Received: 18 October 2017 | Revised: 6 August 2018 | Accepted: 21 August 2018
DOI: 10.1002/fam.2676

RESEARCH ARTICLE

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Experimental study of tenability during a full-scale motorcoach tire fire

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Funding information
National Highway Traffic Safety Administration

Summary

Full-scale fire experiments were conducted at the National Institute of Standards and Technology (NIST) to investigate tire fire interactions with the passenger compartment of a motorcoach. A single full-scale experiment with a partially furnished interior was conducted to investigate tire fire growth within the passenger compartment and the onset of untenable conditions. A tire fire was initiated using a burner designed to imitate the frictional heating of hub and wheel metal caused by failed axle bearings, locked brakes, or dragged blown tires. Measurements of interior and exterior temperatures, interior heat flux, heat release rate, toxic gases, and visibility were performed. Standard and infrared videos and still photographs were also recorded. The results of this single experiment showed that after fire penetration into the passenger compartment, the tenability limits were reached within 8 minutes near the fire and within 11 minutes throughout the passenger compartment.

KEYWORDS

bus fire, compartment tenability, fire growth, flame spread, motorcoach fire, tire fire, transportation fires, vehicle fire

1 | INTRODUCTION

Research concerning vehicle fires is important for the prevention of life and property losses, especially for those vehicles that carry a large number of passengers. Motorcoaches, which can carry several dozen passengers, have been of particular interest in the United States since a motorcoach fire in Texas killed 23 occupants being evacuated from a nursing home during 2005 Hurricane Rita. Many of the occupants were not mobile and could not escape before being overcome by smoke and flames.[1] While typically motorcoach and bus fires do not result in fatalities, they often cause complete loss of the coach and passenger property.[2]

The National Highway Traffic Safety Administration (NHTSA) sponsored the National Institute of Standards and Technology (NIST) to conduct research to support NHTSA's effort on improving motorcoach fire safety based on National Transportation Safety Board (NTSB) recommendations.[1] Earlier articles described experimental research efforts addressing passenger compartment penetration by tire fires[3,4] and potential fire hardening methods.[5] The research described here was intended to assess tenability within the passenger compartment in the event of a wheel-well fire.

A full-scale experiment was conducted to investigate the fire growth within the passenger compartment after penetration by a tire fire and to determine the onset of untenable conditions due to the cumulative effects of heat and toxic gases. For this experiment, the original rear of the motorcoach was complemented by a constructed front to recreate a realistic passenger compartment volume, and the interior was partially furnished to provide fuel for fire spread.

To put the current research in historical context, previous studies related to bus and motorcoach fires and tenability were presented as a detailed literature review.[3] Although our study focused on wheel-well fires, the literature review also covered research related to other types of bus and motorcoach fires. Understanding of motorcoach fire development and spread enables the development of an overall fire mitigation strategy.

FIGURE 1 Photographs of the motorcoach extension. The top photo shows most of the assembly of the original motorcoach rear half and added front extension. The bottom left photo shows the extension doorway and steps. The bottom right photo shows the front end with the window and visibility camera [Colour figure can be viewed at wileyonlinelibrary.com]

2 | EXPERIMENTAL METHODS

2.1 | Experimental setup

This section provides an overview of the experimental setup. The details can be found in the full report.[3] Because enclosure shape and volume have a large influence on fire growth and intensity, heat flux and temperatures, toxic gas production, and the spread and mixing of smoke, the tenability experiment required a test enclosure with the interior dimensions and volume of a full motorcoach. This was accomplished by constructing a mocked-up front half to complement the original rear half (see Figure 1). This provided realistic results for thermal and toxic gas tenability measurements and the timing for the passenger compartment to reach hazardous conditions.

The constructed front of the motorcoach, shown in Figure 1, consisted of a wood frame structure supporting a plywood deck upon which a steel stud frame was built and to which a galvanized sheet steel interior skin was attached. The front-end cap had access holes cut into it for a glass observation window and camera access. A doorway approximately matched that of an MCI* E-series coach. Stairs were built to allow easy access for instrumenting the interior and to approximate the footprint of the original stairwell.

For the tenability experiment, it was necessary to provide a representative and realistic fuel (combustible material) load that would ignite and become a substantial fire within the motorcoach after penetration of the tire fire through the windows. The amount of interior furnishings installed was estimated to be sufficient to bring the fire in the rear of the motorcoach to flashover conditions (all combustibles ignite) that would provide sufficient heat and smoke spread throughout the motorcoach without risking damage to the experimental facility or danger to the research personnel. The planned fire was deemed to be realistic for the time period required (beyond survivable thresholds), and additional furnishings would have provided continued fire growth and conditions far more hazardous and untenable, which were not necessary for this study.

Original furnishings and trim components from the motorcoach were reinstalled. They included three pairs of seats positioned on the right side over the rear axles, a parcel rack with doors along the right side of the entire original rear half, the interior wall trim (extending from the floor duct to the bottom of the windows) on both sides, the foam rubber window post covers, and the right-side window curtain rods and screens (rolled up). The components were required to pass the simple burner test prescribed in Federal Motor Vehicle Safety Standards[6] (FMVSS) 302. The seats were composed of fabric over polyurethane foam and were typical as described in a report[7] on bus material fire performance. They were installed with the original 86.4-

*Certain commercial entities, materials, or equipment are identified in this document in order to describe the experimental procedure adequately. Such identification is not intended to imply recommendation or endorsement by the National Institute of Standards and Technology nor is it intended to imply that the entities, materials, or equipment are necessarily the best available for the purpose.

cm (34-in) spacing in positions corresponding to the second to last row and the next two rows in front of it. This centered the three pairs of seats in the anticipated fire breakthrough area. The parcel rack was installed approximately 12 cm (4 ¾ in) forward of its original position. Figure 2 shows a view of the seats installed in the motorcoach, and Figure 3 shows a parcel rack.

2.2 | Temperature measurements

Thermocouples were positioned inside and around the motorcoach to monitor structural temperatures as well as to track the tenability of gas temperatures. Four thermocouples were located behind the exterior side panel to ascertain the thermal penetration through the exterior panel and to help determine if the foam material behind the panel was at risk for burning. Vertical thermocouple arrays of five thermocouples each (180, 150, 120, 60, and 30 cm above the floor) were installed at rear, middle, and front locations, shown in Figure 4.

Thermocouples were also attached to the top center positions of the headrests of each of the three aisle seats. Photographs of the seats and an example of the thermocouple installation are shown in Figure 2. Thermocouples were attached (with tape) to the parcel rack doors above each of these headrest thermocouple positions. A photograph of the thermocouples installed on the parcel rack is also shown in Figure 3.

