Motorcoach Tire Fires – Passenger Compartment Penetration, Tenability, Mitigation, and Material Performance

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ABSTRACT

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 burner was designed to imitate the frictional heating of hub and wheel metal caused by failed axle bearings, locked brakes, or dragged blown tires. Two experiments were conducted to determine the mode of penetration of a tire fire into the passenger compartment. For the first experiment, heating to obtain tire ignition was initiated on the exterior of the right side tag axle wheel and for the second, on the exterior of the right side drive axle wheel. Three experiments were conducted to examine fire-hardening of the motorcoach against tire fire penetration. The methods explored were: (1) replacing combustible external components with metal, (2) covering combustible external components with an intumescent coating, and (3) placing a metal fire-deflector shield above the fender. A final experiment with a partially furnished interior investigated tire fire growth within the passenger compartment and the onset of untenable conditions. Measurements of interior and exterior temperatures, interior heat flux, heat release rate, toxic gases, and visibility were performed. Also, standard and infrared videos and still photographs were recorded.

The experiments showed that the tire fires ignited the plastic fender and glass-reinforced plastic (GRP) exterior side panel (below the windows) upon which the fires spread quickly and penetrated the passenger compartment by breaking the windows. Measurements showed that other potential fire penetration routes (flooring and lavatory) lagged far behind the windows in heating and degradation. Fire-hardening using steel components had the greatest effect, followed by using an intumescent coating. Tenability limits were reached within 11 min after fire penetration throughout the passenger compartment and by 7 min near the fire.

In addition to the full-scale motorcoach experiments, the flammability performance of four interior combustible motorcoach components was tested beyond the current requirements by applying flammability tests from FAA and FRA standards for comparable aircraft and train passenger car components, respectively.

KEYWORDS: Motorcoach fire, bus fire, tire fire, vehicle fire, window breakage, fire penetration, fire hardening, compartment tenability, transportation fires

INTRODUCTION

Research concerning vehicle fires is important for the prevention of life and property losses. Fires in vehicles such as motorcoaches which carry as many as 56 passengers have potential for a large number of victims and significant property losses from each incident. One such motorcoach fire occurred during the evacuation of Gulf Coast residents during Hurricane Rita in 2005 and cost the lives of twenty-three occupants. [1] This tragedy provided the impetus for the National Highway Traffic Safety Administration (NHTSA) to sponsor the National Institute of Standards and

Technology (NIST) to conduct research to support NHTSA's current effort on improving motorcoach fire safety based on recent National Transportation Safety Board (NTSB) recommendations [1]. NIST's research was designed to accomplish the following tasks:

- Evaluate the material flammability of actual motorcoach components through their performance against various standard flammability test methods.
- Establish an understanding of the development of a motorcoach tire fire and its subsequent spread into the passenger compartment.
- Determine the feasibility of fire-hardening or increasing fire resistance of motorcoach exterior components near the wheel well.
- Assess tenability within the passenger compartment in the event of a wheel-well fire and identify potential mitigation strategies.

Whereas motorcoach fires may result from electrical system malfunctions, engine compartment leaks, component overheating, or tire fires, this research was focused on the penetration of motorcoach tire fires into the passenger compartment, methods of fire-hardening the passenger compartment against tire fires, and untenable conditions and available time to escape for tire fires. Tire fires typically result from the frictional heating of hub and wheel metal caused by failed axle bearings, locked brakes, or dragged blown tires. [2]

For this research project, only the rear half of a motorcoach was used. Six full-scale fire experiments were performed: two passenger compartment penetration experiments, three fire-hardening experiments, and one tenability experiment which examined when conditions due to fire in the motorcoach become too severe for human survival. In order to imitate the frictional heating of hub and wheel metal, a unique burner was designed to heat the metal of the wheel without preheating the tire. In addition to the description of full-scale tire fire experiments, the final report on the project [3] includes: (1) a detailed a literature review providing background on other research related to motorcoach fires and flammability test methods for materials used in transportation and (2) a description of flammability testing of motorcoach interior components using more challenging Federal Aviation Administration (FAA) and Federal Railroad Administration (FRA) requirements.

While much bus fire research has been conducted in the past, few of the efforts focused on tire fires. A recent comprehensive study on bus fire safety was conducted by the SP Technical Research Institute of Sweden [4]. For a full-scale tire fire test involving the use of a motorcoach rear wheel well, SP observed different passenger compartment penetration behavior than NIST, probably due to SP preserving the bus for future testing by putting a protective cover on the combustible exterior.

FLAMMABILITY TESTING OF ACTUAL MOTORCOACH MATERIALS

Flammability testing was conducted on a set of materials taken from used motorcoaches in order to assess how motorcoach materials perform beyond what is normally required by FMVSS 302 [5]. Typical interior materials were selected from seat, wall, and ceiling constructions for flammability tests since these materials constitute the bulk of the contents in the interior compartment. The materials, considered representative of what is found in motorcoaches currently in use, were obtained from two high production volume Motor Coach Industries (MCI) E-series motorcoaches (2000 model year) except for the parcel rack doors which were from 2003 to 2009 J-series models.

