Fire Safety of Passenger Trains: Fire Hazard Assessment

Richard W. Bukowski, P.E.
Senior Research Engineer
NIST Building and Fire Research Laboratory
Gaithersburg, MD USA

Stephanie H. Markos
Transportation Safety Specialist
Volpe National Transportation Systems Center
US Department of Transformation
Cambridge, MA USA

Abstract

Passenger rail systems in the U.S. are experiencing a renaissance as the speed and comfort of modern trains make them competitive with other transportation systems. Commuter and intercity passenger train travel is becoming more popular. The rail transportation community is interested in moving from the use of prescriptive requirements based on bench-scale test methods to the use of a performance-based approach using modern fire hazard assessment methods. Moreover, a comprehensive review of US, French, German, and British requirements showed that the European rail industry is moving toward fire hazard and risk-based methods and away from traditional bench-scale material tests. Thus, the Federal Railroad Administration (FRA)/US Department of Transportation (USDOT) has contracted with the National Institute of Standards and Technology (NIST) under the direction of the Volpe National Transportation Systems Center (USDOT) to develop new approaches to fire hazard analysis based on HAZARD I. The current project involves bench-scale measurements of the fire properties of existing rail materials in the Cone Calorimeter and fire testing of full-scale assemblies to verify the predictive ability of the bench-scale tests. Design scenarios for fire hazard assessment are being developed. Modifications to the HAZARD I software are planned to facilitate its use with rail car configurations. Full-scale verification testing is planned. This presentation will focus on the construction of a baseline fire hazard evaluation of current trains outfitted with existing materials. Using this framework it should be possible to evaluate the potential impact of alternative materials or arrangements on the effect of fire on passenger train system safety.

Presented at the National Fire Protection Research Foundation's Second Fire Risk and Hazard Assessment Research Application Symposium, 25-27 June 1997, San Francisco, CA

Introduction

In many countries passenger train travel is increasing in popularity as trains become faster and more comfortable. For shorter distances, train travel time is not significantly longer than that required for plane travel when the time for ground transportation to and from outlying airports and the possibility of delay due to weather or traffic is included. Even for longer distances, convenience and comfort on high speed rail links are providing an incentive to rail passengers.

This increase in speed and comfort have caused the rail industry to examine materials and construction with lower weight and higher strength, similar to those found in aircraft. Such demands have led to an interest in new methods of evaluating and regulating fire safety which provide for a greater level of safety and better performance while allowing flexibility and cost savings.

Under the sponsorship of the Federal Railroad Administration (FRA)/US Department of Transportation (USDOT), the Volpe National Transportation Systems Center/USDOT, and the Building and Fire Research Laboratory (BFRL) of the National Institute of Standards and Technology (NIST) have been working to develop methods to evaluate the fire safety performance of materials and components in passenger train systems utilizing modern measurement methods and fire hazard analysis techniques. A similar project is underway in Europe under the auspices of the European Railway Research Institute (ERRI)[1].

This paper will focus on the ongoing development of a fire hazard analysis framework for passenger trains. First, the current regulatory guidelines utilizing bench-scale testing will be reviewed. Next, a (fire) hazard load-based method found in the National Fire Protection Association's NFPA 130 Standard for Fixed Guideway Transit Systems[2] will be discussed. Finally, the initial framework for an engineering fire hazard analysis will be presented along with an example calculation for a coach vehicle.

Current Fire Safety Guidelines

Specific requirements for intercity passenger rail car material flammability first appeared in 1966 [3]. These rail car specifications dictated "flame tests" for seat foam materials before its use would be approved for the original Metroliner passenger rail cars. The National Academy of Sciences [4] 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 resistant and that have the lowest smoke and toxic gas emission rates.

In 1984, the FRA issued fire safety guidelines for passenger trains which were identical to the Federal Transit Administration (FTA-now UMTA) tests and performance criteria for rail transit vehicles also issued in 1984. The FRA issued revised guidelines in 1989 which used terms and categories to more closely reflect passenger train design and furnishings and included smoke emission performance criteria for floor coverings and elastomers[5]. These guidelines consist of material fire performance test criteria designed to prevent the fire or retard its initial growth and spread. Based on test methods which evaluate fire properties of individual materials, the FRA guidelines and those that are similar for other rail applications form a prescriptive set of design specifications for material selection.

