Experimental Study on Tire Fire Penetration into a Motorcoach Passenger Compartment[1]

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ABSTRACT

Two full-scale fire experiments were conducted to determine the mode of penetration of a tire fire into the passenger compartment of a motorcoach. A special burner was designed to imitate the frictional heating of hub and wheel metal caused by failed axle bearings, locked brakes, or dragged blown tires. For the first experiment, heating to obtain tire ignition was initiated on the exterior of the passenger side tag axle wheel and for the second, on the exterior of the passenger side drive axle wheel. Measurements of interior and exterior temperatures, interior heat flux, and heat release rate were performed. Standard and infrared videos and still photographs were recorded. Both 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.

KEYWORDS: Transportation fires, fire growth, flame spread, vehicle fires, bus fires, tire fires, fire penetration

INTRODUCTION

Research of vehicle fires is important for the prevention of life and property losses. While death by fire in a burning vehicle is a tragedy, fires in vehicles such as motorcoaches which carry as many as 56 passengers are especially tragic as they impact whole communities, regions, or a nation. One such fire occurred during the evacuation of Gulf Coast residents from Hurricane Rita in 2005. On September 23, 2005, near Wilmer, TX, a motorcoach carrying nursing home residents experienced a failed right bearing on the tag axle resulting in a tire fire which spread to consume the motorcoach. Twenty-three occupants died because many passengers were not mobile and could not escape the motorcoach before being overcome by smoke and flames.[1] Even when there are no fatalities in motorcoach or bus fires, complete loss of the coach and passenger property is typical.[2]

The National Highway Traffic Safety Administration (NHTSA) has sponsored 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]

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The research described here is to establish an understanding of the development of a motorcoach fire and its subsequent spread into the passenger compartment. Whereas motorcoach fires may result from electrical system shorts, engine compartment leaks, component overheating, or tire fires, this research was focused on the penetration of motorcoach tire fires into the passenger compartment. The causes of tire fires (failed axle bearings, locked brakes, or dragged blown tires) are common to all makes and models of motorcoaches.[2]

There is a small body of previous research related to motorcoach fires and tire fires at the Scandinavian research institutes. Hansen at the Norwegian Fire Research Laboratory (SINTEF NBL) focused on tire fire experiments as related to vehicles in general, but not buses in particular. [3] Hammarström et al. at SP Technical Research Institute of Sweden (SP) studied major fire causes in buses.[4] A more recent, follow-up paper from SP provided an overview of the entire bus fire problem and included the results of full-scale bus experiments.[5]

EXPERIMENTAL SET-UP

The motorcoach used for these experiments was the same model as the one which burned near Wilmer, TX, during the Hurricane Rita evacuation. This model has a capacity of 55 passengers, includes a lavatory, has a mass of approximately 17 000 kg (38 000 lb) empty, and has a 13.92 m (45.7 ft) length, 2.59 m (8.5 ft) width, and 3.59 m (11.77 ft) height. Initially, the motorcoach was employed in a front-end crash test at the U.S. Department of Transportation Vehicle Research and Test Center in Ohio. Damage to the rear half of the motorcoach was minor and expected to have negligible effect on the tire fire experiments. A specialist at cutting motorcoaches was brought in to cut the motorcoach approximately in half using multiple types of saws. Undamaged or intact components from the crashed front of the motorcoach, such as exterior glass reinforced plastic (GRP) panels, windows, seats, luggage racks, and trim panels, were salvaged and secured in the rear of the motorcoach. The motorcoach was transported to the National Fire Research Laboratory at the NIST campus in Maryland. Figure 1 is a drawing which shows the rear half of the motorcoach with labels and dimensions of the most important components. Expanded uncertainties on the measured dimensions are estimated to be ± 3 mm. The width of the interior floor (not shown) was 2.44 m.

Once the test section was safely transported to the designated anchoring area underneath the hood, it was secured with the undercarriage approximately 30 cm above the floor (above protective gypsum panels) on wooden cribbing [multiple 15 cm (6 in) by 15 cm (6 in) timber beams and smaller pieces of wood]. The lifting and securing was accomplished with jacks and jack stands.

