geometry, fire detection, fire suppression, and evacuation, and of tradeoffs in the design which may arise from combinations of the parameters may be accomplished. However, further testing and analysis is necessary to evaluate the suitability of fire modeling and hazard analysis techniques when applied to typical passenger train fire scenarios.

HRR is considered to be a key indicator of fire performance and is defined as the amount of energy that a material produces while burning. For a given confined space (e.g., rail car interior), the air temperature is increased as the HRR increases. Even if passengers do not come into direct contact with the fire, they could be injured from high temperatures, heat fluxes, and toxic gases emitted by materials involved in the fire. Accordingly, the fire hazard to passengers of these materials can be directly correlated to the HRR of a real fire.

The Cone Calorimeter (ASTM E 1354)[8] is a single test method which provides measurements of HRR, specimen mass loss, smoke production, and combustion gases. Accordingly, Cone Calorimeter tests were conducted on selected passenger rail car materials. These measurements include ignitability, HRR, and release rate for smoke, toxic gases, and corrosive products of combustion. With the use of a single test method for all materials, measured properties, such as HRR and smoke generation rate, are obtained under identical fire exposure conditions.

Much of the data obtained from the test methods cited in the current FRA guidelines, although providing relative ranking of materials under the exposure conditions of the test methods, do not provide quantitative data which can be used for such analysis. However, the HRR and other measurements generated from the Cone Calorimeter can also be used as an input to fire modeling and hazard analysis techniques to evaluate the contribution of the individual components and materials to overall passenger train fire safety.

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 are 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. 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. List of Passenger Train Materials Used in This Study

Category	Sample Number*	Material Description (Components)
Seat and Bed Assemblies	1a, 1b, 1c, 1d	Seat cushion, fabric/PVC cover (Foam, Interliner, Fabric, PVC)
	2a, 2b, 2c	Seat cushion, fabric cover (Foam, Interliner, Fabric)
	3	Graphite-filled foam
	4	Seat support diaphragm, chloroprene
	5	Seat support diaphragm, FR cotton
	6	Chair shroud, PVC/Acrylic
	7	Armrest pad, coach seat (foam on metal support)
	8	Footrest cover, coach seat
	9	Seat track cover, chloroprene
	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, polycarbonate
Curtains, Drapes, and Fabrics	19	Privacy door curtain and window drape, wool/nylon
	20	Window curtain, polyester
	21	Blanket, wool fabric
	22	Blanket, modacrylic fabric
	23a, 23b	Pillow, cotton fabric/polyester filler
Floor Covering	24	Carpet, nylon
	25	Rubber mat, styrene butadiene
Misc	26	Café/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 same type

COMPARISON OF CONE CALORIMETER TEST RESULTS WITH EXISTING FRA GUIDELINE TEST DATA

Existing FRA guideline test performance criteria and data were analyzed for the selected materials. Preliminary results indicate that certain materials do not meet the FRA performance criteria. While some of these materials represent only a small proportion of the interior rail car fire load, further analysis will be conducted to ensure that they do not present a hazard in real-scale fires. Ignition time, time-to-peak HRR, peak HRR, and several other values were measured in the Cone Calorimeter for each of the various materials. A detailed report of the test results from both the FRA Guideline test methods and the Cone Calorimeter is available[9].

HRR and fire hazard analysis is appropriately the primary focus of this current project on passenger train fire safety. HRR is the key indicator of real-scale fire performance of a material or construction, including ignition, flammability[10], and toxic product generation properties[11]. In addition to providing the data necessary for fire hazard analysis, test methods based on HRR can also be used to predict real-scale fire behavior. The fire behavior of current passenger car materials is quite good, although tested according to test methods which are not directly related to HRR. Thus, it is of considerable interest if the HRR-based Cone Calorimeter test data predict material performance when compared to test performance data as specified in the current FRA guidelines.

In this section, the Cone Calorimeter test data are compared to the test data from the test methods specified in the FRA guidelines. 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 test data from the Cone Calorimeter relative to test data from FRA-specified test methods.