TABLE 1. U.S. FLAMMABILITY AND SMOKE EMISSION REQUIREMENTS FOR PASSENGER RAIL VEHICLES

Materials		Flammability		Smoke Emission	
Category [a]	Function [a]	Test Procedure	Performance Criteria	Test Procedure	Performance Criteria
Passenger seats, sleeping and dining car components	Cushions, mattresses	ASTM D 3675	$I_s \leq 25$	ASTM E 662	D_s (1.5) $\leq$ 100; D_s (4.0) $\leq$ 175 [b]
	Seat frames, mattress frames	ASTM E 162	$I_s \leq 35$	ASTM E 662	D_s (1.5) $\leq$ 100; D_s (4.0) $\leq$ 200
	Seat and toilet shroud, food trays	ASTM E 162	$I_s \leq 35$	ASTM E 662	D_s (1.5) $\leq$ 100; D_s (4.0) $\leq$ 200
	Seat upholstery, mattress ticking and covers, curtains	FAR 25.853 (vertical)	Flame time $\leq$ 10 s Burn length $\leq$ 6 in	ASTM E 662	D_s (4.0) $\leq$ 250 coated D_s (4.0) $\leq$ 100 uncoated
Panels	Wall, ceiling, partition, tables and shelves, windscreen, HVAC ducting	ASTM E 162	$I_s \leq 35$	ASTM E 662	D_s (1.5) $\leq$ 100; D_s (4.0) $\leq$ 200
		ASTM E 119	as appropriate [c]	ASTM E 662	
	Window, light diffuser	ASTM E 162	$I_s \leq 100$	ASTM E 662	
Flooring	Structural	ASTM E 119	nominal evacuation time, at least 15 min		
	Covering	ASTM E 648	C.R.F. $\geq$ 5 kW/m^2 [d]	ASTM E 662^2 [f]	D_s (1.5) $\leq$ 100; D_s (4.0) $\leq$ 200
		ASTM E 162 [e]	$I_s \leq 25$		
Insulation	Thermal, acoustic	ASTM E 162	$I_s \leq 25$ [g]	ASTM E 662	D_s (4.0) $\leq$ 100
Elastomers	Window gaskets, door nosing, diaphragms, roof mat	ASTM C 542	Pass	ASTM E 662	D_s (1.5) $\leq$ 100; D_s (4.0) $\leq$ 200
Exterior Plastic Components	End cap roof housings	ASTM E 162	$I_s \leq 35$	ASTM E 662	D_s (1.5) $\leq$ 100; D_s (4.0) $\leq$ 200
Component Box Covers	Interior, exterior boxes	ASTM E 162	$I_s \leq 35$	ASTM E 662	D_s (1.5) $\leq$ 100; D_s (4.0) $\leq$ 200

a Categories and functions follow the FRA guidelines. FTA guidelines are similar, but not identical
b FTA and NFPA 130 requirement is D_s (1.5) $\leq$ 100; D_s (4.0) $\leq$ 200
c "May use test criteria for floors or criteria appropriate to the physical locations and magnitude of the major ignition, energy, or fuel loading sources."
d Amtrak requirement is C.R.F. $\geq$ 6 kW/m^2
e NFPA 130 only
f FRA only
g Amtrak requirement is $I_s \leq 35$

The FRA passenger train flammability and smoke emission guidelines are summarized in Table 1. The FTA[6], Amtrak [7], and National Fire Protection Association (NFPA) 130 requirements are nearly identical to the FRA guidelines; differences are noted in the table. Individual test methods are intended to measure one or more out of four different fire performance phenomena - flame spread, ignition resistance, smoke generation, and fire endurance. 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" (with a variant, ASTM D 3675 for cellular materials) and ASTM E 662, "Specific Optical Density of Smoke Generated by Solid Materials". Several additional standards are specified for individual material applications. Except for ASTM E 119, a large scale fire endurance test, the test methods are bench-scale tests designed to study aspects of a material's fire behavior in a fixed configuration and exposure. All of these requirements are reviewed and discussed in detail in Appendix B of reference[8].