FMVSS 302, a corresponding European version (ECE 118 [6]), FAA, and FRA flammability tests were performed on four motorcoach interior materials: interior wall panels, parcel rack doors, seat fronts, and seat backs. The applicable fire tests found in these regulations are shown in Table 1. The selected materials were subjected to the FMVSS 302 standard to verify compliance. From the other, more stringent standards, a test procedure was utilized for a motorcoach material when the corresponding material for the same function (e.g. seat), but different application (i.e. train or airplane versus bus) would be subject to that test under the regulations for trains or airplanes.

Table 1 Material selection and appropriate flammability tests.

Material	Regulations and Relevant Tests			
	FMVSS 302	**ECE 118**	**FAA 14 CFR Part 25.853 [7] (also called FAR Part 25.853)**	**FRA 49 CFR Part 238.103 [8]**
Seat bottom and back cushion	Horizontal spread	Horizontal spread; drip test	Horizontal, vertical burn tests; heat release rate; smoke tests; seat cushion test	ASTM D3675 [9]; ASTM E662 [10]
Wall trim panel	Horizontal spread	Horizontal spread; drip test	Horizontal, vertical burn tests; heat release rate; smoke tests	ASTM E162 [11]; ASTM E662
Parcel rack door	Horizontal spread	Horizontal spread; drip test	Horizontal, vertical burn tests; heat release rate; smoke tests	ASTM E162; ASTM E662
Back of seat back	Horizontal spread	Horizontal spread; drip test	Horizontal, vertical burn tests; heat release rate; smoke tests	ASTM E648 [12]; ASTM E662

Of the four materials tested using FMVSS 302, only the back of the seat backrest failed by exceeding the horizontal burn rate criteria by 25 %. The fact that the seat backrest was used and ten years old could have had some impact on its performance. Of the four components tested under the FAA flammability requirements (standards not required for motorcoach materials), only the interior wall panel passed. All four components failed the FRA flammability requirements (also not required for motorcoach materials). The degree to which the failure criteria were exceeded in the tests failed by the seat components and the parcel rack door indicate that these motorcoach interior materials burn significantly more easily than comparable components approved for use in aircraft and railcars.

FULL-SCALE EXPERIMENT SET-UP

The test matrix is listed in Table 2. A diagram of the rear half of the motorcoach used for all of the full-scale experiments is shown in Figure 1.

Table 2 Test matrix

Test No.	Experimental Focus	Axle of Heated Wheel
1	Passenger compartment penetration	Tag
2	Passenger compartment penetration	Drive
3	Fire-hardening, metal exterior	Tag
4	Fire-hardening, intumescent coating	Tag
5	Fire-hardening, flame deflector	Tag
6	Passenger compartment tenability	Tag

Burner

A special burner was designed and built that would focus substantial heat, (up to 100 kW) on the metal of a motorcoach wheel without the flames or exhaust gases impinging on the rubber. The purpose of this design was to cause the rubber to ignite just from heat conduction with hot metal, which qualitatively simulates the frictional heat generated from failed axle bearings, locked brakes, or dragged blown tires. Figure 2 shows photographs of the burner and shield.

The design of the burner was a 25 mm OD stainless steel (type 304) tube bent into a 30.5 cm circle with ten high output heating torch nozzles attached perpendicular to the plane of the circle. An assembly of valves and a mixing chamber for the natural gas and high-pressure air was attached to the circular tube. The flames were meant to be pre-mixed so nearly all of the heat was efficiently generated at the flames. The burner was mounted on a long, wheeled cart to enable positioning of the flame tips and fast removal of the burner after tire ignition. A tire shield was fabricated and placed between the wheel and tire to prevent direct heating of the tire by burner flames and gases. For the second test (and subsequent tests), a calcium silicate blanket was placed on top of the shield for additional insulation to minimize radiation and convection from the shield to the tire.