During the crash test, the roof was pushed backward between 7 cm and 10 cm. The window posts were angled back with the tops behind the bottoms which created non-rectangular window openings preventing window closure. To straighten the posts and maintain the latching mechanisms in the centers of the window openings, the tops of the posts were cut completely and the bottoms were notched on 3 sides to enable the top to be bent towards the front. In the new vertical positions, the posts were reattached to the roof with self tapping screws.

Safety being paramount, motorcoach components that might prove dangerous during the fire experiments were removed or made safe. The tires were deflated and then cut so they could not burst under pressure. The coach was supported by the cribbing under the frame and axles and not by the tires during testing. The batteries and the fuel tank were removed. Pressurized air and nitrogen tanks for the pneumatic and other systems were removed or punctured. Coolant, transmission, hydraulic, and brake fluids were drained from their systems.

For the second experiment, fire damaged parts of the motorcoach were replaced. Wheels [aluminum, 57 cm (22.5 in) diameter by 23 cm (9.00 in) wide], tires (315/80R22.5), and long side windows were replaced with non-fire-exposed replacements. The exterior side panel was replaced with the front right portion salvaged from the front of the motorcoach. A new short right side window, fender, and fender trim were purchased from the manufacturer. Installation of the fender and exterior panel generally followed the maintenance manual for the motorcoach and utilized some off-the-shelf comparable sealants and fasteners.

A special burner was designed and built that would direct 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 from hot metal, which qualitatively simulates the frictional heat generated from failed axle bearings, locked brakes, and dragged blown tires.

The design of the burner was a circular 25 mm outer diameter stainless steel (type 304) tube with 10 high output heating torch nozzles attached perpendicular to the plane of the circular tube. Figure 2 shows a schematic of this design. 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. Flame arresting torch tips were used. The burner was designed with the requirement of a heat output between 50 kW and 100 kW based on a calculation using an estimate of the total mass of the wheel and associated metal and a target heating duration between 30 min and 1 h.

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, 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 2 includes a photograph of the burner and shield.

Measurements of heat release rate, heat fluxes, and interior and exterior temperatures were recorded for each experiment. The types of measurements and locations are described below, and more detail is available in the full report.[6] A data acquisition system (DAQ), described in [7], was used to record 151 channels of sensor output voltages every second. Each voltage was the average of 200 readings scanned each second. This DAQ was separate from that used for the calorimetry system described below.

The total heat release rates (HRR) were measured using oxygen depletion calorimetry. Details of the constituent measurements and calculations can be found in [7]. The experiments were performed under the NIST National Fire Research Laboratory (NFRL) 9 m by 12 m hood. Calibrations of the hood up to 8 MW are performed with metered natural gas fires. The calorimeter combined expanded uncertainty for natural gas was about ± 7.6 % based on a natural gas calibration burner test performed two weeks before the motorcoach experiments. That uncertainty was calculated over the whole range of the calorimeter's operation. Uncertainties in a narrow range, for example around 1 MW as for these fires, can be much lower. Since the motorcoach experiments involved an unknown mixture of fuels, the expanded uncertainty increases by 5 % (in quadrature) to 9.1 %. The increased uncertainty is from an empirical constant for heat released per mole of oxygen consumed for a range of hydrocarbon fuels.[8]

Measurements regarding the flow of natural gas to the burner were recorded with the DAQ of the calorimeter for an accurate and independent calculation of ideal (assumed 100 % efficient) HRR solely related to the burner. The burner HRR expanded uncertainty was calculated to be ± 2.5 % for the 60 kW level at which it operated for these experiments.

Temperatures were measured on and around the wheels and tires, along the exterior panel and windows, and inside the motorcoach along the windows and on the floor. K-type thermocouples (TCs) were used throughout. For locations where flames were expected such as near the heated wheels and over the exterior panel and windows, special ceramic fiber insulation was used while the rest had a fiberglass braid. The numbers of temperature measurements at specific locations are listed in Table 1. Thermocouples were attached to the floor with staples, and the beads were bent to touch the surface. Wheel TCs were secured with screws and washers and tire TCs were held in place with screws. The main purposes of the temperature measurements were to monitor progress of the tires toward ignition and identify relatively hotter locations generated by the tire fire in and around the motorcoach.