The bench-scale test methods are used to evaluate individual component materials and not necessarily end use assemblies. For example, Amtrak seat cushions consist of cover fabric, interliner, and foam. According to the current FRA guidelines, the requirements for each component material is different. Each component material is tested individually and not as an assembly. The cover fabric and interliner are tested by FAR 25.853 for ignition resistance and the foam is tested by ASTM D 3675 for flame spread and heat generation. All three components are tested by ASTM E 662 for smoke generation potential. Bench-scale tests of individual component materials have advantages over assembly and real-scale testing. Bench-scale tests of component materials have been used as screening devices to select materials, allowing parties to select preferred combinations of components and allowing material suppliers to independently evaluate the adequacy of their materials. However, the inability of these individual test methods to account for interactions between materials and for different end use geometries is one of the concerns in the use of such test methods and performance criteria.

Assembly and real-scale testing provide the advantage of assessment in an actual end-use configuration. However, such larger-scale testing has disadvantages. Real-scale tests of complete assemblies are often orders of magnitude more expensive than bench-scale tests. In addition, the advantage of providing an overall assessment of the fire behavior of a material also can represent a disadvantage. By quantifying the outcome of the fire without a knowledge of the factors leading to the resulting fire and without relating the observed fire behavior to basic material properties, little insight into the intrinsic performance of the materials may result [9]. However, real-scale testing is critical to permit the evaluation of the effects of material interaction and geometry in an end-use condition.

Hazard Load Calculations

In the 1970s, Prof. E. E. Smith and co-workers at Ohio State University (OSU) proposed a computational model for predicting fire growth in rail transit vehicles [10]. Heat release rate (HRR) data were used to describe limits on the combustibility parameters of products that could be used in rail transit vehicles. The model from which the suggested limits were derived was based on a simplified ignition concept, not one consistent with current-day understanding of ignition and flame spread (for example, see [11]). The needed HRR data were obtained from the OSU Calorimeter (ASTM E 906). Results of a comparison with real-scale fires were presented.

Most notable was a conclusion that bench-scale tests are more reliable than real-scale fire tests for screening *individual* materials used in rail transit systems. In contrast, the primary purpose of real-scale testing is to evaluate the effects of material interaction and geometry in an actual train fire.

The majority of the flammability and smoke emission tests and performance criteria for rail transit vehicle interior materials contained in the NFPA 130 "Standard for Fixed Guideway Transit Systems" are identical to the FRA guidelines and the Amtrak specification. NFPA 130 encourages the use of tests which evaluate materials in certain subassemblies and the use of full-scale tests. NFPA 130 also includes requirements for ventilation, electrical fire safety and communications. Further, NFPA 130 specifies station, trainway, and vehicle storage and maintenance area, and emergency procedure requirements, as part of a systems approach to fire safety.

As an option, NFPA 130 contains a "hazard load analysis" in an appendix to evaluate overall material flammability in a rail transit vehicle. Based on previously cited work [10,11,12], a heat release rate test such as ASTM E 906 is utilized to determine a 180 second average heat release and smoke emission. These values are multiplied by the exposed surface area for each material and totaled. Finally, the total values are divided by the volume of the vehicle to obtain "fire and smoke load" for the vehicle per unit volume. A suggested performance criteria of 3000 kJ/m^3 (80 BTU/ft^3) is included as "the maximum allowable loading to assure that a self-propagating fire will not occur with an initiating fire consisting of the equivalent of one pound of newsprint or 8 oz. of lighter fluid." It is not clear how the authors of the original work at Ohio State arrived at this performance criteria; in later work Smith acknowledges that such a "hazard load" calculation does not provide a complete description of a fire[12]. The geometry of the vehicle and placement of combustibles in the vehicle can play a significant role in actual fire exposure of a given material.