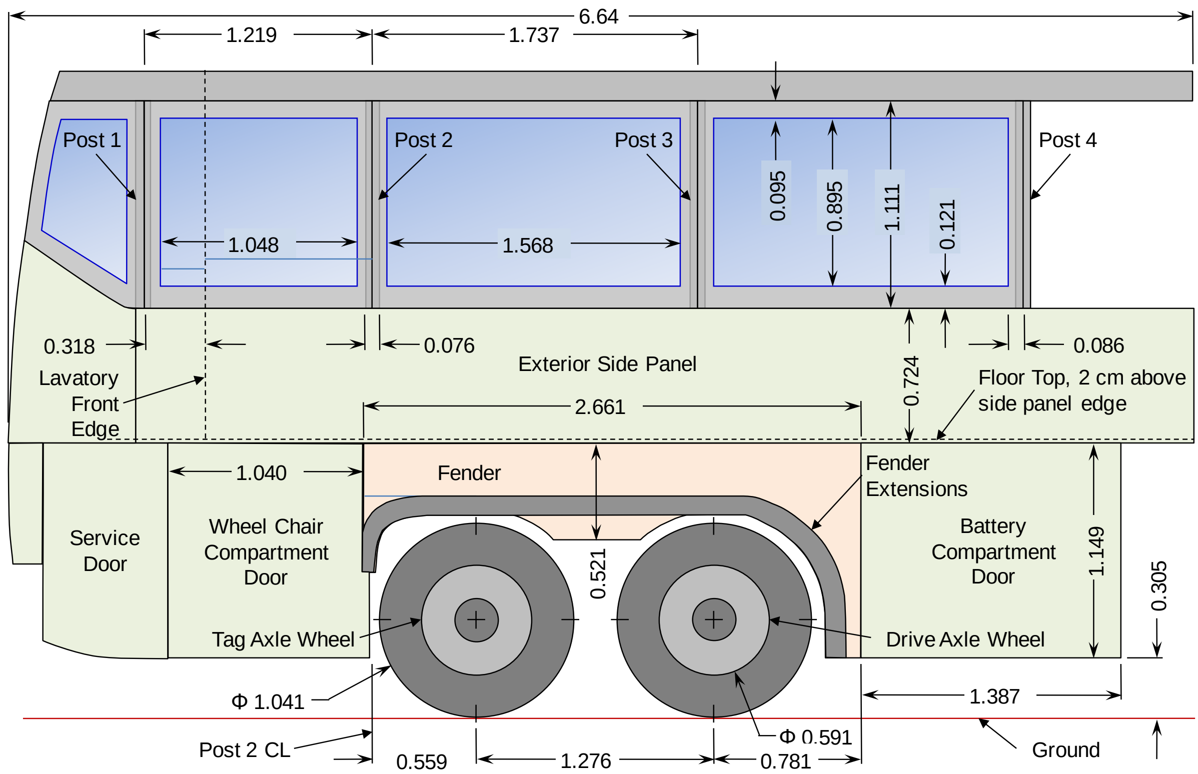

Figure 1 *A drawing of the motorcoach rear half which was used for tire fire experiments. Dimensions are in meters. Distance measurement uncertainty is ± 0.3 %.*

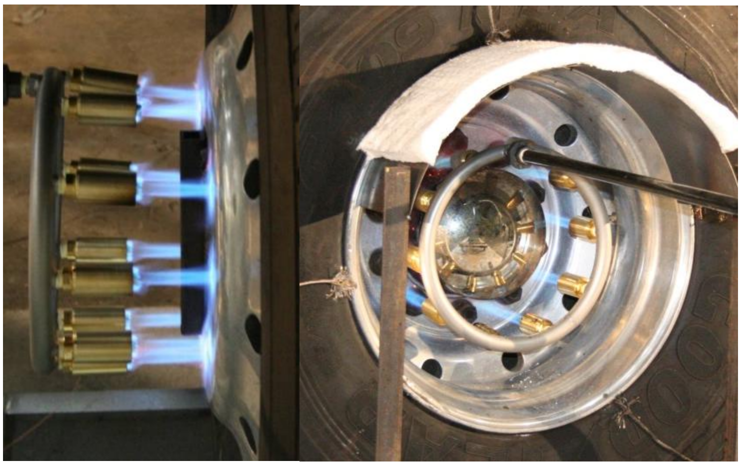

Figure 2 *(Left) A photograph showing the burner pre-mixed natural gas and air torches impinging on a tag axle wheel. (Right) A photograph showing the tire shield inside a drive axle wheel rim with an insulating cover to minimize heating from the shield to the tire.*

Measurements

For each tire fire experiment, temperature measurements were made and recorded in the interior near the windows and on the floor, on the exterior near the windows and body panels, on the wheels and tires, and in the wheel well and axle regions. Interior heat fluxes were measured in several locations, and the total heat release rate (HRR) of the fire was calculated from the hood exhaust using oxygen depletion calorimetry. For the tenability experiment, the locations of the temperature and heat flux measurements were changed and many more locations were added. Also, combustion gases (O_2, CO_2) as well as toxic gases (CO, HCN, HCl) were measured, and visibility was analyzed. Several standard and infrared videos and many photographs were recorded for each experiment. Figure 3 is a diagram of the measurement locations for the penetration and fire-hardening experiments.

Penetration Experiments

For each of the two penetration experiments (described in detail in the full report [3]), the tires were ignited by heating different wheels. For all of the experiments, the heated wheels were on the right side (when facing forward) of the motorcoach which was also the passenger entry door side and opposite the driver's side. The first tire fire was started on the tag (rearmost, also called dead or lazy) axle, which only had one wheel and tire per side. The second experiment started on the drive axle (in front of the tag axle), which had two wheels and tires per side.

Fire-Hardening Experiments

Three methods of fire-hardening, to limit penetration of the passenger compartment by tire fires, were explored: (1) replacing the combustible exterior with steel, (2) covering the combustible exterior with intumescent coating, and (3) adding a flame deflector. For all of the fire-hardening experiments, the tag axle wheel was heated.