The uncertainties associated with the gas and surface temperature measurements away from the fire were approximately ± 2 °C.[7] For thermocouples impinged by fire, the gas temperatures recorded may be as much as 10 % (90 °C) low for a 600 °C reading and 20 % (220 °C) low for a 850 °C reading.[9] These offsets are due to radiative heat losses from the thermocouple beads to the relatively cold surroundings. Uncertainties of surface temperatures for thermocouples exposed to fire were estimated to be approximately ± 10 °C.

The exterior window and panel thermocouples were spaced 38 cm apart (vertically and horizontally) in 12 columns of 4 rows each for a total of 48 measurements. Three of the rows were over the glass while the bottom row was over the panel. Thermocouples were placed about 1 cm from the window surface.

For the interior thermocouples near the windows, the spacing was generally the same as the exterior, and over the window area, both interior and exterior thermocouples were aligned on the same grid. The interior grid of thermocouples was shifted upward by one row so that the bottom row was over glass, and the top row was above the window in the space below the parcel rack. That top interior row was spaced only 17 cm above the top window row as the only exception to the 38 cm spacing. As on the exterior, the distance of the thermocouples from the glass was about 1 cm.

The approximate locations of interior floor thermocouples are depicted in Figure 3. The diagram differentiates those near the wall under the windows, those along the lavatory wall and door, and those under the floor in the central tunnel. The locations are further described in Table 1.

Heat fluxes were measured in 5 locations to help indicate the transfer of heat from the fire through the windows or floor. These measurements also provided insight as to when interior heat fluxes would have threatened to ignite materials if they had been present. Table 2 lists the locations and directions of the gauges, and Figure 3 is a diagram depicting the top view of the motorcoach and the approximate locations and directions of the gauges. The heat flux gauges were water-cooled, Schmidt-Boelter type, which measured total heat flux, including both radiation and convection.

Seven standard and two infrared (IR) video recordings were made around and inside the motorcoach. The IR cameras were used to determine if penetration of the fire into the passenger compartment could be better observed using infrared imaging. The positions of all of the cameras are shown in Figure 4. Two of the standard video cameras were high resolution versions. One was located at a position facing the tire fire from the side of the motorcoach, and the other was directed at the interior from a position several meters in front of the motorcoach's cut end. The video camera facing the tire fire from the side was paired with an infrared (IR) camera. Two other IR video cameras were mounted together on a ladder at the front end and trained on the interior, but one of these IR cameras was set to normal mode to provide contrast to the IR images. The remaining four video cameras were located closer to the motorcoach. These cameras were "bullet" type, low cost cameras for which damage from the fire was allowable. Multiple roaming cameras were also used for digital still photography.

Two full-scale fire experiments were performed. Each experiment was ignited by heating a different wheel. The first started on the passenger side (right side when facing forward) tag (rearmost, also called dead or lazy) axle, which only had one wheel and tire per side. The second experiment started on the passenger side drive axle (in front of the tag axle), which had two wheels and tires per side.

EXPERIMENTAL RESULTS

Numerous plots of experimental data and more discussion of results are available in the full report.[6]

Both experiments initiated on each axle showed penetration of the fire into the passenger compartment through the long window between the axles. Table 3 lists the duration of the main periods of interest in these experiments: the period of heating before the tire was burning steadily, and the period between heating and penetration of the fire into the passenger compartment.

Sustained or established burning for the tag axle wheel fire was defined as continuous (versus intermittent) burning of the tire rubber at one or more locations in the bottom half of the tire (away from the top which received additional heat from buoyant convection). Sustained burning for the drive axle wheel fire was more difficult to determine since the flames were between the dual tires and mostly obscured. A consistent, non-intermittent flame plume proceeding from between the tires was considered sustained or sufficiently established burning for that experiment. Figure 5 shows the appearance of the drive axle tire about 30 s after sustained burning was declared.