A variant of this method was utilized in the procurement of vehicles for the Los Angeles County Transit Commission light rail system currently under construction. The specifications limited the total combustible content of these cars to $6.3x10^7$ kJ ($6 x10^7$ BTU) of which no more than 55% could be located in the interior above the floor. These limits were based on NFPA 130's design limit of $5x10^9$ kJ/m^2 (45,000 BTU/ft^2) of interior combustibles above the floor of subway cars in order to maintain tenable conditions in underground portions of the system. At the gross floor area of the proposed cars this resulted in a limit of $3.5x10^7$ kJ ($3.3 x10^7$ BTU), which is 55% of $6.3x10^7$ kJ ($6 x10^7$ BTU)[13].

This "hazard load analysis" method attempts to provide a simplified and semi-quantitative analysis to assess the overall contribution to fire hazard of the materials used in interior linings and fittings. The method recognizes HRR as the key variable in fire hazard and ties performance to real-scale testing results. However, adding values for all exposed materials in a vehicle to obtain a hazard load assumes that every part of every material ignites and burns simultaneously. It further does not account for phenomena such as combustion efficiency and the effect of reduced oxygen on both HRR and smoke/gas release rates making this a highly conservative approach. Fire hazard modeling techniques and correlations developed in the past decade can provide a more realistic assessment of the contribution of materials to overall fire hazard.

Fire Hazard Analysis (FHA)

The refinement of deterministic fire models in recent years has spawned interest in the application of fire hazard analysis to passenger rail fire safety. Here, the likely consequences of fire scenarios of interest are evaluated using models which take into account the complex physics and chemistry of the combustion process, and predict the time-dependent impact on the vehicle and its occupants. These techniques can also evaluate the effectiveness of mitigation strategies involving both hardware systems and emergency procedures as a complete system.

Performance-based regulation of building fire safety is in place in several countries and is under development in many others, including the United States[14]. Explicit goals, objectives, and performance criteria are specified and accepted analytical methods are used to evaluate the degree to which these are met for specific fire scenarios which define expectations for the design.

In discussions with staff from passenger railroad operators, vehicle manufacturers, and material suppliers, several representative fire scenarios have been identified. These include:

- an ignition under a coach seat by a small source (crumpled newspaper),
- fire in a trash bag placed on a coach seat,
- an external fuel spill (100 or 500 gallons of diesel fuel representing a truck or locomotive fuel tank rupture, respectively) exposing a rail car door,
- overheated equipment (motor, pump, battery failure) in a sleeping car, and
- a sterno can igniting a tablecloth in a dining or lounge car.

Each of these scenarios along with any additional, relevant scenarios would be evaluated in the specific context of the rail vehicles under consideration. Other factors, such as vandalism of seats often assumed in inner city and commuter rail applications, would be included where applicable. If the goals and objectives are met for all scenarios, the design would be considered acceptable. In the next section, an example calculation for the trash bag fire will be presented.

Example Fire Hazard Calculation

In this example, the consequences of a fire involving a trashbag placed on a pair of seats in a coach car is evaluated using CFAST[15] v3.0 (CFAST is the fire model in HAZARD I). The goal is life safety of passengers and crew; the objective is to evacuate the car of origin to adjacent cars before being exposed to "untenable" conditions. Burning rates for the seats are for actual passenger rail seats tested in a Cal TB133 room test configuration[16]. The trash bag is from the SFPE Handbook[17].

Conditions predicted within the car of origin are presented in figures 1-5 with the top axis representing the hazard limit for that condition. Note that the upper layer temperature never reaches the lethal limit (100 °C) and, while it exceeds the discomfort limit (66 °C), the layer interface (fig 2) is high enough for people to pass below by only bending over. Radiant flux to the seats in front and across the aisle from those involved is insufficient to ignite those materials, so the fire will not spread beyond the two seats initially ignited.

Since the time needed to evacuate the car is short and all seats are visible from any point in the car (i.e., no delay in starting to evacuate), there is no threat to passengers or crew from this scenario. More than enough time is available to evacuate to the adjacent cars. CO does not become a limiting factor in the evacuation (see figure 4). Since the fire would not spread, the crew could extinguish the fire with portable extinguishers or the train could proceed to the next station for assistance from the fire service.