Flammability

Several test methods cited in the FRA guidelines include measures of material flammability – flame spread (ASTM E 162, D 3675, and E 648), or ignition/self-extinguishment (FAR 25.853 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). ASTM E 648 measures lateral flame spread on a horizontally mounted specimen. Since ASTM E 648 was specifically designed to measure fire performance of flooring materials, it is the only test method that attempts to replicate end use conditions. FAR 25.853 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 162 and ASTM D 3675: The flame spread index, I_S, calculated from the ASTM E 162 or D 3675 test data is composed of two factors - a flame spread factor, F_S, comparable to an average flame spread rate down the sample surface, and a heat release factor, Q, which represents a measure of the peak HRR. The test is conducted under an incident heat flux that decreases down the length of the sample. F_S and Q are coupled parameters – as the burning area increases, the heat released increases. The burning area will increase as the flame spreads along the sample surface. At any moment in time, the larger the burning area, the higher the measure of the heat released will be.

Conventional flame spread tests, such as ASTM E 162 and D 3675, evaluate material performance under specific laboratory conditions and the measured parameters rank material performance relative to other materials. Still, researchers have applied models of flame spread to these devices. Gross and Loftus[12] were early pioneers in developing a flame spread model for E 162. This model was subsequently generalized for other applications by Rockett[13] who demonstrated that:

$$V_v \propto q(t)_f^2 \qquad (1)$$

where V_f is the flame spread rate and $q(t)_f$ is the heat flux radiated back to the sample surface.

Since only a fraction of the total heat released in an given time interval by the combustion process is radiated back to the sample surface, this shows that flame spread rate is directly related to the total heat released from the flame. The remaining energy is lost to the surroundings. The heat generation potential, Q, is a measure of this heat release.

The work of Rockett further showed that sample pyrolysis, i.e., mass burning rate of the sample, is an important burning characteristic that influences the measurement of Q. Assuming that the sample is completely consumed, the mass burning rate, $\dot{m}$, can be related to the flame spread rate by:

$$\dot{m} = \rho_m A_S V_f \tag{2}$$

where $\dot{m}$ is the sample density and A_S is the cross sectional area of the sample. In an idealized system, the HRR, $\dot{q}$, is related to the mass burning rate, $\dot{m}$, by:

$$\dot{q} = \dot{m}\Delta H \tag{3}$$

where ΔH is the heat of combustion assuming complete combustion. The $\dot{q}$ represents the energy released by a burning material. In the Cone Calorimeter, an estimate of $\dot{q}$ is derived from measurements of the oxygen concentration and flow velocity in the exhaust duct and is measured directly. While ΔH is not known, an effective heat of combustion, ΔH_{eff} , can be determined from the ratio of $\dot{q}/\dot{m}$. As in the case of ASTM E 162, the Cone Calorimeter also imposes an external heat flux across the sample surface to augment the energy reradiated to the sample surface from the flame. Thus a correlation would be expected between Q measured in the ASTM E 162 test and peak $\dot{q}$ measured in the Cone Calorimeter test.

The overall measure from ASTM E 162, I_S, is a combination of the flame spread factor and the heat generation factor. The relative importance of the flame spread factor and the heat generation factor will dictate how well this overall measure from ASTM E 162 will correlate with the peak HRR in the Cone Calorimeter. It should be noted from equation (2) that the flame spread factor is proportional to the mass burning rate, $\dot{m}$. Equation (3) shows that $\dot{m}$ is also proportional to $\dot{q}$. Therefore, peak $\dot{q}$ should provide an appropriate parameter for comparison between the Cone Calorimeter and the ASTM E 162 / D 3675 data.