The periods of heating before sustained burning were quite different for each experiment with the experiment initiated on the tag axle wheel requiring about 15 min more than the one initiated on the drive axle wheel. The likely reason for this is that the tag axle wheel had more conduits for heat loss than the drive axle wheel. The outside of the tag axle wheel was convex and exposed to ambient air, while the outside of the drive axle wheel was concave and recessed (see Figure 5). This allowed the drive axle wheel to trap more heat than the tag axle wheel. The heat from the burner that did not go into the tag axle wheel would be convected along the bottom of the shield and away, but for the drive axle wheel would heat the upper portion of the wheel first before reaching the shield. Also, while the back of the tag axle wheel could radiate and convect heat away, the drive axle wheel was connected to the second inner wheel, promoting overall heating of the dual tire system and blocking convective cooling on the backside of the outer wheel and tire. The rubber of the tires acts as an insulator as well, trapping heat between the tires and near their surfaces.

The period between heating and compartment penetration was about 1.5 min shorter for the tag axle experiment than for the drive axle experiment. While the time periods are both short and their difference could be due to random variation, there are some factors that could explain the distinction. The tag axle tire started burning on the outside and had access to air for more complete and hotter combustion. The drive axle tires started burning at the surfaces between the inner and outer tire, away from the outer surface of the outer tire. The narrow region between tires limited the flow of air and decreased the rate of growth. Also, the fire between the drive axle tires had to grow sufficiently to send a plume horizontally to spread outward and then upward onto the combustible GRP fender and exterior panel. This extra path for fire spread took longer (363 s) than for the more direct path of the tag axle (280 s) up to the fender and panel. Figure 6 shows the large fire plumes resulting from the burning tires, fender, and exterior panel during the drive axle experiment.

Penetration was defined as fire entering the motorcoach by some path such as a hole created by the fire or evidence of flame spread into the interior due to the tire fire. In these experiments, both tire fires resulted in compartment penetration by breaking through the windows. If the floor had been the pathway of fire spread, observation of a sustained and growing fire in a region of the floor heated by the tire fire would have been required, but not necessarily a hole in the floor as occurred with the windows.

While breaking the windows was the path by which the fire penetrated into the passenger compartment, the windows did not break easily. The window design was two glass layers with a clear laminate layer between them. The inner glass was a safety type which shattered, and the outer was not. It is noteworthy that the glazing layers often broke independently from each other with the fire impinging on the outside. For the drive axle experiment, glass layers would sometimes fall in or out, but it took about 2 min from cracking of glass to the time that layers started falling away and another minute for any areas to have both layers break off, creating a hole and path for fire entry. Some of the pieces of glass with burning laminate fell inside and burned on the floor, but this was not considered fire penetration although it is possible that the burning material could have ignited seat cushions if they had been installed. Also, material between the frontmost window and post 3 was burning during the second test but was not considered fire penetration. Figure 7 shows the view of the windows from the interior at the time of fire penetration for the tag axle experiment. The locations of the heat flux gauges and interior bullet camera are also shown.

The peak heat release rates were 1180 kW and 1480 kW for the first and second tests, respectively, with ± 9 % uncertainty. Figure 8 shows plots of the HRRs versus time for each experiment. The rates of increase of each fire were between 300 kW/min and 400 kW/min during the final 2 min of each test before water and foam were applied with a commercial portable foam system. During extinguishment, most of the flames for each experiment were doused in less than 10 s. The natural gas burner HRR was calculated using measurements of the gas flow, temperature, and pressure and a chemical analysis of the natural gas. The calculated average values were 61.7 kW for the first test and 60.3 kW for the second with uncertainties estimated at ± 2.5 %.[7]

For the first test, the total heat released by the burner and motorcoach materials was 323 MJ, which consisted of 138 MJ (43 %) from the burner and 185 MJ (57 %) from the bus materials. For the second test, the total heat released by the burner and motorcoach materials was 341 MJ, which consisted of 77 MJ (32 %) from the burner and 264 MJ (77 %) from the bus materials. The total heat released during each test was similar, but the drive axle test required much less heating (56 %) for the reasons described in the previous section on event timing. During the drive axle experiment (test 2), 43 % more bus material was burned than in the tag axle experiment (test 1). The drive axle tire fire actually spread to the tag axle tire causing two plumes to merge and involving more of the exterior panel than the single plume from the tag axle test. Also, the tires and exterior panels burned longer before penetration during the drive axle test.