It is interesting to note that the HRR from the trash bag exceeds that from the pair of seats. If the seats alone are burned (such as from ignition by a small source), the conditions in the car remain tenable throughout (see figures 5-8).

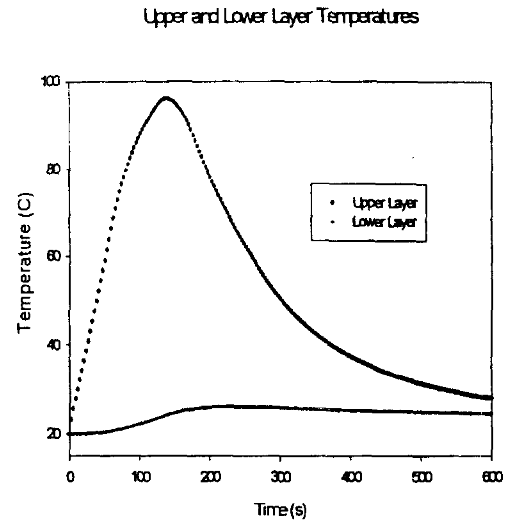

Figure 1: Upper and Lower Layer Temperatures for Two Seats and Trash Bag

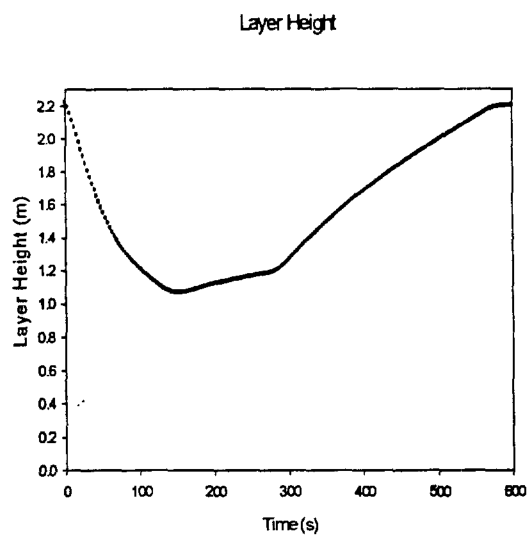

Figure 2: Layer Height for Two Seats and Trash Bag

Advantages of Fire Hazard Analysis

The hazard load approach in NFPA 130 was clearly an advance over guidelines which specify bench-scale tests of component materials. Its assumption that all items burn simultaneously at their peak rate is conservative, and can lead to inefficient use of resources.

The advantage of the FHA approach is that performance is evaluated as a system, rather than of individual components in isolation. Seats interact with other seats and with wall and ceiling panels. Conditions which might complicate evacuation of passengers or emergency procedures expected of crew should be apparent. It is possible to determine when changes might have little or no impact on improved safety, avoiding investments without tangible results.

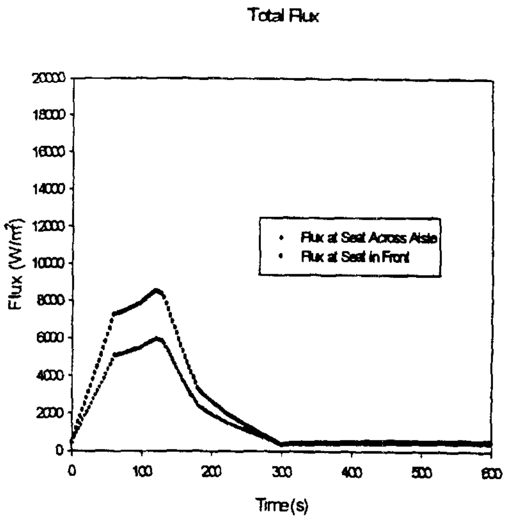

Figure 3: Total Flux for Two Seats and Trash Bag

Conclusions

As passenger rail transportation advances into the 21st century, equipment and operations will likely change drastically. High-speed rail links like those of Europe and Japan have been proposed for a number of locations in the United States. These systems will involve new, light-weight materials and systems for both energy efficiency and increasing speed. The fire hazard analysis-based approach to assuring acceptable passenger train fire performance for these systems may be useful.