2.3 | Heat flux measurements

Five heat flux gauges were arranged to monitor wide areas of the passenger compartment. Four gauges were located in the original rear of the motorcoach at 1, 2, 3, and 4 m from the rear of the interior as defined by the lavatory door. Their height was 1.5 m, and each faced the right-side windows. The lateral location was 69 cm toward the driver's side from the centerline of the motorcoach. The fifth heat flux gauge was at the same height, but near the middle gas sampling and thermocouple array location, and it faced rearward. Its location was 8 cm from the centerline and 5.66 m from the rear of the motorcoach. Table 1 details the heat flux gauge locations, and Figure 4 shows their locations relative to other features of the motorcoach.

2.4 | Gas volume fractions

Three 9.5-mm (0.375-in) OD stainless steel probes were installed at rear, middle, and front positions to sample the gas and measure volume fractions of carbon monoxide (CO), carbon dioxide (CO_2), oxygen

FIGURE 2 Two photographs showing the three pairs of seats installed for the experiment. The right photograph shows one of the thermocouples installed on the top of an aisle seat headrest [Colour figure can be viewed at wileyonlinelibrary.com]

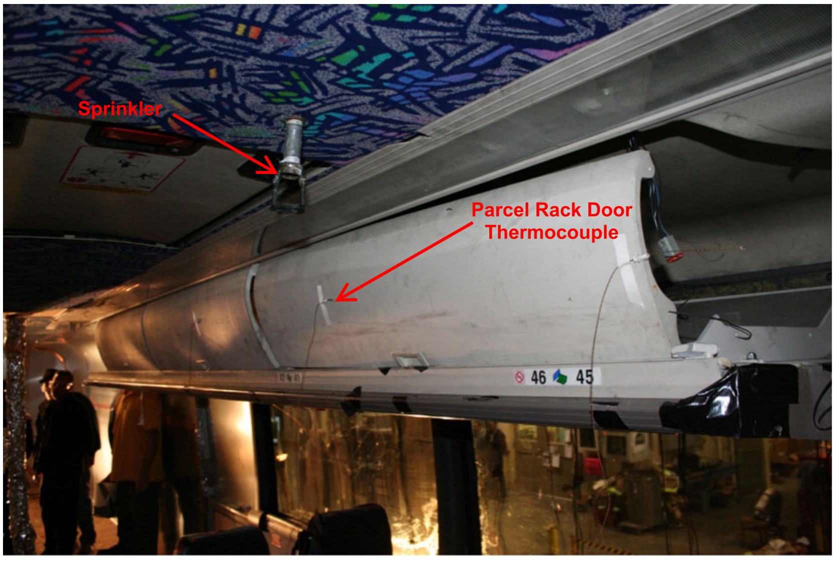

FIGURE 3 A photograph showing the right side parcel rack installed for the experiment. Three thermocouples are shown attached about half way up the doors [Colour figure can be viewed at wileyonlinelibrary.com]

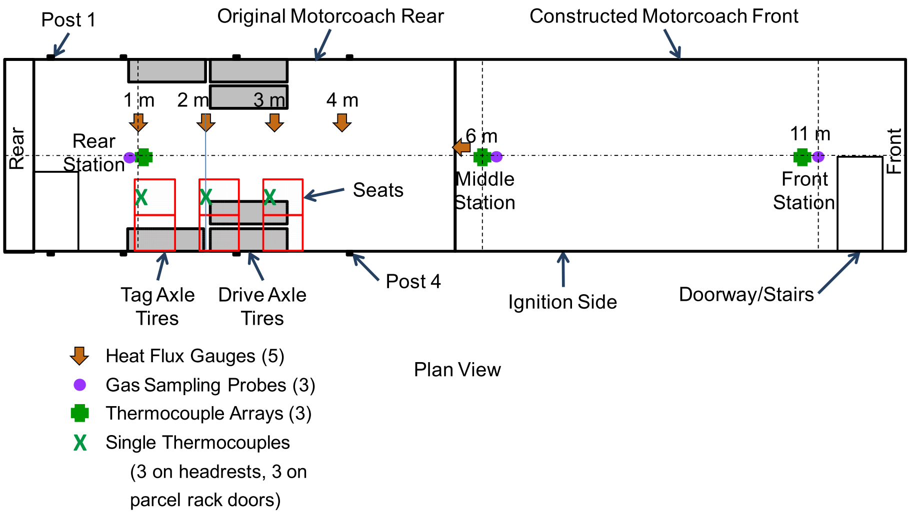

FIGURE 4 Schematic of the whole motorcoach assembly used for the experiment showing locations of the three sampling stations, heat flux gauges, and thermocouples [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 1 Heat flux gauge locations

Gauge Label	Location Description
HF1m	1 m forward of lavatory door, 1.5 m high, facing horizontally toward windows, 69 cm toward driver's side from motorcoach centerline
HF2m	2 m forward of lavatory door, 1.5 m high, facing horizontally toward windows, 69 cm toward driver's side from motorcoach centerline
HF3m	3 m forward of lavatory door, 1.5 m high, facing horizontally toward windows, 69 cm toward driver's side from motorcoach centerline
HF4m	4 m forward of lavatory door, 1.5 m high, facing horizontally toward windows, 69 cm toward driver's side from motorcoach centerline
HF6m	5.66 m forward of lavatory door, 1.47 m high, facing rearward, 8 cm toward driver's side from motorcoach centerline

(O_2), and unburned hydrocarbons in the interior of the motorcoach. The probe locations are shown in Figure 4. Overall combined expanded uncertainties in the gas measurements were about ±3% of the measured values.

The rear sample probe also provided sample gas to a Fourier transform infrared spectrometer (FTIR) that was used to measure hydrogen cyanide (HCN), hydrogen chloride (HCl), water (H_2O), and other gases with relatively lower volume fractions. The FTIR measurements generally had total uncertainties estimated at ±10% of the measured values. Larger uncertainties were estimated for measurement ranges far from the gas volume fractions at which the FTIR was calibrated. These instances are discussed later.

2.5 | Visibility

Two methods were used to determine when smoke in the passenger compartment reached sufficient levels to inhibit visibility. One method involved installing a smoke meter across the motorcoach interior near the middle sampling station. The position is shown in Figure 5. The smoke meter consisted of a laser and detector. Decreases in the detector signal indicated smoke attenuation of the laser beam. The laser and detector were mounted on stands that did not touch the walls to prevent thermal expansion effects on their mountings that would change the laser beam alignment. The centers of the holes were located 1.5 m from the floor and 6.26 m from the lavatory door or 67 cm forward of the front edge of the original motorcoach rear half.