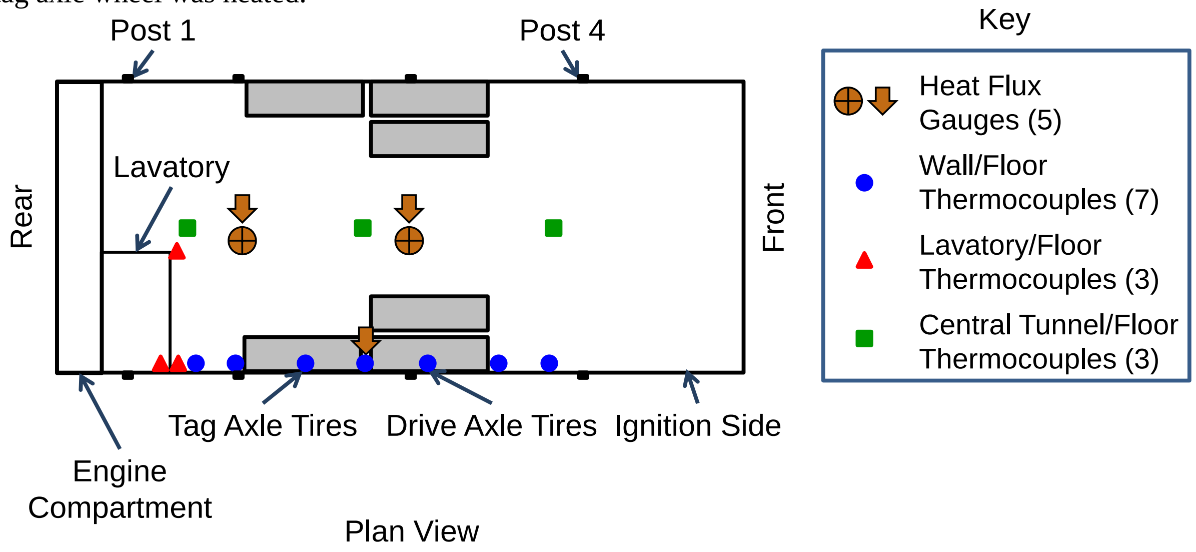

Figure 3 A diagram of the motorcoach showing locations of interior floor thermocouples and the locations and directions of heat flux gauges for penetration and hardening tests.

The first method involved removing material which acts as fuel during a tire fire by replacing the external glass-reinforced plastic (GRP) exterior side panel below the windows and the plastic fender with sheet metal. The type of sheet metal used for the side panel and fender was 0.79 mm (22 gauge or 1/32 in thick) type 304 stainless steel. A diagram of the motorcoach with both the stainless steel panel and fender is shown in Figure 4 (upper left).

The second fire-hardening method was to cover the motorcoach exterior above the tires with an intumescent coating which put a physical barrier between the combustible materials and the tire fire plume. An intumescent coating is a polymer that swells and creates a char barrier to heat and mass transfer when heated by flame. An effective char barrier can limit pyrolysis of the combustible material underneath and prevent fuel (combustible material) vapors that are generated from escaping and burning. A used exterior GRP panel and used fender were shipped to PPG Industries Protective & Marine Coatings for application of the coating. The particular coating, PITT-CHAR XP®, is a weather and abrasion resistant epoxy designed for marine applications. A diagram of the motorcoach with the coated panel and fender is shown in Figure 4 (upper right).

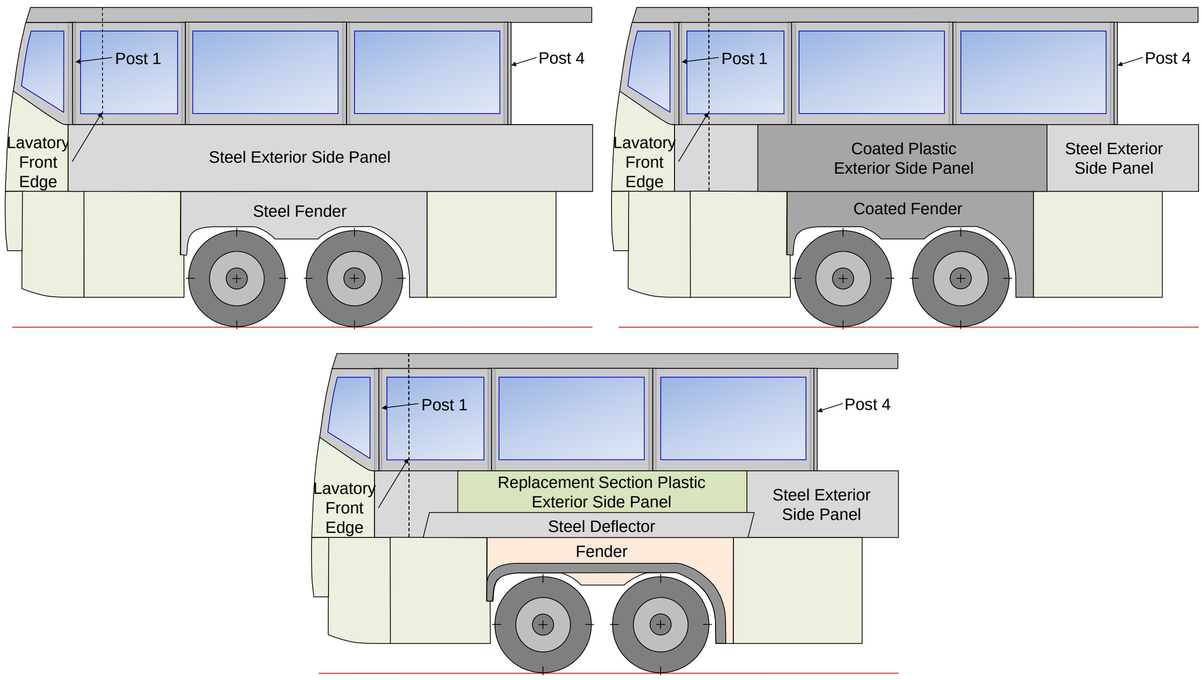

Figure 4 Diagrams of the right side of the motorcoach showing the three fire hardening configurations: steel exterior side panel and fender (upper left); intumescent coating on panel and fender (upper right); steel deflector between the fender and panel (bottom).