For the heated tag axle wheel experiment, the wheel temperatures led the tire temperatures by about 40 °C. Some intermittent ignition of the tire was occurring at 1860 s. By that point, the tire temperatures at the top and bottom positions had exceeded 360 °C. At that same time, the maximum wheel temperatures had just surpassed 400 °C. For the heated drive axle wheel experiment, the wheel temperatures led the tire temperatures by 100 °C to 150 °C. This is easily explained by the fact that the tire temperatures were measured on the outside interface between the tire and wheel rim, but wheel thermocouples were located on the inside surface of the wheel between the outer and inner wheels. Also, the heat from the burner was focused at the inside surface of the wheel which preferentially heated up the inside parts of the tire as well. At the time when flames were seen rising between the tires, the wheel temperatures all exceeded 420 °C. Because a lot of smoke was visible and some wheel temperatures exceeded 400 °C about 7 min prior to visible flames, it's likely that a smoldering or small flaming fire existed between the tires well before flames were seen.

The heated tag axle wheel experiment produced the highest wheel-well gas temperatures (850 °C) directly over the rear tire and the second highest temperatures (650 °C) directly behind and between the tag and drive axle tires. For the heated drive axle wheel experiment, all but the frontmost temperature exceeded (900 °C). Far (driver's) side wheel-well temperatures were rising, but were below 300 °C at the time of penetration. For the minute prior to penetration, the far-side wheel-well temperatures were rising at about 20 °C/min for the tag axle test and between 40 °C/min and 60 °C/min for the drive axle test.

Before penetration for both experiments where the fire plume was located, the temperatures along the exterior panel and just below the windows ranged from 600 °C to 850 °C. The temperatures in the plume along the windows at the top ranged from 400 °C to 800 °C.

For the lowest interior thermocouples located about 3 cm from the bottom of the windows, the temperature near the penetration site during test 1 approached 200 °C for about 30 s and briefly exceeded 600 °C at penetration while the other interior temperatures remained below 100 °C. This indicates that the windows acted as fairly successful thermal barriers until actual penetration. For test 2, the temperature near the penetration site rose steadily to 200 °C for the 3 min prior to penetration and then quickly exceeded 500 °C in the last 20 s. Again, except when breakthrough occurred, the temperatures remained relatively low. Further examination of the interior temperatures near the windows showed a rapid degradation of the windows in the 30 s prior to penetration, when temperatures inside the window increase dramatically.

Floor, lavatory floor, and central-tunnel temperatures were measured because the path of the fire penetration into the passenger compartment was unknown and the floor was deemed to have a significant possibility of being that path. The central tunnel runs under the central aisle and contains tubing and wiring harnesses. Refer to Table 1 and Figure 3 to review locations of these measurements. All of the temperatures of thermocouples along the floor by the passenger side wall show barely any impact from the nearby fire and remain near the ambient starting temperatures. This revealed that the floor structure for this particular motorcoach was insulated from the tire fire's heat. Inspection of the floor design showed between 15 cm and 20 cm of fiberglass thermal insulation under the floor in the vicinity of the fire. Just before test 2 penetration, there was a sharp rise of the temperature midway between the tires, but it was only a rise of about 15 °C and may be related to some piece of glass with burning laminate attached or debris that fell from the window. The lavatory floor temperatures only rose about 1 °C during each test. The floor area near the lavatory is similarly protected as the wall/floor areas from heating from below.

The central-tunnel temperature measurements showed some heating behavior. The test 1 front position rose 7 °C, but the change occurred after penetration and extinguishment. The test 2 front position rose over 25 °C prior to penetration and the center position rose about 15 °C after penetration. The small temperature increase for any of these positions indicates that the central tunnel under the center of the floor was protected sufficiently for this particular motorcoach to not be a likely pathway for passenger compartment penetration in the *early* stages of a tire fire.