A second method to determine visibility involved mounting six luminous signs spaced at 2-m intervals from the lavatory door forward 10 m to about 2 m from the front wall. Figure 5 shows their positions in the motorcoach. A video camera was mounted in the front-end cap of the motorcoach to record the deterioration of visibility. The luminous signs were made of white thermoplastic with LED lights and red letters. The signs were installed with their centers 69 cm (27 in) toward the driver's side from the centerline. Their vertical centers were located 1.5 m from the floor or about 47.5 cm (18.7 in) from the ceiling. Each sign had a different letter left unmasked to enable easier analysis of the video recording. Figure 6 shows the rearmost sign as installed. Figure 7 shows the front most visibility sign and the others toward the rear.

Visibility was determined based on a visual analysis of the video recording. During the course of the experiment, after a sign could no longer be distinguished from its surroundings due to smoke, visibility was considered impossible for that particular sign. The motorcoach interior was not lit during the experiment, so it was relatively dark inside except for some low-level laboratory light that came in through the windows. Uncertainty in this somewhat subjective measurement was approximately ±5 seconds.

2.6 | Other measurements

The total heat release rates produced by the burner and the motorcoach fire were also measured. Details of these measurements and their uncertainties are presented in the full report.[3]

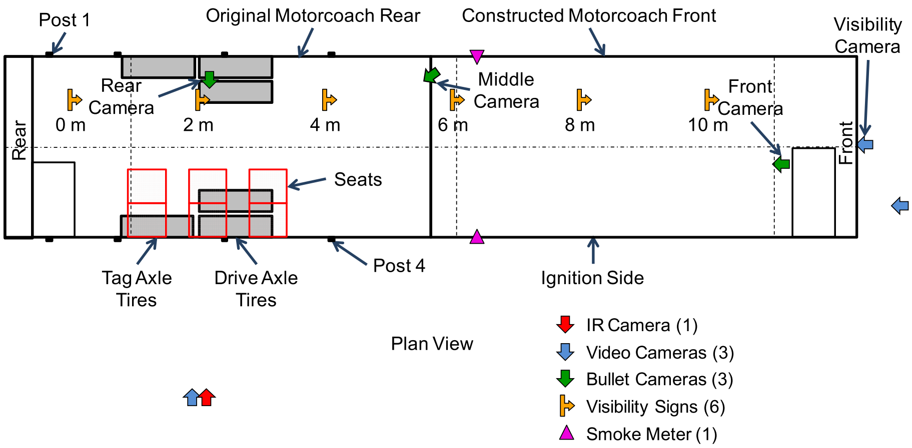

FIGURE 5 Schematic of the whole motorcoach assembly used for the experiment showing approximate locations of IR, video, and bullet cameras [Colour figure can be viewed at wileyonlinelibrary.com]

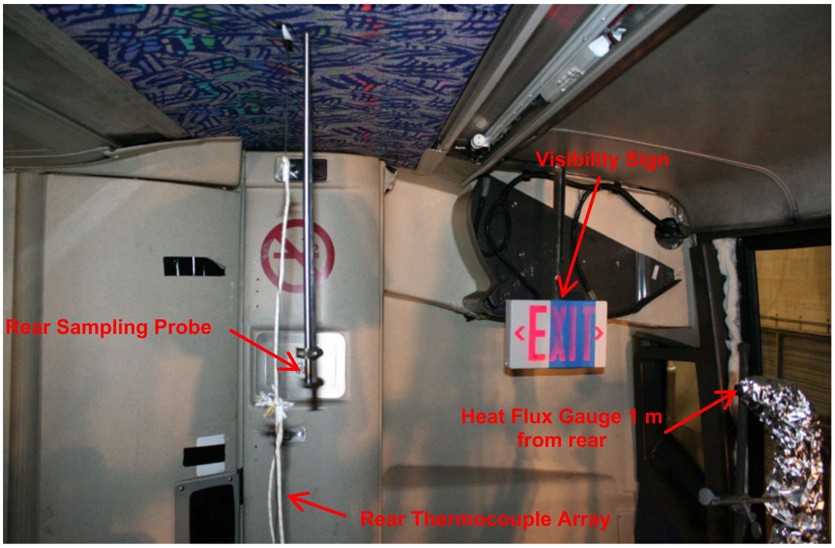

FIGURE 6 A photograph showing the rear gas sampling position, rear visibility sign, rear thermocouple array, and rear heat flux gauge used for the experiment [Colour figure can be viewed at wileyonlinelibrary.com]

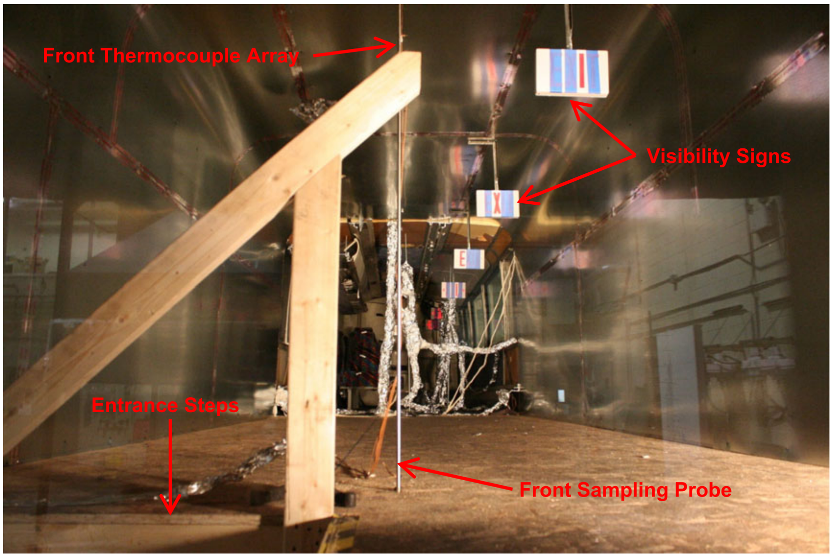

FIGURE 7 A photograph of the interior of the motorcoach and front extension looking toward the rear. The lit exit signs were used to determine visibility deterioration during the experiment [Colour figure can be viewed at wileyonlinelibrary.com]

Video recordings were made with one infrared (IR) camera, three standard cameras, and three standard bullet cameras. Figure 5 is a schematic showing the approximate locations or viewing directions of the various interior and exterior cameras. Three digital still cameras were used to acquire a sufficient number of images from multiple views.

2.7 | Experimental procedure

Detailed experimental procedure can be found in the full report.[3] Briefly described, a fire was initiated on the tag (rearmost) axle tire using a burner designed to imitate the frictional heating of wheel metal. The tire fire then spread into the passenger compartment through a window and ignited the installed compartment contents. Measurements and observations were then made. The fire was extinguished using multiple manual fire hoses (one with water and foam) once the fire HRR exceeded 5 MW or smoke was observed starting to escape the exhaust hood. A fixed sprinkler installed in the roof of the motorcoach near the rear sampling station for remote extinguishment was also used.