The third fire-hardening method consisted of a deflector shield located above the fender and below the exterior side panel. The deflector was designed to deflect the fire plume away from side of the motorcoach sufficiently to impede flame spread to the exterior side panel and thus delay or prevent window breakage. Application of the Fire Dynamics Simulator (FDS) [13] software was used to estimate the effect of such a shield on the tire fire plume. While wider designs had slightly larger effects on the average plume temperatures near the windows, a 15 cm width was chosen due to the combination of its plume temperature impact and less protruding profile. The shield was made with 0.79 mm (22 gauge or 1/32 in thick) type 304 stainless steel. The deflector was 15 cm wide and protruded from the side of the motorcoach at a 45° angle above horizontal. A diagram of the motorcoach with the deflector between the panel and fender is shown in Figure 4 (bottom).

Tenability Experiment

A final 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 the tenability experiment, a complete interior motorcoach volume with the same dimensions was necessary in order to provide realistic results for temperatures, heat fluxes, toxic gas volume fractions, and the time for the passenger compartment to reach dangerous absolute or cumulative thresholds for each of these hazards. A motorcoach front half was constructed to complement the original rear and make a whole interior volume with similar dimensions to an E-series model. The constructed front of the motorcoach consisted of a wood frame structure supporting a plywood deck upon which a steel stud frame was built and to which a galvanized steel interior skin was attached. The doorway was sized to approximately match that of an MCI E-series model. Stairs were built to allow easy access for instrumenting the interior and also to approximate the footprint of the original stairwell. Figure 5 (top) is a photograph of the exterior of the complete motorcoach assembly and Figure 5 (bottom) is a diagram showing the measurement layout.

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 reinstalled was estimated to be sufficient to bring the fire in the rear of the motorcoach to flashover conditions (all combustibles ignite) which would provide sufficient heat and smoke spread throughout the motorcoach without risking damage to the experimental facility or danger to the research personnel. Reinstalled, original furnishings 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 on both sides, the foam rubber window post covers, and the right side window curtain rods and screens (rolled up). The seats were installed with the original 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 close to its original position.