Possible spread of fire along the axles and upward through the floor or to the far-side tires and panels was a concern that prompted monitoring of this region. Plots of the axle temperatures are shown in Figure 9. For the tag axle wheel heating test, both of the passenger side thermocouples over each axle showed significant heating with the tag axle at a maximum temperature of 700 °C and the drive axle maximum at 450 °C. It is surprising that the tag axle passenger side temperature reached its maximum over 2 min prior to penetration and then dropped down to 350 °C. For test 1, the center and driver's side axle temperatures barely exceeded 100 °C before penetration which indicates that along the axle to the far side was not a significant pathway for fire spread.

The drive axle passenger side and center thermocouples rose to 950 °C and 550 °C, respectively. Even the drive axle driver's side thermocouple rose to 300 °C before penetration which is significant in that temperatures over 400 °C generally will ignite combustible materials such as the tire and GRP panels. While passenger side and center position axle temperatures greater than 550 °C were significant for causing ignition of nearby combustible materials, the interior floor and central-tunnel temperatures showed very little thermal penetration. The far position rose past 300 °C at about 50 °C/min, but it is unknown whether this rate would have continued and whether combustible materials would have eventually ignited if the fire were allowed to continue.

Table 2 lists the locations and orientations of the heat flux gauges corresponding to the following results. Figure 10 shows plots of the seat gauge total heat flux for each experiment. For test 1 (tag axle wheel heating), only the seat position heat flux rose significantly to about 1.5 kW/m^2 before penetration. After penetration, despite extinguishment activities, the heat flux increased to about 4 kW/m^2. The other fluxes in test 1 remained below 0.4 kW/m^2 before penetration.

For test 2 (drive axle wheel heating), the seat position heat flux rose to about 3 kW/m^2 before penetration and the front side-facing gauge rose to 1.5 kW/m^2. The other fluxes remained below 0.5 kW/m^2.

The heat flux required for piloted ignition of materials such as fabric covered seat cushions is typically greater than 6 kW/m^2.[10] The situation in these experiments was unpiloted which requires much greater heat flux for ignition so the thermal radiation through the windows was not nearly enough to ignite combustible materials inside. At the stages of growth of the tire/motorcoach fires upon window penetration, the heat fluxes were not sufficient alone to ignite the seat material before or after the window breakage. Without extinguishment, additional glass breakage/removal and further fire growth would allow greater heat fluxes on the interior materials as well as direct impingement of hot gases and flames leading to ignition by thermal radiation alone or piloted.

SUMMARY OF FINDINGS AND CONCLUSIONS

Two full-scale motorcoach tire fire experiments were conducted to investigate the mode by which tire fires penetrate the passenger compartment. A novel burner was designed to simulate frictional heating by failed axle bearings, locked brakes, or dragged blown tires with localized heating of wheel metal without substantially preheating the tire rubber. Temperatures and heat fluxes were recorded along with video and still images. 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 resulting glass breakage. This finding is in contrast with research conducted by SP [5] (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 materials 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 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 window penetration. 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 with 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 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.

- The relatively easy extinguishment of these tire fires (less than 15 s) with foam and water suggests that these tire fires, while established, were not yet fully involved (when all tire rubber in contact with the wheel is burning simultaneously).[11] If heating of wheel metal was substantially greater for an actual moving motorcoach than it was for these experiments, it is possible that a much larger initial fire would ensue involving the whole tire when the coach stopped rolling. A tire fire which was more fully involved initially than for these tests could have a different spreading behavior which could change the timing of window penetration.

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Table 1. Numbers of thermocouples (TC) and location descriptions.