TABLE 2 Timing of events and observations during experiment (uncertainty = ±3 s)

Time, s	Event Description
−3450	Data recording initiated
0	Burner placed on wheel
720	Starting to see smoke from top of tire
1462	Cameras started
1800	Started FTIR
1832	A lot of smoke coming from under the back of the bus
2111	Small flame at 7 o'clock on the tire
2201	Tire ignited
2210	Burner removed
2232	Shield removed
2400	Fender ignited
2648	Glass broke
2861	Glass fell out and front of fender fell
2889	Flames in interior
2998	Seats on fire
3581	Suppression
4660	Visible flame in wheel well-suppressed

Abbreviation: FTIR, Fourier transform infrared spectrometer.

3 | RESULTS AND DISCUSSION

3.1 | Event timing and heat release rate

The times of events during the experiment are listed in Table 2. The times have uncertainties of about ±3 seconds.

Only after flames penetrated the window could the interior materials ignite. It took about 2 minutes after window penetration for the front window seat to ignite. Based on analysis of the interior video, fire spread from the front and middle window seats to the aisle and rear seats and other combustibles such as wall trim and parcel racks were gradual over the next 7 minutes. During the final 2 minutes (prior to suppression), the fire growth, temperatures, and toxic gases ramped up quickly. Figure 8 is a photograph of the interior of the motorcoach about 8 minutes after fire penetrated the passenger compartment through a window. Figure 9 is a photograph of the exterior of the motorcoach about 20 minutes after the burner was removed and 13 minutes after the window broke.

The peak HRR was 5633 kW with an expanded uncertainty of ±8.9%. The average HRR for the wheel burner was 60.8 kW with an expanded uncertainty of ±2.5%. Uncertainties were calculated according to a detailed study of the calorimetry and fuel delivery systems.[8]

3.2 | Interior gas temperatures

Figure 10 shows the thermocouple array temperatures plotted versus time after fire penetration for the 3 minutes before suppression. By 100 seconds prior to suppression, all the temperatures at or above 1.2 m from the floor exceeded 100°C. The thermocouples at 30 cm from the floor at the middle and front arrays had maximum temperatures of 54°C and 34°C, respectively, before extinguishment. The

FIGURE 8 Tenability experiment passenger compartment about 15 minutes after burner removal [Colour figure can be viewed at wileyonlinelibrary.com]

FIGURE 9 Tenability experiment almost 20 minutes after burner removal [Colour figure can be viewed at wileyonlinelibrary.com]

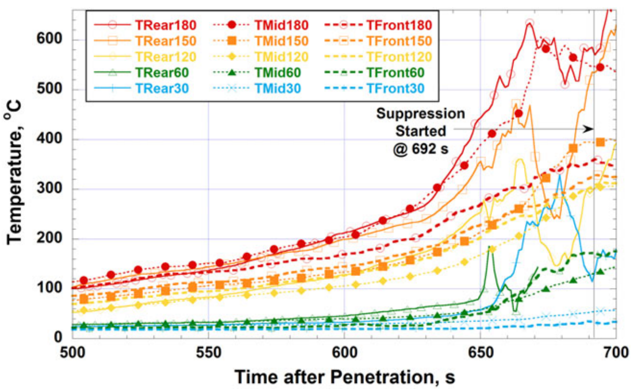

FIGURE 10 A plot of interior rear, middle, and front gas temperatures versus time after penetration. Numbers 30 through 180 represent distance from the floor in centimeters [Colour figure can be viewed at wileyonlinelibrary.com]

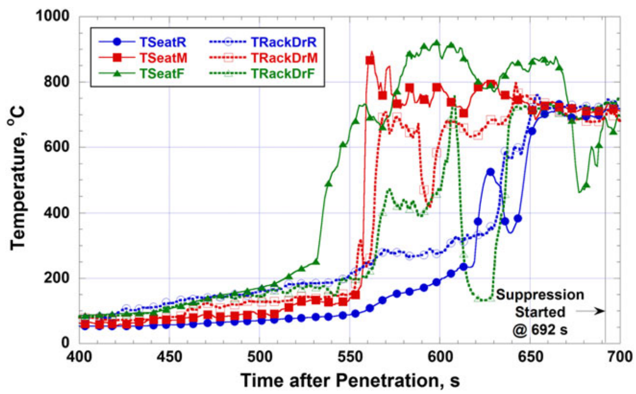

FIGURE 11 Seat headrest and parcel rack door temperatures plotted versus time after penetration. Locations were on or over the rear (R), middle (M), and front (F) seats [Colour figure can be viewed at wileyonlinelibrary.com]

60-cm height middle and front maximum temperatures were 133°C and 172°C, respectively. These peaks occurred at or within several seconds of extinguishment. This indicates that even the most tenable location, near the floor, was becoming untenable at the end of the experiment.

3.3 | Other temperature measurements

The temperatures of the tops of the aisle seat headrests and the parcel rack doors above them were measured with thermocouples (see locations in Figures 2–4). Figure 11 shows a plot of these temperatures versus time after fire penetration of the passenger compartment. Each pair of headrest and door temperatures tracked somewhat with each other, which indicates that the thermal environment varied more with the axis of the motorcoach and not as much vertically at each row. The front seat seems to have been involved in the fire first followed by the middle and then rear. The front and middle parcel rack door temperatures lagged their matching headrest temperatures indicating that they were receiving heat from the flaming seats but may not have been as involved in the fire as the seats. At the rear headrest, this was reversed indicating that the parcel rack door was being heated more by the burning of the middle and front seats than the rear seat. At about 620 seconds after penetration, the rear seat appears to ignite, and the seat and door temperatures rose rapidly.

3.4 | Heat fluxes

Figure 12 shows the heat flux results plotted versus time after penetration for about 4 minutes before suppression. The threshold for flashover, when all fuels (combustible materials) may simultaneously ignite in an enclosure, is often defined[9] at 20 kW/m^2. The times after penetration when the heat flux gauges reached this level were 626 seconds for the 3-m gauge, 629 seconds for the 2-m gauge, 647 seconds for the 4-m gauge, 650 seconds for the 1-m gauge, and 665 seconds for the 6-m gauge. All the rear measurement locations exceeded the flashover condition within 40 seconds of each other.