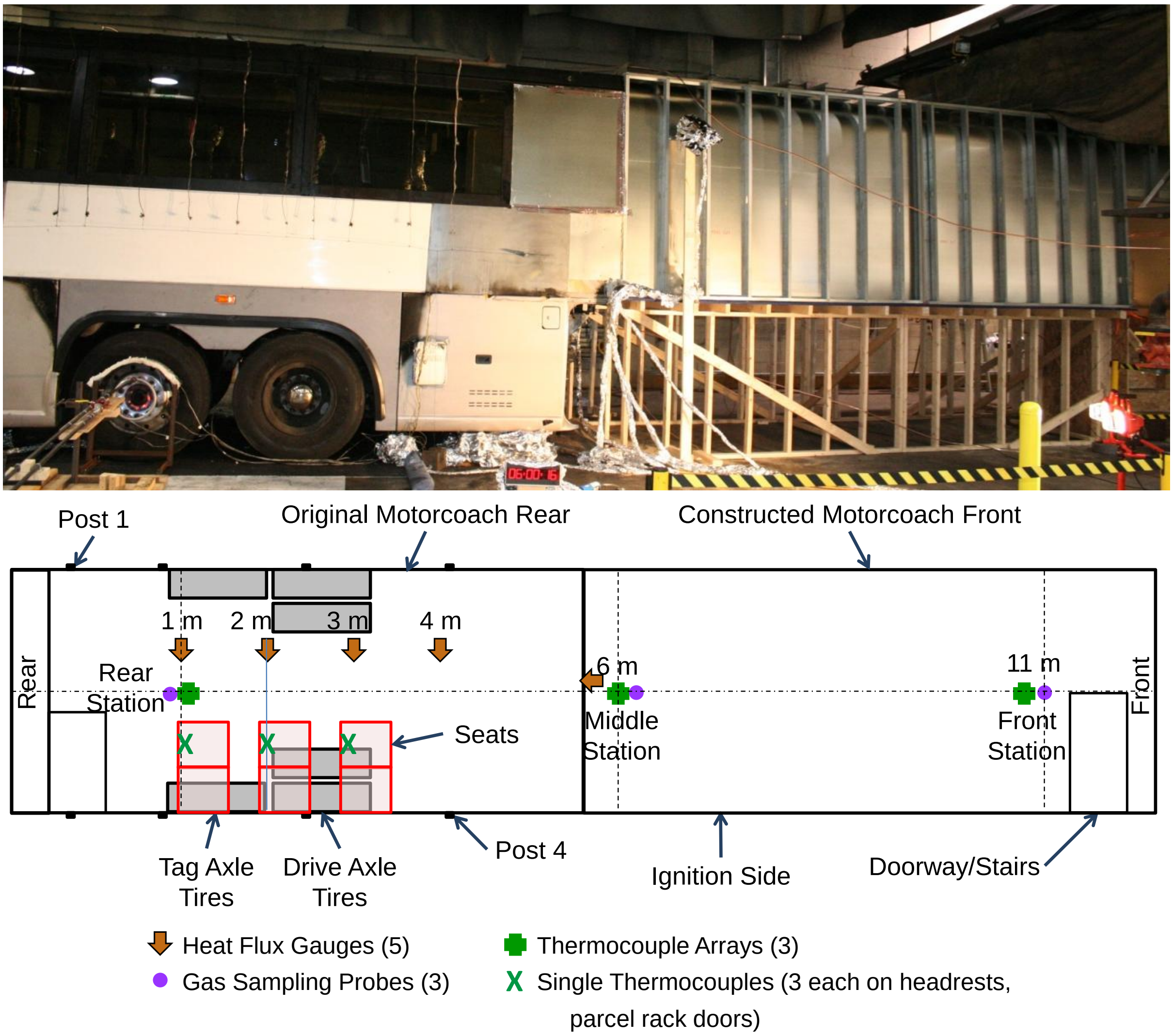

Figure 6 (Top) Photograph showing the assembly of the original motorcoach rear half and added front. (Bottom) Diagram showing the layout of measurements for the tenability test.

RESULTS

Penetration Experiments

Both experiments initiated on each axle showed penetration of the fire into the passenger compartment through the long window between the axles. This finding is in contrast with research conducted by SP [4] when a non-combustible barrier was placed on the exterior above the tires, and fire penetration through the windows did not occur. Table 3 lists the duration of the main periods of interest in these experiments: the period of heating with the burner before the tire was burning steadily, and the period between burner removal and penetration of the fire into the passenger compartment. The maximum uncertainty (combined, expanded) in the times listed is approximately

± 3 s. The period between burner removal and compartment penetration was about 1.5 min shorter for the tag axle experiment than for the drive axle experiment. In these experiments, both tire fires resulted in compartment penetration by breaking through the windows. Temperatures on the floor, near the lavatory, and in the central cable tunnel showed little increase over initial temperatures indicating that the floor and lavatory were not close to providing a pathway for fire spread into the compartment. The interior heat fluxes also stayed very low until fire penetrated the windows.

Table 3 Duration of periods of heating and between heating and window penetration.

Period	Duration (s) (min:s)	
	Test 1 (Heated Tag Axle Wheel)	**Test 2 (Heated Drive Axle Wheel)**
Burner heating wheel to sustained tire burning	2177 (36:17)	1255 (20:55)
Burner removed to fire penetration of window	280 (4:40)	363 (6:03)

Fire-Hardening Experiments

Table 4 summarizes the key periods for the 5 experiments initiated at the tag axle wheel. It is notable that the periods for heating the tag axle wheel before sustained tire burning varied widely (between 28 min and 48 min), mainly due to intermittent blowoff of some burner torches. Tests 3, 4, and 5 listed in the table were the fire-hardening experiments. The shortest duration between burner removal and window penetration (9 min 48 s) was for test 5, the deflector experiment. The longest duration (41 min 4 s) was for test 3, the steel fender/panel experiment, although this experiment was stopped (through fire suppression) before window penetration occurred after 600 °C temperatures were measured behind the panel which threatened to ignite the paper-covered foam wall insulation. Test 4, the experiment using the intumescent coating for the panel and fender, exhibited a duration from burner removal to window penetration of 32 min 26 s. Throughout the experiment, the coating remained intact over much of the fender and nearly all of the panel, but along the bottom edge of the fender, the coating degraded sufficiently to allow some flame spread upward over the fender.

Table 4 Duration of periods of heating and between heating and penetration for the tag axle experiments with and without fire-hardening.

Test Details					
Test Number	**1**	**3**	**4**	**5**	**6**
Axle of Heated Wheel	Tag	Tag	Tag	Tag	Tag
Fire-hardening/Protection	None	Metal	Coating	Deflector	None
Period	**Duration (s) (min:s)**				
Burner heating wheel to sustained tire burning	2177 36:17	1705 28:25	2848 47:28	2015 33:35	2210 36:50
Burner stopped to fire penetration of window	280 4:40	2464[a] 41:04[a]	1946 32:26	588 9:48	679 11:19

[a] This test was stopped to prevent damage due to 600 °C temperatures behind the side panel and not fire penetration.

Tenability Experiment

The burner heating times required to generate sustained tire fires for the tenability experiment and the first tag axle penetration experiment were very similar. The time for penetration for the tenability experiment was significantly longer (6 min 39 s) than for the first tag axle experiment. Only after flames penetrated the window during the tenability experiment could the interior materials ignite. It still took nearly 2 min after window penetration for the seats to ignite. After the seats ignited, fire growth was gradual over the next 7 min until the final 2 min (prior to suppression) when the fire growth, temperatures, and toxic gases ramped up quickly. Extinguishment was initiated when the HRR approached 6 MW which was considered potentially unsafe for the facility.