Figure 1 shows a comparison of the peak HRR, peak, as measured in the Cone Calorimeter and the flame spread index I_S, as measured by ASTM E 162 / D 3675. Data from the current study are shown as black circles. Additional data from the 1984 NBS study are included as gray circles. Figure 1 shows an excellent relationship between I_S, and peak $\dot{q}$. Although a straight line regression of $\dot{q}_{\text{peak}}$ and I_S, yields a poor correlation coefficient of r^2 = 0.13, the I_S, is predictive of a minimum value for the HRR. This implies that a low flame spread index is required but not necessarily sufficient to guarantee a low HRR. For example, from the solid line in figure 1, an I_S value of 25 would indicate that the peak HRR measured in the Cone Calorimeter would be at least 125 kW/m^2. It does not indicate an upper limit on the HRR. A number of materials which had low values of I_S, had high HRR values. These are labeled in the figure indicating the material and the Sample number. Conversely, the HRR provides an upper boundary for the flame spread index. The solid line shown in figure 1 is a simple linear estimate of the boundary. Again, with the exception of the graphite foam, materials with a low HRR have a low flame spread index. The FRA guidelines for ASTM E 162 / D 3675 use several

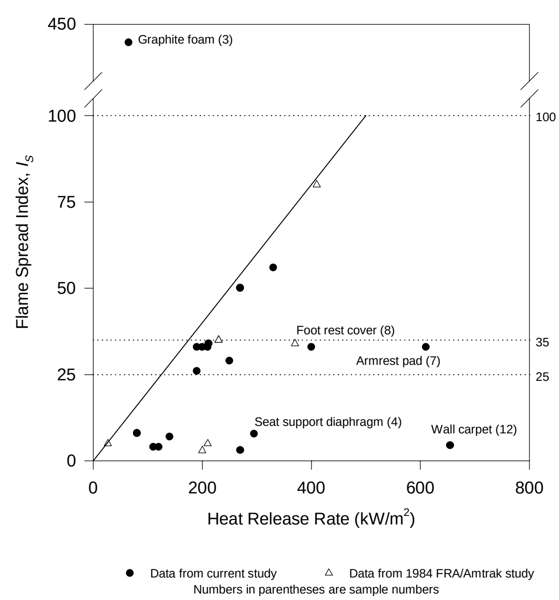

Figure 1. Comparison of I_S as measured according to ASTM E 162 / D 3675 and peak HRR as measured in the Cone Calorimeter.

performance levels for I_S, depending on the end use application. These levels of 15, 35, and 100 are superimposed on figure 1 as horizontal dashed lines at I_S values of 25, 35, and 100. Most of the test data shown in figure 1 represents materials which meet the FRA guidelines performance criteria and are comparable in the Cone Calorimeter. These data values are shown in figure 2 without additional labeling. Materials which have unexpectedly low or high HRR values relative to the corresponding flame spread index values are labeled in figure 1 with both the material name and sample number. For most of the exceptions, the HRR was higher than would be expected from the I_S value of the material. The following currently used materials have higher than expected values in Cone Calorimeter tests:

- The wall carpet had an I_S of 4.5 according ASTM E 162 and an HRR value of 655 kW/m^2.
- The chloroprene seat support diaphragm had an I_S of 7.8 for ASTM E 162 and an HRR value of 295 kW/m^2.
- The armrest pad, had an I_S of 33 according to ASTM E 162 and an HRR value of 610 kW/m^2.
- The footrest pad, had an I_S of 33 according to ASTM E 162 and an HRR value of 400 kW/m^2.

Conversely, the polycarbonate space divider and graphite foam had Cone Calorimeter values within comparable limits, but did not meet the FRA guideline performance criteria. The polycarbonate space divider had an I_S of 50 according to ASTM E 162 and an HRR value of 270 kW/m^2. This HRR value is near the upper limit of 275 kW/m^2 in the Cone Calorimeter and the same material used as a window glazing would meet the FRA performance criteria. Thus, this discrepancy should not be of great concern.

The graphite foam, a new foam material which was being considered for use in seat assemblies, is the only material which does not meet the FRA guideline performance criteria yet meets the comparable Cone Calorimeter performance levels. The ASTM 3675 test has indicated this material has an I_S value of. The Cone Calorimeter value of 65 kW/m^2 is comparable to the other foam materials tested. The different performance in the two test methods is likely due to the different wire grid sizes and sample sizes used in the two test methods. In ASTM D 3675, a wire grid with approximately 25 mm holes is used. The grid size used in the Cone Calorimeter is smaller, approximately 6 mm. This smaller size prevents the intumescing of the material and thus the expansion of the material toward the radiant heat source. In ASTM D 3675, this expansion and additional exposure heat flux leads to rapid flame spread along the sample. The smaller size of the Cone Calorimeter sample limits the expansion further.