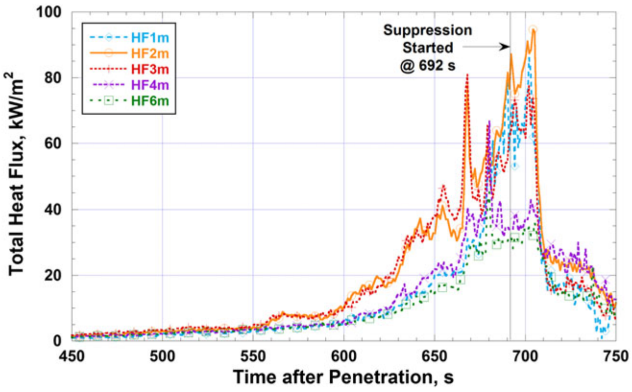

FIGURE 12 A plot of total heat flux versus time after penetration for the five heat flux gauges in the passenger compartment. Table 1 provides additional descriptions of the locations [Colour figure can be viewed at wileyonlinelibrary.com]

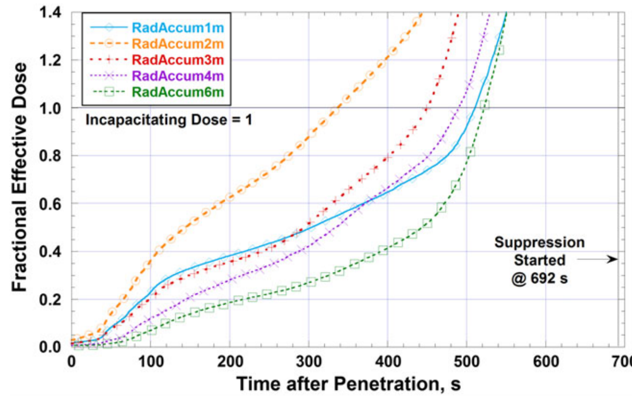

FIGURE 13 Fractional effective doses from thermal radiation plotted versus time after penetration for the six heat flux gauges located 1, 2, 3, 4, and 6 m from the rear (lavatory door) of the motorcoach [Colour figure can be viewed at wileyonlinelibrary.com]

3.5 | Thermal tenability analysis

ISO 13571[10] was used to analyze the thermal and chemical species volume fraction. The standard uses fractional effective dose (FED) and fractional effective concentration (FEC) analyses. FED is the ratio of the exposure dose for an asphyxiant toxicant to that exposure dose of the asphyxiant expected to produce a specified effect on an exposed subject of average susceptibility. FEC is the ratio of the concentration of an irritant to that expected to produce a specified effect on an exposed subject of average susceptibility. The specified effect is usually incapacitation that would prevent escape; death would typically follow. According to the standard, an FED or FEC value of 1.0 corresponds to a median value of a log-normal distribution of physiological responses, with half of a population less susceptible and half more susceptible to the exposure. This means that statistically, half of the population would experience tenable conditions (able to perform cognitive and motor skill functions at an acceptable level) and half would not.

Thermal phenomena such as high temperature convective heat transfer and radiative heat flux are treated as asphyxiant toxicants and use the same FED definition as toxic gases. In this analysis, the response of the total heat flux gauges was assumed to be due to thermal radiation only and not convection. For heat flux, while the tenability limit for exposure of skin to radiant heat is 2.5 kW/m^2, the FED considers accumulated exposure. Equation (1) defines the time in minutes, t_{Irad}, to second degree burning of skin due to radiant heat, q in kW/m^2. It has a 25% uncertainty (specified in the standard) associated with it.

$$t_{Irad} = 6.9q^{-1.56} \tag{1}$$

The reciprocal of t_{Irad} is the FED for radiant heat. Figure 13 is a plot of the FEDs for the five total heat flux gauges plotted versus time after penetration. The FED value of 1 reflects the tenability threshold. According to this analysis, the times after penetration for untenable conditions (in increasing order) were 337 seconds for the 2-m gauge, 450 seconds for 3 m, 490 seconds for 4 m, 511 seconds for 1 m, and 522 seconds for 6 m. Therefore, because of thermal radiation alone, the rear half of the motorcoach started to become untenable 5 minutes 37 seconds after penetration and became completely untenable within 9 minutes.

For thermal convection due to high temperatures, the time in minutes to experiencing pain is expressed in Equation (2) for fully clothed persons and Equation (3) for lightly clothed or unclothed persons. The equations have 25% uncertainty (specified in the standard). The reciprocal of t_{Iconv} is the FED for accumulated exposure.

$$t_{Iconv} = \left(4.1 \times 10^{8}\right)T^{-3.61} \tag{2}$$

$$t_{Iconv} = \left(5 \times 10^{7}\right)T^{-3.4} \tag{3}$$

Figure 14 is a plot of the FEDs for thermal convection plotted versus time after penetration. The FED value of 1 reflects the tenability threshold. According to this analysis, the times after penetration for untenable conditions for fully clothed passengers would be 641 seconds at the rear station, 675 seconds at the middle, and 676 seconds at the front. For lightly clothed passengers, the times would be 595 seconds at the rear station, 648 seconds at the middle, and

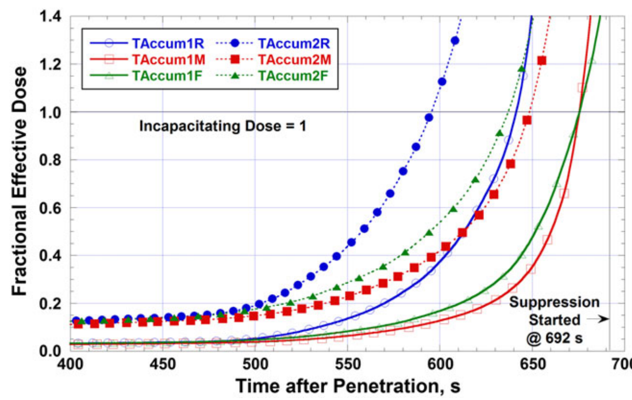

FIGURE 14 Fractional effective doses from thermal convection plotted versus time after penetration for the thermocouples 1.5 m from the floor at the rear (R), middle (M), and front (F) thermocouple arrays. The type 1 analysis treats occupants as fully clothed while type 2 is for more lightly clothed occupants with more skin exposure [Colour figure can be viewed at wileyonlinelibrary.com]

637 seconds at the front. From these times, the rear of the motorcoach became untenable 10 minutes 41 seconds after penetration for fully clothed persons and 9 minutes 55 seconds for lightly clothed persons. For the middle station, the times from penetration were 11 minutes 15 seconds and 10 minutes 48 seconds, and for the front, the times were 11 minutes 16 seconds and 10 minutes 37 seconds. In summary, from thermal convection alone and for any clothing type, the motorcoach began to be untenable in the rear just under 10 minutes after penetration and the whole motorcoach became untenable by 11 minutes 16 seconds.

Combining the two thermal effects is a more practical measure of the real tenability deterioration in the motorcoach passenger compartment. The total thermal tenability FED is the sum of the radiative and thermal convection FEDs. Figure 15 shows a plot of the total thermal FEDs for the rear and middle stations. The front station was not analyzed because there was no heat flux measurement associated with that location. The rear analysis used the rear station thermocouple at 1.5-m height and the heat flux at 1 m from the back. The middle analysis used the middle station 1.5-m thermocouple and the 6-m heat flux gauge.