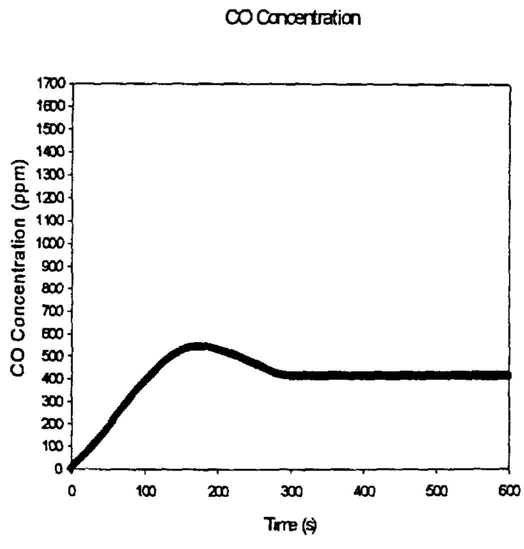

Figure 4: Carbon Monoxide Concentrations for Two Seats and Trash Bag

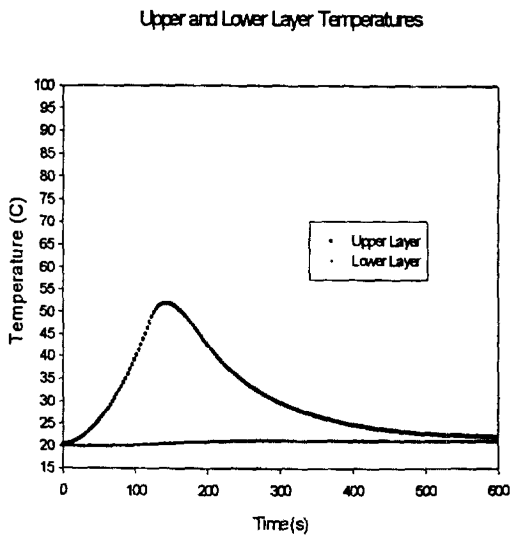

Figure 5: Upper and Lower Layer Temperatures for Two Seats Alone

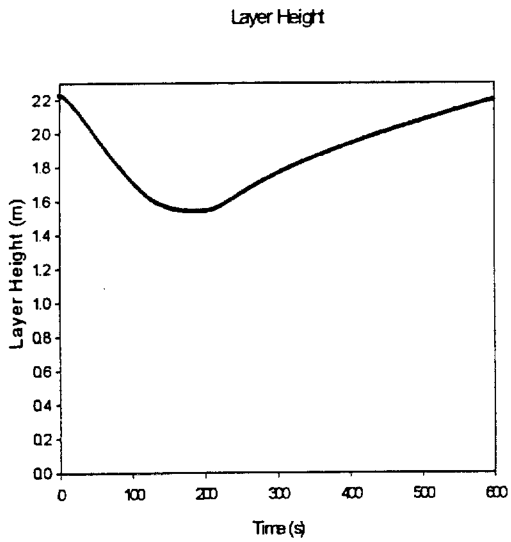

Figure 6: Layer Height for Two Seats Alone

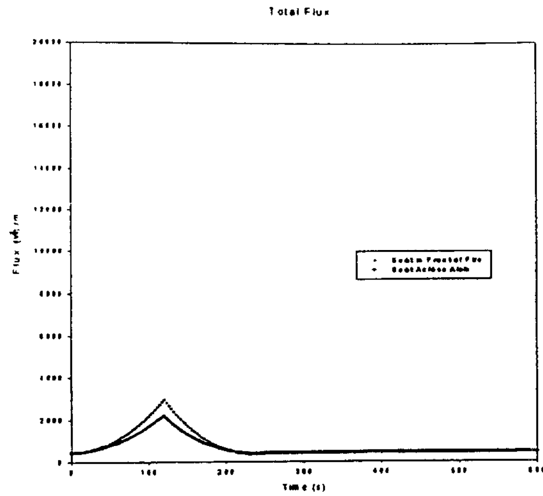

Figure 7: Total Flux to Adjacent Seats for Two Seats Alone

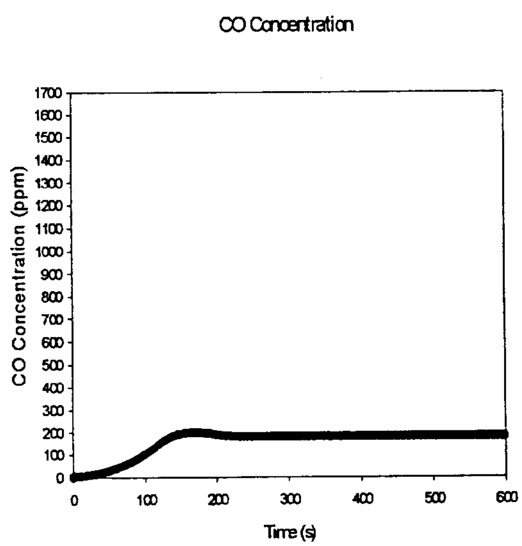

Figure 8: Carbon Monoxide Concentration for Two Seats Alone

References

1. "Feasibility Study of Computer Modeling of Fires in Railway Vehicles With a View to Improving Passenger Safety," ERRI B 106/RP 25, European Rail Research Institute, Utrecht (1992).

2. National Fire Protection Association, "NFPA 130, Standard for Fixed Guideway Transit Systems," NFPA, Quincy, MA (1995).

3. Wilkins, J. J. and Cavanaugh, R. R., "Plastics and Rail Transportation, Polymeric Materials and Their Use in Transportation", April 27-29, 1977, The Polytechnic Institute of New York (1977).

4. "Fire Safety Aspects of Polymeric Materials", Volume 8, Land Transportation Vehicles, National Materials Advisory Board Pub. NMAB 318-8, National Academy of Sciences (1979).

5. Federal Railroad Administration. "Rail Passenger Equipment; Reissuance of Guidelines for Selecting Materials to Improve Their Fire Safety Characteristics," Federal Register, 54, No. 10 (1989): 1837-1840.

6. Urban Mass Transportation Administration, "Recommended Fire Safety Practices for Rail Transit Materials Selection," Federal Register, 49, No. 158 (1984).

7. National Railroad Passenger Corporation. "Specification for Flammability, Smoke Emissions and Toxicity," Amtrak Specification No. 352 (April 29, 1991).