ASTM E 648: ASTM E 648 measures the response of a floor covering sample 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. After ignition by a small line burner at the high energy end of the specimen, the distance at which the burning floor covering material self-extinguishes is determined. This point defines the minimum or critical radiant flux (CRF) necessary to support continued flame spread.

ASTM E 648 utilizes a radiant panel similar in design to that used by ASTM E 162. The orientation of the sample in ASTM E 648 is horizontal rather than slanted vertically as in ASTM E 162 and the maximum exposure intensity is less, only 11 kW/m^2. However, like ASTM E 162, flame spread in ASTM E 648 can be modeled as an opposed flow analog. Therefore, much of the previous analysis is also appropriate to this test method. Since the test criterion is self-extinguishment and the CRF is the heat flux at the point where flame spread stops, i.e., extinguishment occurs, HRR should provide a suitable comparison parameter between ASTM E 648 and the Cone Calorimeter. For simplicity, the peak HRR will be used; additional Cone Calorimeter tests (at varying incident flux levels) could allow estimation of a CRF directly from Cone Calorimeter data. For material qualification tests or simple comparisons between test methods, peak HRR provides a sufficient parameter.

Only two floor covering materials were included in the evaluation. These materials exhibited CRF values of 1.1 and 0.7 W/cm^2 according to ASTM E 648 and peak HRR values, peak, of 250 and 300 kW/m^2 in the Cone Calorimeter.

These data are consistent with test data for wall and floor carpet from the 1984 NIST study. In the 1984 study, three carpet samples were tested according to ASTM E 162 and in the Cone Calorimeter (although at a lower heat flux exposure of 25 kW/m^2) and one sample was tested in ASTM E 648. The three samples were all outside the performance criteria in the FRA guidelines and had peak values greater than 300 kW/m^2. With the extremely limited amount of data, no specific correlation is appropriate.

Bench-Scale Burner Tests: FAR 25.853 and ASTM C 542 test the ability of a material to self-extinguish once a small gas burner flame has been withdrawn. The test methods are used primarily to evaluate the fire performance of textile and elastomeric materials.

Vertical flame spread mechanisms have been developed for thermally thick and thermally thin materials. Many of these have been reviewed by Janssens[14]. These models have generally been applied to cases of one-sided burning. Although two-sided burning can be expected in the bench-burner tests, the same parameters control flame spread and extinguishment.

Vertical upward burning flame spread has been shown to be a function of heat flux received by a material and a material's ease of ignition, i.e., ignition time. The heat flux received by a material in a test is a combination of an externally imposed heat flux and the heat flux radiated to the material from the flame created by the burning material. Janssens shows that Hasemi and Delichatsios derived a comparable expression that relates the velocity of the base of the flame, V_p, to HRR and the ignition time of the material:

$$V_p \propto \frac{(\dot{q}')^n}{t_{ig}} \tag{4}$$

where $\dot{q}'$ (kW·m^{-1}) is the HRR per unit width over the material surface ahead of the base of the flame, t_{ig} (s) is the ignition time of the material at the exposure heat flux, and n is an empirical constant.

In the case of vertical upward flame spread, as $\dot{q}'$ decreases, the flame spread rate, V_P, decreases. The upward flame spread rate is also lower the longer it takes a material to reach its ignition temperature. Janssens has shown that a criterion for continued flame spread is:

$$t_b \geq \frac{t_{ig}}{K'\dot{q}'' - 1} \tag{5}$$

where t_b (s) is the burn time of a segment of material, K' is an empirical constant for the case of n=1 in equation (16) and $\dot{q}''$ (kW·m^{-2}) is the HRR per unit area. In general, K' is not known and must be determined from experiments. Conversely, extinguishment will occur if t_b is less than zero. As a first approximation, the burn time, t_b, is simply proportional to:

$$t_b \propto \frac{t_{ig}}{\dot{q}''} \tag{6}$$

and should represent a suitable measure for comparing FAR 25.853 char length data to Cone Calorimeter data.