The rear of the motorcoach became thermally untenable for fully clothed persons 503 seconds after fire penetrated the passenger compartment and at 485 seconds for lightly clothed persons. The middle of the motorcoach became thermally untenable for fully clothed persons 518 seconds after penetration and at 508 seconds for lightly clothed persons. The total thermal tenability deteriorated at the middle station in less than 30 seconds after the tenability at the rear station. Adding the effect of thermal convection to the radiation effect accelerated the process to untenable conditions at the rear station by almost 30 seconds for lightly clothed persons. The total thermal tenability analysis was conducted with the 1- and 6-m heat flux gauge results because those were the locations of the rear and middle thermocouple trees, respectively, and their associated convection data. It should be noted that the locations closer to the center of the burning seats, especially near the 2-m heat flux gauge, reached untenable conditions due to radiation up to 3 minutes earlier than the 1- and 6-m gauge locations. Thermal radiation from the fire was the driving component for deteriorating thermal tenability, which was only slightly accelerated by thermal convection.

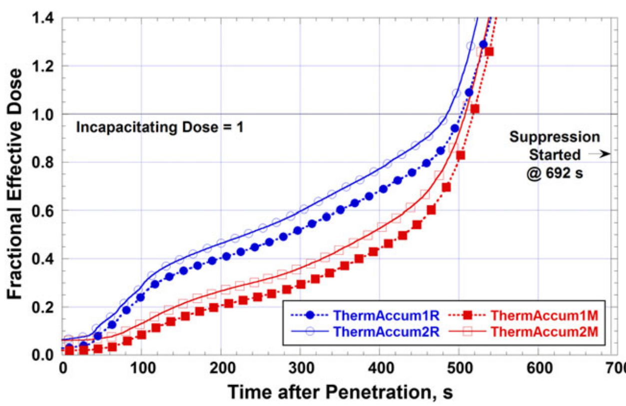

FIGURE 15 Fractional effective doses from combined radiation and convection plotted versus time after penetration for the rear (1-m) and middle (6-m) heat flux gauges and thermocouples 1.5 m above the floor. The type 1 analysis treats occupants as fully clothed while type 2 is for more lightly clothed occupants with more skin exposure [Colour figure can be viewed at wileyonlinelibrary.com]

3.6 | Gas volume fractions

The volume fractions O_2, CO_2, and CO are plotted in Figure 16 for the period 7.5 minutes after window penetration to just after extinguishment was initiated. The volume fraction is plotted as a "dry" measurement because water was trapped out of the sample before it went through the gas analyzers. FTIR measurements of water showed about 3.5% water vapor near the time of the largest fire just before extinguishment.

O_2 decreased all three locations from near ambient levels over 20% to about 19% by 110 seconds after fire penetration. From 110 to 460 seconds, O_2 decreased slowly to about 18% before beginning a more rapid decrease to 4% (rear), 4.5% (front), and 5% (middle) when extinguishment was initiated at 692 seconds after penetration. On the same plot, CO_2 increased at all three locations from ambient to about 1.5% by 110 seconds. From 110 to 460 seconds, CO_2 rose slowly to about 2% before beginning a more rapid rise to 12.5% (rear) and 11.5% (middle and front) when extinguishment was initiated at 692 seconds. Also shown in Figure 16, CO increased at all three locations from 0% to about 0.1% and stayed below 0.2% until about 510 seconds. After 510 seconds, CO rose more rapidly. CO in the rear peaked at 3.1% and decreased slightly to 3.0% at 692 seconds when extinguishment was initiated. The middle and front CO volume fractions lagged the rear position and were only about 2.6% at the beginning of extinguishment. The extinguishment process took tens of seconds and was focused in the rear of the motorcoach, so the CO volume fractions peaked at about 3.3% about 30 seconds after extinguishment were started for both the front and middle positions.

Unburned hydrocarbons were measured at each sampling location. The hydrocarbon analyzers were not calibrated for levels (as methane) of over 5%, but there were more than 5% hydrocarbons generated. For the rear station, between 5% and about 10% (based on extrapolating the peak) were generated prior to the beginning of extinguishment. For the middle and front stations, levels of 4.1% and 3.8% were measured, respectively.

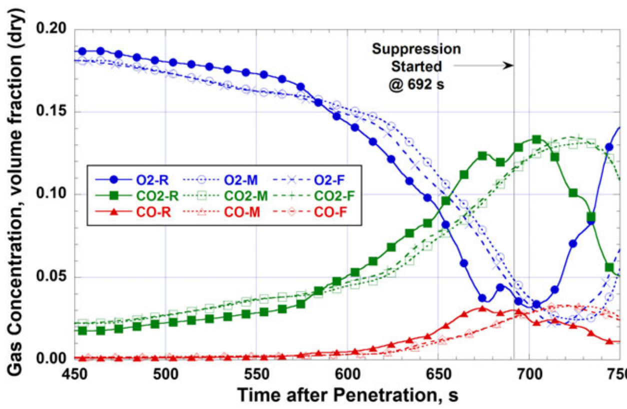

FIGURE 16 O2, CO2, and CO volume fractions measured at the rear (R), middle (M), and front (F) sampling locations plotted versus time after penetration [Colour figure can be viewed at wileyonlinelibrary.com]

Figure 17 is a plot of some of the gases measured using FTIR at the rear sampling position in the motorcoach. The CO volume fraction is slightly lower but comparable with the analyzer measurement at the same location. HCl peaked at about 1.5% while HCN only reached about 500 μL/L.

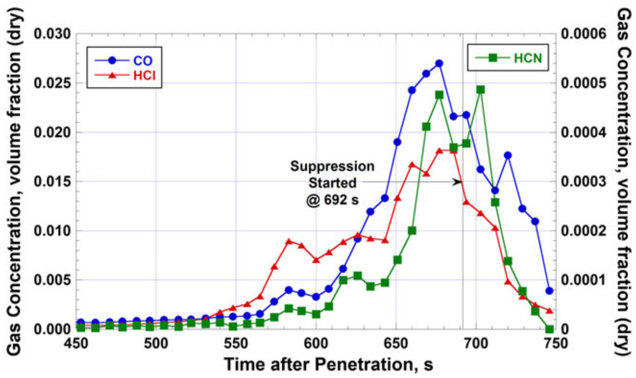

FIGURE 17 CO, HCl, and HCN volume fractions measured with FTIR at the rear sampling location plotted versus time after penetration [Colour figure can be viewed at wileyonlinelibrary.com]