General Location	**Specific Location**	**Number of TCs**
Wheels	Heated wheel on back side in a plus pattern, 0°, 90°, 180°, and 270° from top	4
Tires	Heated tire on front side between wheel rim and tire in plus pattern, 0°, 90°, 180°, and 270° from top	4
Wheel well	Rearmost corner of wheel well, over center of rear (tag axle) wheel, above center between wheels, over center of front (drive axle) wheel, and at frontmost corner of wheel well.	5
Above axles	Left, center, and right above each axle.	6
Outside windows and exterior panel	In a grid with 38 cm spacing consisting of 12 columns and 4 rows. Bottom row over exterior panel, other rows over windows.	48
Inside windows and in space above	In a grid with (generally) 38 cm spacing consisting of 12 columns and 4 rows. Bottom 3 rows over windows, top row in space above window 17 cm above top window row.	48
Interior floor	Along fire-side wall aligned with wheel--well TCs with extra 46 cm behind rearmost and 46 cm in front of frontmost	7
	Along outside and inside of lavatory wall joint with floor	3
	In central cable tunnel under center of floor aligned with the rear most, center, and frontmost interior TCs at the side wall.	3

Table 2. Heat flux gauge locations.

Gauge Label	Location Description	Location Details
HFRS	Rear position, facing horizontally toward windows	127.8 cm from floor, centerline of bus, centered over rear tire (tag axle)
HFFS	Front position, facing horizontally toward windows	130.9 cm from floor, centerline of bus, centered over front tire.
HFRD	Rear position, facing down toward floor	132.8 cm from floor, centerline of bus, centered over rear tire (tag axle)
HFFD	Front position, facing down toward floor	133.8 cm from floor, centerline of bus, centered over front tire.
HFSeat	At seat headrest position, facing horizontally toward windows	111.2 cm from floor, 14.9 cm from window, centered between tires which is 51.8 cm rearward of rear facing side of window post 3 above front (drive axle) tire.

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

Period	**Duration (s) (Combined Expanded Uncertainty = ± 3 s)**	
	Test 1 (Heated Tag Axle Wheel)	**Test 2 (Heated Drive Axle Wheel)**
Burner heating wheel to steady tire burning	2177	1255
Burner stopped to fire penetration of passenger compartment	280	363

LIST OF FIGURES

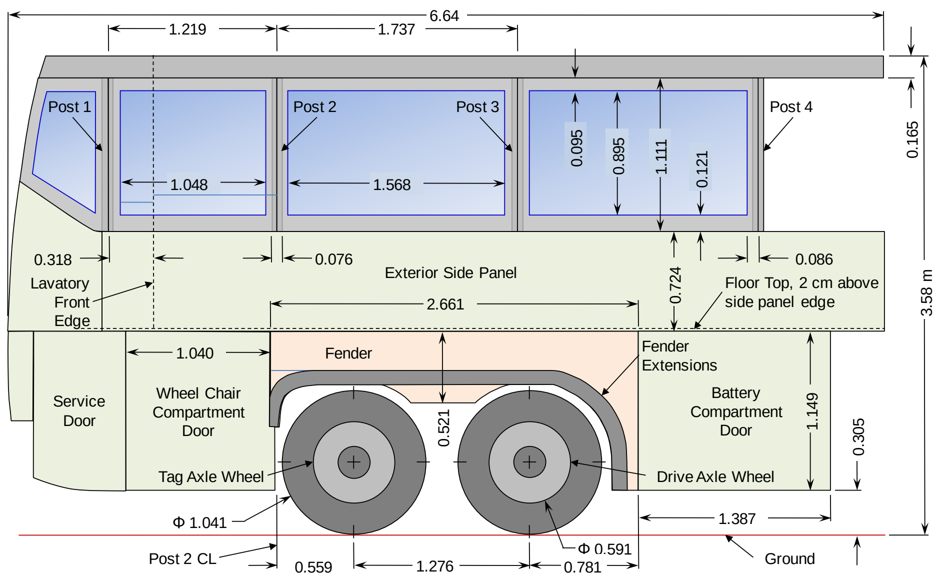


Figure 1. A drawing of the motorcoach rear half which was used for tire fire experiments. Dimensions are in meters.