8. Braun, E. and Peacock, R.D., "Fire Safety of Passenger Trains, Material Evaluation in the Cone Calorimeter", Interim Report Phase I, US DOT, Federal Railroad Administration, Office of Research and Development, Washington, DC, 1997 (in press).

9. Peacock, R. D. and V. Babrauskas. "Analysis of Large-scale Fire Test Data," *Fire Safety Journal*, 17, 387-414 (1991).

10. Smith E. E. "Fire Safety Evaluation of Rapid Transit Systems," *Proceedings of the International Conference on Fire Safety*, January 17 to 21, 1983, San Francisco, CA, 85-100 (1983).

11. Mikkola, E., and I.S. Wichman. "On the Thermal Ignition of Combustible Materials," *Fire and Materials*, 14, 87-96. (1989).

12. Smith, E. E. "Application of Release Rate Data for Hazard Load Calculations," *Fire Technology*, 10, No. 3, 181-186 (1974).

13. Zicherman, J.B. private communication

14. Bukowski, R. W., "A Review of International Fire Risk Prediction Methods", ***Interflam '93***. Fire Safety. 6th International Fire Conference March 30-April 1, 1993, Oxford England, Interscience Communications, Ltd., London, England, C.A. Franks, editor, pp 437-466, 1993.

15. Peacock, R.D., Forney, G.P., Reneke, P., Portier, R., and Jones, W.W., "CFAST, the Consolidated Model of Fire Growth and Smoke Transport", NIST TV 1299, Nat. Inst. Stand. Tech., 1993.

16. Zicherman, J.B., "Report of Cal TB133 Tests on Passenger Rail Car Seats", in press.

17. Babrauskas, V., "Burning Rates", Section 3/Chapter 1, figure 3-1.19 in *SFPE Handbook of Fire Protection Engineering*, second edition, P. DiNenno ed., 1995.