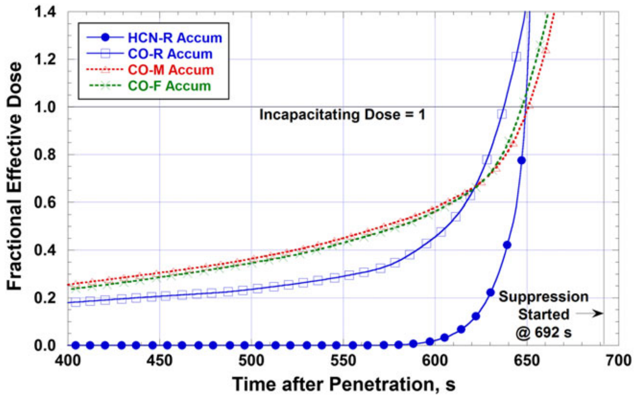

FIGURE 18 Fractional effective doses for HCN and CO measured at the rear (R), middle (M), and front (F) sampling locations plotted versus time after penetration [Colour figure can be viewed at wileyonlinelibrary.com]

Most of the FTIR measurements had uncertainties estimated at ±10% of the measured values, but CO and CO_2 had special uncertainty issues. The maximum CO volume fraction measured using FTIR was 2.7% versus 3.3% measured with the NDIR CO analyzer. For CO_2, the maximum FTIR measurement was only about 44% of that measured by the NDIR CO_2 analyzer. There were questions about whether the appropriate calibration libraries were used as well as the possibility of stray light intruding into the FTIR cell and impacting the results at high volume fractions. While the uncertainties for the FTIR measurements of CO_2 and CO at low volume fractions were probably good within 10%, the high volume fractions, which were most important for our analyses, were too suspect to be included.

3.7 | Toxic gas tenability

ISO 13571[10] was also utilized for tenability analysis for the toxic gases measured in the experiment. The toxic gases considered here were CO, HCl, and HCN. CO_2 is considered as well in that it can cause more labored breathing and enhance the effects of the toxic gases. If the CO_2 measurement at a given time was over 2%, a toxicity enhancement multiplying factor, $e^{(CO2)/5}$, was applied to the CO and HCN volume fractions due to hyperventilation caused by the high CO_2 levels.[10] HCN from the rear FTIR measurement was assumed to be uniform throughout the motorcoach and was combined with the middle and front CO measurements for some analyses.

Equation (4) defines the total FED accumulated exposure for both CO and HCN.[10] The equation has a 35% uncertainty (specified in the standard).

$$X_{FED} = \sum_{t1}^{t2} \frac{CO}{35000} \Delta t + \sum_{t1}^{t2} \frac{HCN^{2.36}}{1.2 \times 10^6} \Delta t, \tag{4}$$

where X_{FED} is the FED, CO and HCN are gas volume fractions in μL/L, t is time in minutes, and $t1$ and $t2$ are time interval limits in minutes.

The two terms are plotted separately in Figure 18 for the rear (CO and HCN), middle (CO), and front (CO) sampling positions. When acting alone, the time after penetration to incapacitation was 649 seconds

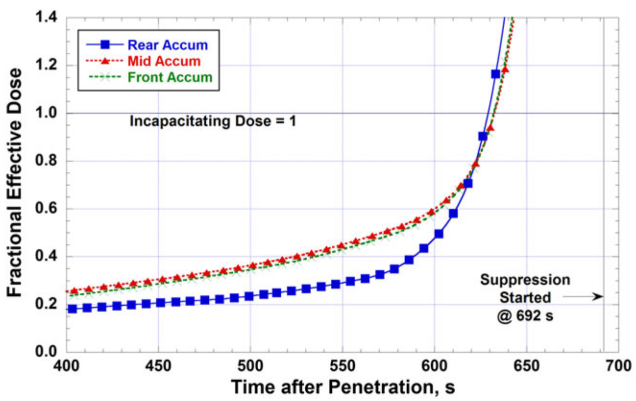

FIGURE 19 Total (both CO and HCN) fractional effective doses for the rear (R), middle (M), and front (F) sampling locations plotted versus time after penetration [Colour figure can be viewed at wileyonlinelibrary.com]

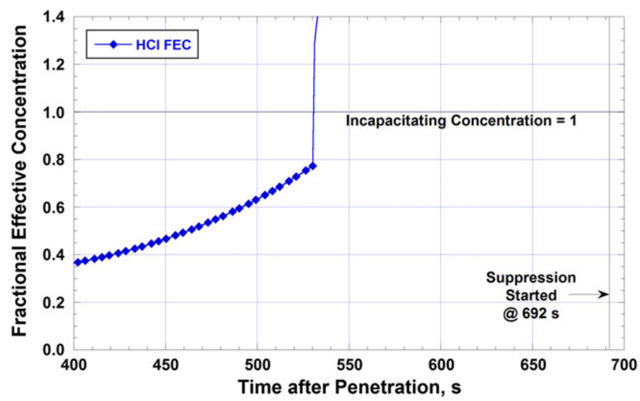

FIGURE 20 Fractional effective concentration for HCl measured with Fourier transform infrared spectrometer at the rear sampling location plotted versus time after penetration [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 3 Comparison of times from fire penetration to untenable conditions

Location Hazard	Time from Fire Penetration to Untenable Conditions					
	Rear		Middle		Front	
	s	min:s	s	min:s	s	min:s
Radiative (heat flux)	511	8:31	522	8:42	N/A	N/A
Convective (temperature) fully clothed	641	10:41	675	11:15	676	11:16
Convective (temperature) lightly clothed	595	9:55	648	10:48	637	10:37
Combined radiative and convective (fully clothed)	503	8:23	518	8:38	N/A	N/A
Combined radiative and convective (lightly clothed)	485	8:05	508	8:28	N/A	N/A
Carbon monoxide (CO)	637	10:37	651	10:51	647	10:47
Hydrogen cyanide (HCN)	649	10:49	[a]649	[a]10:49	[a]649	[a]10:49
Combined CO and HCN	629	10:29	633	10:33	632	10:32
Hydrogen chloride (HCl)	531	8:51	[a]531	[a]8:51	[a]531	[a]8:51
Oxygen vitiation	642	10:42	659	10:59	654	10:54

[a]Levels assumed at locations (middle and front) other than where measured (rear).

for rear HCN,[†] 637 seconds for rear CO, 651 seconds for middle CO, and 647 seconds for front CO. Combining the rear HCN with the CO for each position results in the plot in Figure 19. All the curves converge because of the strong influence of HCN on the totals. The incapacitating dose is reached within 2 seconds of 631 seconds for all three positions. The time to untenable conditions throughout the motorcoach due to these gases was 10 minutes 33 seconds after penetration.

HCl, as an upper-respiratory irritant, requires a FEC analysis. Equation (5) shows that it is a simple ratio of the concentration to the compromising threshold concentration.[10] The uncertainty in this equation is 50% (specified in the standard).

$$X_{FEC} = \frac{HCl}{F_{HCl}}, \tag{5}$$

where X_{FEC} is the FEC, HCl is the gas volume fraction in μL/L, F_{HCl} is the gas volume fraction in μL/L of HCl expected to seriously compromise an occupant's ability to accomplish escape (1000 μL/L from ISO 13571:2012[10]).