Figure 2 shows a comparison of char length data from FAR 25.853 and the ratio of ignition time, t_{ig}, to the peak HRR, peak. In figure 3, the values for the ratio of ignition time, t_{ig}, to the peak HRR, peak, have been normalized by multiplying by 100. Although the comparison is based on a limited number of data values, the correlation coefficient is quite high at r^2 = 0.98.

Smoke Emission – ASTM E 662

ASTM E 662 measures the smoke generation from small, solid specimens exposed in:

- a flaming mode to a radiant heat flux augmented by the presence of a specially designed pilot burner for an estimated total heat flux of 35 kW/m^2, and
- a non-flaming mode to only a radiant heat flux of 25 kW/m^2.

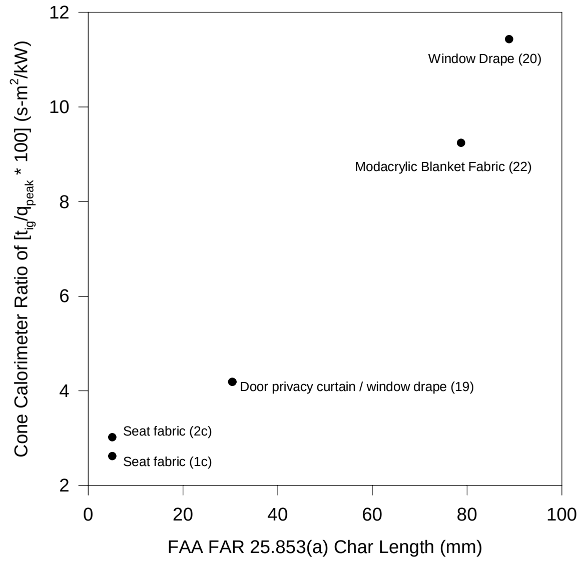

Figure 2. Comparison of char length as measured according to FAR 25.853 to the ratio of time to ignition and peak HRR as measured in the Cone Calorimeter

The nonflaming mode is an example of nonflaming oxidative decomposition. As long as the exposure remains at a low level of heat flux, the sample will rarely transition into flaming combustion. While it may produce large quantities of smoke relative to the amount of sample burned, the total smoke production and the maximum smoke density in the non-flaming mode has generally been found to be less than during the flaming exposure mode. The detection by train occupants or installation of smoke detection systems also reduces the risk of prolonged nonflaming combustion. Since the total smoke production for a material is a function of both the rate of smoke production and the burning rate of the material, the typically dramatically higher burning rate in a flaming fire leads to correspondingly higher total smoke production in flaming fires. Therefore, the smoke data from the Cone Calorimeter is more appropriately correlated to the ASTM E 662 flaming mode results.

An engineering comparison between ASTM E 662 and the Cone Calorimeter must reconcile the differences in the combustion system and the measurement procedures. ASTM E 662 measures a specific optical density, D_S, of smoke during the combustion process in a closed chamber. Also, the measurement is performed with a polychromatic light beam. Performance criteria are based on smoke density concentrations not exceeding prescribed values in 1.5 and 4.0 minutes from the start of the exposure. The measurement of smoke in the Cone Calorimeter is based on an instantaneous measurement of smoke concentration in a flowing system, i.e., an open system. In the Cone Calorimeter, smoke is measured by a monochromatic light beam. The standard reporting units for the smoke parameter in the Cone Calorimeter is the extinction coefficient, k, or the specific extinction area, σ_S (m^2/kg). While no direct comparison would be expected between D_S and σ_S, several researchers[15,16,17] have derived relationships between the accumulated smoke density concentration, D_S, and measurements made in real-scale fire tests of the extinction coefficient.

In general, the specific optical density, D_S, is defined as:

$$D_S = \frac{V}{AL}\log\left(\frac{I_0}{I}\right) \qquad (7)$$

where L is the path length of the light beam through the smoke, I_o is the intensity of the original light beam, and I is the intensity of the light beam attenuated by the smoke. For ASTM E 662, the right hand side of equation (7) includes a a geometric factor V/A, where V is the volume of the chamber and A is the area of the exposed sample.