The ISO 13571 [14] standard provides guidance for calculating incapacitation and time for escape from the life-threatening components of fires. It was used to analyze the thermal and chemical species volume fraction data from the tenability experiment. 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. 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. The specified effect is usually incapacitation which would prevent escape; death would typically follow. A detailed analysis of the thermal and hazardous gas exposures is included in the final report [3].

Table 5 lists the various hazardous conditions that were measured during the tenability experiment and the corresponding times for untenable levels to be reached from the time of fire penetration. The calculations for accumulated doses in the ISO standard have uncertainties of up to 50 % which in turn impact these results for time to untenable conditions. 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 to 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 min. Oxygen vitiation was the last hazard to reach untenable levels. All of these hazards would normally act synergistically which would cause incapacitation leading to death earlier than any single component alone.

Table 5 Comparison of times from fire penetration to untenable conditions

	Time from Fire Penetration to Untenable Conditions					
Location	**Rear**		**Middle**		**Front**	
Hazard	**(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)	627	10:27	627[b]	10:27[b]	627[b]	10:27[b]
Combined CO and HCN	619	10:19	619	10:19	619	10:19
Hydrogen chloride (HCl)	531	8:51	531[b]	8:51[b]	531[b]	8:51[b]
Oxygen vitiation	642	10:42	659	10:59	654	10:54

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

SUMMARY OF FINDINGS AND CONCLUSIONS

Material Flammability Testing

While there may be a significant number of combinations of manufacturer, model, age, and component design, the performance of these components is considered representative of what is found in motorcoaches currently in use. Based on the flammability test results, the following are the findings and the conclusions which can be drawn:

- One interior material, the back of the seat backrest, failed the FMVSS 302 requirement by exceeding the permitted horizontal burn rate by 25 %.
- Other than the interior wall panel, all of the other components (parcel rack doors, seat fronts, and seat backs) failed the Federal Aviation Administration (FAA) flammability requirements.
- All of the components tested failed the Federal Railroad Administration (FRA) flammability requirements.
- The poor flammability test performance of the seat components and the parcel rack door showed that they burn significantly more easily than comparable components approved for use in aircraft and railcars.
- The seats and the parcel rack doors were the first interior components involved in the tenability tire fire experiment, and they constitute a majority of the combustible interior mass. Improved flammability performance of these items may significantly increase time for fire spread and untenable conditions once a fire penetrates into the passenger compartment of a motorcoach. This research was not able to examine the relationship between improved material flammability performance and fire spread within the passenger compartment.

Penetration Experiments

Based on this specific motorcoach and the conditions of these particular experiments, the following are the findings and the conclusions which can be drawn:

- Tire fire penetration into the passenger compartment occurred from flame impingement on windows and the resulting glass breakage. This finding is in contrast with research conducted by SP [4] (on a different model motorcoach) when a non-combustible barrier was placed on the exterior above the tires and fire penetration through the windows did not occur.
- A tire fire can spread to combustible exterior fenders or panels within 2 min of a sustained fire on the tire.
- The time between the start of a self-sustained or established tire fire and window breakage by fire can be less than 5 min.
- The slow rates of rise of floor and central tunnel temperatures indicate that the floor, lavatory, and central tunnel are protected sufficiently for this particular motorcoach and are not likely pathways for passenger compartment penetration in the early stages of a tire fire (i.e., prior to or immediately following window penetration).
- For the drive axle experiment, based on the rates of temperature increase observed before extinguishment, there is a possibility of an initial tire fire crossing the motorcoach by way of the drive axle within several minutes of fire penetration through the window. Window penetration on the second side would lag behind that on the primary side by the delay of the spread of fire across the axle. The tag axle experiment did not show significant heating along either axle at the center of the motorcoach or on the driver's side.
- Temperatures in the wheel well and along the axles were sufficiently high so as to have the potential to ignite or damage any combustible materials underneath the motorcoach, but the floor and interior areas near the fire were protected by stainless steel sheet metal and a layer of insulation. Additional penetration points could occur from local degradation of less protected areas, but this was not observed for the conditions experienced in these tests with the design of this particular motorcoach.
- There was a wide range of timing for window penetration as demonstrated by the first tag axle experiment which experienced penetration in less than 5 min and the tenability tag axle experiment which experienced penetration in over 11 min. It is not known why the penetration times are different. Possible reasons include: variation in the wheel burner heating which could have caused different initial fire conditions for the two tire fires, variation in window strength and performance, and natural variation in how the plumes interacted with the windows.