The plot in Figure 20 shows that the FEC for HCl increases rapidly at 530 seconds after penetration and crosses the incapacitating dose line at 531 seconds, which is 8 minutes 51 seconds after penetration.

Related to toxic gas tenability is asphyxiation due to oxygen vitiation. Oxygen volume fractions below 10% are considered lethal.[11] For this experiment, this threshold was reached at 642, 654, and 659 seconds after penetration for the rear, front, and middle stations, respectively.

3.8 | Combined effects of thermal and toxic gas tenability

Table 3 lists the various hazardous conditions that were measured during the experiment and the corresponding times for untenable levels to be reached from the time of fire penetration. Both thermal and gaseous hazards are listed. For the rear and middle locations, the thermal hazards reached untenable levels earlier than the other hazards. For the front location, heat flux was not measured, but the time for convective untenable conditions was comparable with those for gaseous hazards. Adding heat flux to the front location analysis could put thermal conditions as the leading hazard there, similarly to the other locations, or HCl may have been the fastest hazard at the front to reach an untenable level. Of the toxicity, asphyxiation, and irritant hazards, HCl led the others to untenable conditions by over 1.5 minutes. Oxygen vitiation was the last hazard to reach untenable levels. All of these hazards would normally act synergistically that would cause incapacitation leading to death earlier than any single component alone, but there is not a standard model to estimate the combined effect of the thermal and gaseous hazards.

[†]The original report[3] listed 627 s for HCN to reach untenable levels because the previous (2007) version of the ISO standard[10] used a different and, in this case, more conservative model.

3.9 | Visibility

The smoke measurements had indeterminate results. The instrument signal shifted dramatically at times that seemed unrelated to smoke attenuation and was possibly due to beam shifting (sometimes caused by heating of mounting apparatus). The voltage became negative during part of the experiment, which precluded a meaningful analysis.

The video recording of the exit signs to determine visibility resulted in the times and distances listed in Table 4. Analysis was accomplished by viewing of the video recording and determining the times that signs could not be seen based on the judgment of the viewer. Sign visibility may have been slightly enhanced by the low level of ambient light within the motorcoach. The plot in Figure 21

TABLE 4 List of distances and time visibility ended for the exit signs

Exit Sign Location from Lavatory Door, m	Exit Sign Distance from Video Camera, m	Time After Burner Removed for No Visibility, s
0	12	237
2	10	411
4	8	462
6	6	589
8	4	603
10	2	711

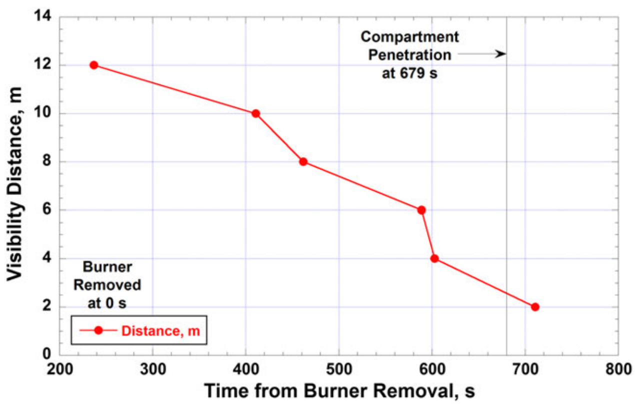

FIGURE 21 Visibility distance plotted versus the time from burner removal for the exit signs [Colour figure can be viewed at wileyonlinelibrary.com]

shows the relationship between the visibility distance and tire ignition time. The trend in the plot shows a linear decrease in visibility distance with time. It is interesting that smoke from the tire fire resulted in nearly no visibility in the motorcoach interior even before fire penetrated the passenger compartment.

4 | CONCLUSIONS

A single full-scale experiment was conducted to ascertain the approximate time for conditions to become untenable in the passenger compartment of a motorcoach with a tire fire. A mock-up of a motorcoach front end was constructed and attached to the rear half of the test motorcoach. Temperatures, heat fluxes, gas volume fractions, and visibility were measured and analyzed with regard to tenability criteria. The calculations of accumulated doses of thermal or toxic conditions have uncertainties of up to 50%, which in turn impact the estimates for time to untenable conditions. Based on this specific motorcoach, the design of its extension, the open door and fuel loading configurations, and the conditions of this particular experiment, there are several findings and conclusions that can be drawn.

The primary findings are related to the timing of an untenable environment in the passenger compartment. Thermally untenable conditions were reached at both the rear and middle measurement stations of the motorcoach by about 8 minutes after fire penetration with local areas in the rear near the seats untenable in less than 6 minutes after fire penetration. The front of the motorcoach became thermally untenable by about 11 minutes. Assuming smoke layer uniformity, CO and HCN combined to make conditions untenable throughout the motorcoach at just under 11 minutes after fire penetration, and HCl caused untenable conditions in the rear of the motorcoach at just under 9 minutes after fire penetration. Oxygen vitiation caused untenable conditions throughout the motorcoach by 11 minutes after fire penetration. Thermal conditions were generally more severe at earlier times than toxic, irritant, or asphyxiant gas conditions. Combination of the incapacitating effects of thermal and toxic gas effects would shorten tenability time and time to escape.

In addition to tenability, visibility conditions (evaluated 1.5 m from the floor) deteriorated significantly prior to fire penetration of the motorcoach. Within 30 seconds after penetration, visibility decreased to less than 2 m. Poor visibility could have made egress from this motorcoach difficult several minutes before conditions became untenable. The combination of three pairs of seats and partial trim installation was sufficient to provide fuel loading to cause flashover in the rear half of the passenger compartment in less than 11 minutes after fire penetration. Untenable conditions for this experiment were attained with a very limited fuel loading. Additional fuel loading due to more complete and realistic installation of combustible furnishings and trim may not have accelerated untenable conditions significantly since untenable conditions were reached on the order of 2 minutes before the fire involved the limited furnishings installed for this experiment. Since only one tenability experiment was performed, and it had only a limited fuel loading, these results should not be assumed to be typical for motorcoach tire fires.

ACKNOWLEDGEMENTS

This work was sponsored by the National Highway Traffic Safety Administration. Thanks to Marco Fernandez of NIST and the National Fire Research Laboratory staff for all the hard work preparing for and running this challenging experimental project, to Ed Hnetkovsky of NIST for help with the burner, and to the NIST Fire Protection and Fire Fighting Technology Groups for providing backup fire suppression. Also, the NIST Plant Division is appreciated for providing crews to move our motorcoach. NIST thanks Randy Smith and Alex Cook of Greyhound for their helpful technical advice.

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How to cite this article: Johnsson EL, Yang JC. Experimental study of tenability during a full-scale motorcoach tire fire. *Fire and Materials*. 2019;43:131–143. https://doi.org/10.1002/fam.2676