For the flow through system of the Cone Calorimeter, an equivalent geometric factor can be defined as the volumetric flowrate through the duct, v_i, divided by the exposed surface area of the burning sample, A. Using the extinction coefficient, k_i, the integrated specific optical density can then be expressed as

$$D_S = \frac{\int k_i v_i dt}{2.303A} \tag{8}$$

Equation (8) indicates that, if the instantaneous values for the extinction coefficient, weighted by v_i/A, are integrated from the start of the burning until the test specimen burns out, an accumulated value for D_S is computed as a function of time. Equation (8) can be applied to the smoke data from the Cone Calorimeter. The computed D_S will differ from that measured in ASTM E 662 by the geometric constant and the difference in exposure heat flux incident on the sample surface. Additional differences will appear for those materials that become liquid during the combustion process. For these materials, ASTM E 662 results may be lower than comparable results in the Cone Calorimeter. Since materials can flow out of the vertically oriented sample holder in ASTM E 662, the total smoke production may be underestimated for some samples.

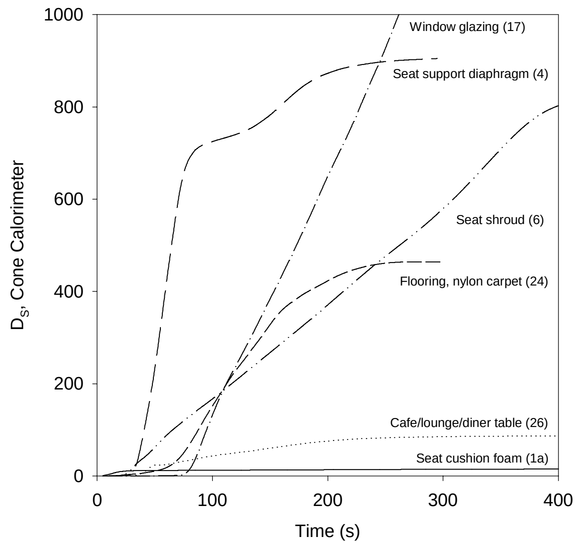

Figure 3. Specific optical density for several materials as determined from the specific extinction area as measured in the Cone Calorimeter.

Figure 3 shows the results of applying equation (8) to the smoke data from the Cone Calorimeter. Because of differences in sample size, geometric factor, external heat flux imposed on the sample, and, perhaps, sample orientation, these results may or may not be directly compared to the time dependent data obtained from ASTM E 662.

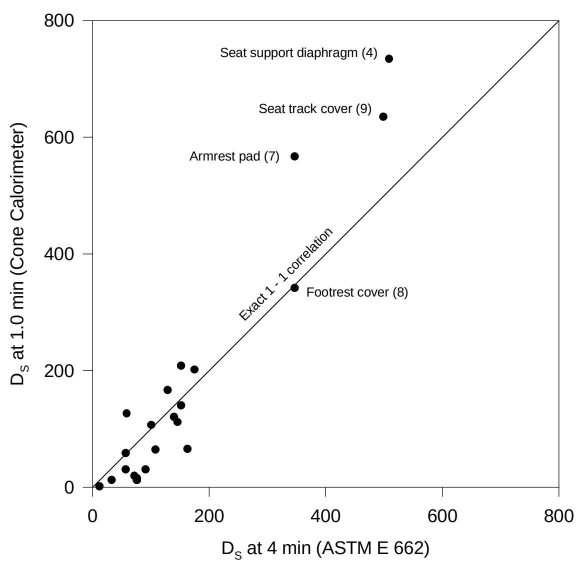

Figure 4. Comparison of ASTM E 662 D_S (4.0) with calculated Cone Calorimeter D_S (1.0)