Fire-hardening Experiments

Based on this specific motorcoach, the conditions of these particular experiments, and the particular protective designs which were attempted, the following are the findings and the conclusions which can be drawn:

- Of the three fire-hardening methods examined here, two (replacing exterior combustible components with metal or coating existing combustible panels with intumescent materials) appear to be effective approaches to improving fire safety for wheel-well fires.
- Replacing the combustible exterior side components directly over the tires with sheet metal was the most effective design for preventing the tire fire from penetrating through the windows. For the conditions tested here, it prevented penetration, but materials behind the replacement panels approached temperatures which may have led to interior ignition and flame spread. Fire penetration was delayed approximately 30 min before the test was terminated compared to the tag axle experiments without fire-hardening.
- The intumescent coating on the combustible exterior side components near the tires was the second most effective design for preventing the tire fire from penetrating through the windows. Fire penetration did occur, but it was delayed approximately 20 min compared to the tag axle experiments without fire-hardening.
- A steel deflector shield had an indeterminate effectiveness on preventing the tire fire from penetrating through the windows. The penetration time was 5 min longer than one tag axle experiment, but was 1.5 min shorter than that for the tenability tag axle experiment. Larger deflector designs that push the fire plume further from the windows could be more effective, but could create other issues related to practical implementation.
- The ABS sensor as deployed for these experiments did not respond to heating from the adjacent wheel and hub metal consistently or sufficiently to provide an effective signal of an approaching or occurring tire fire; however, a simple temperature measurement device such as a thermocouple located near the wheel could provide early warning of adverse heating in the vicinity well before tire ignition temperatures are reached.

Tenability Experiment

Based on this specific motorcoach, the design of its extension, the open door and fuel loading configurations, and the conditions of these particular experiments, the following are the findings and the conclusions which can be drawn:

- Thermally untenable conditions were reached at both the rear and middle measurement stations of the motorcoach by about 8 min after fire penetration with local areas in the rear near the seats untenable in less than 6 min after fire penetration. The front of the motorcoach became thermally untenable by about 11 min.
- Assuming smoke layer uniformity, carbon monoxide and hydrogen cyanide combined to make conditions untenable throughout the motorcoach just over 11 min after fire penetration.
- Assuming smoke layer uniformity, hydrogen chloride caused untenable conditions in the rear of the motorcoach at just under 9 min after fire penetration.
- Oxygen vitiation caused untenable conditions throughout the motorcoach by 11 min 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.
- Visibility conditions (evaluated 1.5 m from the floor) deteriorated significantly prior to fire penetration of the motorcoach. Within 30 s 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 fuel loading

to cause flashover (bring to 600 °C and 20 kW/m2) in the rear half of the passenger compartment in less than 11 min after fire penetration.
- Untenable conditions for this experiment were attained with a limited fuel loading suggesting that the conditions and timing observed in this experiment were not the most conservative.

ACKNOWLEDGEMENTS

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Disclaimer: Certain trade names or company products are mentioned in the text to specify adequately the experimental procedure and equipment used. In no case does such identification imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the equipment is the best available for the purpose.

REFERENCES

1. National Transportation Safety Board, “Motorcoach fire on Interstate 45 during Hurricane Rita evacuation near Wilmer, Texas, September 23, 2005”, NTSB/HAR-07/01, NTSB, Washington, DC, February 21, 2007.
2. Meltzer, N., Ayres, G., and Truong, M., “Motorcoach Fire Safety Analysis”, Volpe National Transportation Systems Center for Federal Motor Carrier Safety Administration, Cambridge, MA, July 2009.
3. Johnsson, E. and Yang, J., “Motorcoach Flammability Project Final Report: Tire Fires - Passenger Compartment Penetration, Tenability, Mitigation, and Material Performance”, NIST Technical Note 1705, National Institute of Standards & Technology, Gaithersburg, MD, July 2011.
4. Hammarström, R., Axelsson, J., Försth, M., Johansson, P., and Sundström, B., “Bus Fire Safety”, SP Report 2008:41, SP Technical Research Institute of Sweden, 2008.
5. 49 CFR Part 571.302, Federal Motor Vehicle Safety Standards, Standard No. 302, “Flammability of Interior Materials”, National Highway Traffic Safety Administration, U.S. Department of Transportation.
6. United Nationals Economic Commission for Europe (ECE), Regulation No. 118, “Uniform Technical Descriptions Concerning the Burning Behaviour of Materials Used in the Interior Construction of Certain Categories of Motor Vehicles”.
7. 14 CFR Part 25.853, “Compartment Interiors”, Federal Aviation Administration, U.S. Department of Transportation.
8. 49 CFR Part 238.103, “Passenger Equipment Safety Standards, Fire Safety”, Federal Railroad Administration, U.S. Department of Transportation.
9. ASTM Standard D3675 - 09, “Standard Test Method for Surface Flammability of Flexible Cellular Materials Using a Radiant Heat Energy Source”, ASTM International, West Conshohocken, PA.
10. ASTM Standard E662 – 09, “Standard Test Method for Specific Optical Density of Smoke Generated by Solid Materials”, ASTM International, West Conshohocken, PA.
11. ASTM Standard E162 – 09, “Standard Test Method for Surface Flammability of Materials Using a Radiant Heat Energy Source”, ASTM International, West Conshohocken, PA.
12. ASTM Standard E648 - 09a, “Standard Test Method for Critical Radiant Flux of Floor-Covering Systems Using a Radiant Heat Energy Source”, ASTM International, West Conshohocken, PA.
13. McGrattan, K. and Forney, G., “Fire Dynamics Simulator (Version 4), User’s Guide”, NIST Special Publication 1019, U.S. Department of Commerce, Washington, DC, July 2004.
14. ISO 13571:2007, “Life-Threatening Components of Fire – Guidelines for the Estimation of Time Available for Escape using Fire Data”, International Organization of Standardization, Geneva, Switzerland.