Two specimen exposure times for smoke emission data are specified in the FRA guidelines with multiple performance levels depending on the end use application: D_S (1.5 minutes) $\leq$ 100 and D_S (4.0 minutes) $\leq$ 100, 200, or 250, depending upon end-use application. Figure 4 shows the comparison of these two test methods using D_S (4.0) for ASTM E 662 on the horizontal axis and D_S (1.0) for the Cone Calorimeter on the vertical axis for the materials in this study. The data show that a D_S (1.0) in ASTM E 1354 of $\leq$ 250 would result in comparable material performance. The longer time averaging of the 4-minute time scale (compared to the 1.5-minute values) kept uncertainty in the smoke measurement within sufficient limits to allow an adequate comparison. No similar comparison could be found for data at the shorter 1.5-minute exposure time in ASTM E 662. Since the main purpose of using the D_S values derived from Cone Calorimeter data is to demonstrate the comparability of Cone Calorimeter data to E 662 data, the 4-minute values provide a sufficient comparison. In addition, for fire hazard analysis, smoke production rates from the Cone Calorimeter (in the form of kg of soot produced per kg of sample burned) are used. These production rates are expressed as a function of time and thus are not unique to a particular exposure time.

In general, materials which have a high D_S value in ASTM E 662 have a correspondingly high D_S value in the Cone Calorimeter. A simple straight line regression, shown as a diagonal line in the figure, is a good representation of the comparison. The correlation coefficient for this straight line is $r^2 = 0.87$. Much of the test data is grouped in the lower left quarter of the figure indicating that the materials meet both the FRA guidelines and have correspondingly lower D_S value in the Cone Calorimeter. Materials which do not meet the FRA guideline performance criteria for smoke emission are labeled in figure 4 with the material name and sample number. The majority of the materials which do not meet the FRA guideline performance criteria for smoke emission are also noted as exceptions to the HRR comparison in figure 4. This consistency with the HRR results was also noted by Hirschler for a wide range of plastics – "the better performing materials in terms of HRR and smoke emission are mostly identical materials"[18].

SUMMARY

The Cone Calorimeter test data were compared to the data from the test methods specified in the FRA guidelines. Although the primary use of the HRR data is as input to a fire hazard analysis, this comparison provides a better understanding of the test data from the Cone Calorimeter relative to the data from the current FRA guideline test methods.

For many of the materials, the Cone Calorimeter results were strong indicators of results from the FRA guideline tests. Equally, there were Cone Calorimeter results which were not indicative of the FRA guideline test results. For example, several materials which had low I_S values in the ASTM E 162 test had higher HRR values in the Cone Calorimeter. One material had a low HRR value and a high I_S.

The following rationale was used in comparing the Cone Calorimeter test data with data from the FRA guideline tests:

- The comparison between ASTM E 162 / D 3675 and the Cone Calorimeter shows that peak HRR in the Cone Calorimeter is predictive of an upper bound on I_S. With one exception, materials which have a low HRR values have a correspondingly low I_S.
- The Bunsen-burner test specified in FAR 25.853 is a self-extinguishment test which assesses a material's resistance to small ignition sources. For the Cone Calorimeter, a comparable value is based upon the ratio of the ignition time to the peak HRR. A simple linear regression resulted in a high correlation coefficient of $r^2 = 0.98$. The char length comparison is based on a limited amount of data.
- Only two flooring materials were available for Cone Calorimeter testing in the current study. Thus, there is too little data for a meaningful comparison between the test methods for passenger train applications.
- For equivalence to ASTM E 662, an optical density measure was derived as an integrated value based upon the smoke extinction coefficient from the Cone Calorimeter. Comparing values from the Cone Calorimeter and ASTM E 662 for this calculated smoke density showed an appropriate comparison for the 4 minute E 662 values in 17 of the 22 cases where data were available. A simple linear regression resulted in a good correlation coefficient of $r^2 = 0.87$.

  No appropriate comparison was apparent for the 1.5 minute values. Since the main purpose of using the D_S values derived from Cone Calorimeter data is to demonstrate the comparability of Cone Calorimeter data to ASTM E 662 data, the 4 minute values provide a sufficient comparison.

Although the materials tested represent a range of those currently used in passenger trains, the comparisons are intended only to show that the Cone Calorimeter provides an approach to screen passenger rail car materials similar to that provided in the current FRA guidelines. In some cases, no appropriate comparison was evident. In addition, the uncertainty inherent in all of the test methods

make the use of such individual test methods less meaningful. 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 can provide such an overall system evaluation.

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