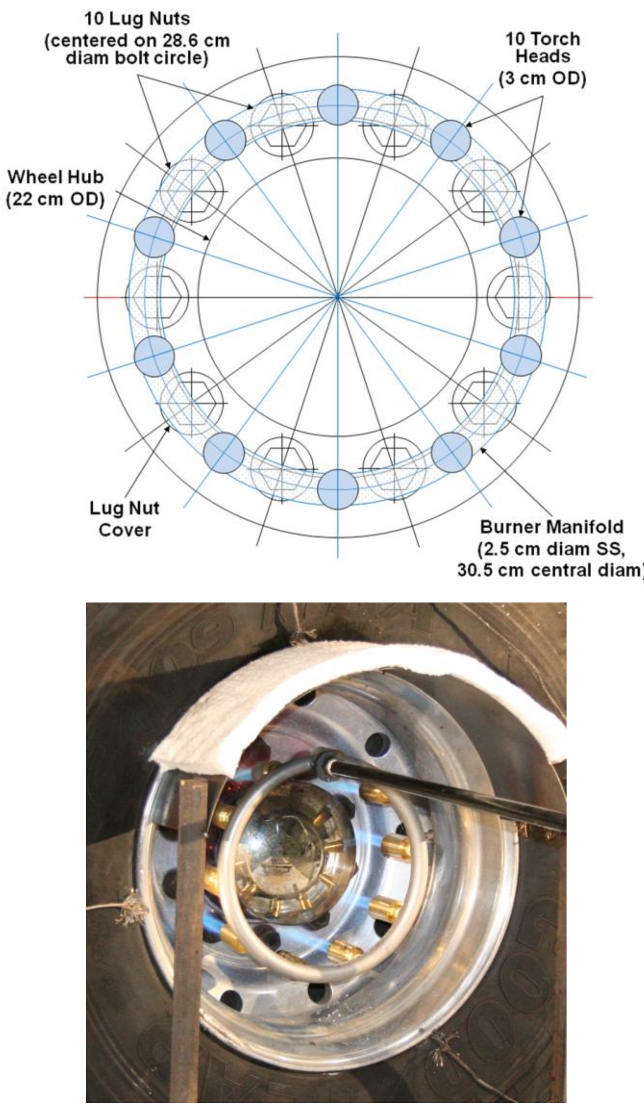


Figure 2. A schematic of the wheel burner design showing the relative locations of the torch heads and manifold compared to the wheel's hub, lug nuts, and lug nut covers (upper). The outer circle represents the wheel's curvature away from the lug nut surface plane. A photograph showing the tire shield nested inside a drive axle wheel rim with an insulating cover to minimize convective and radiative heating to the tire (lower).

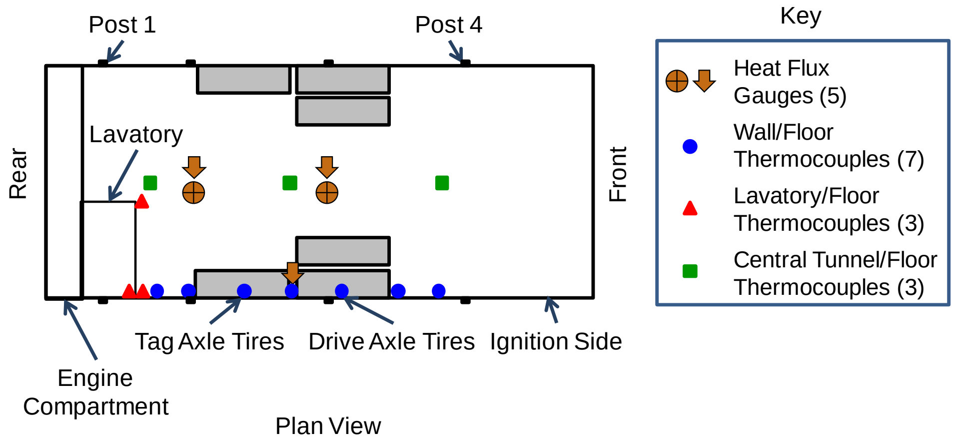


Figure 3. A diagram of the top view of the motorcoach showing approximate locations of interior floor thermocouples and the locations and directions of heat flux gauges.

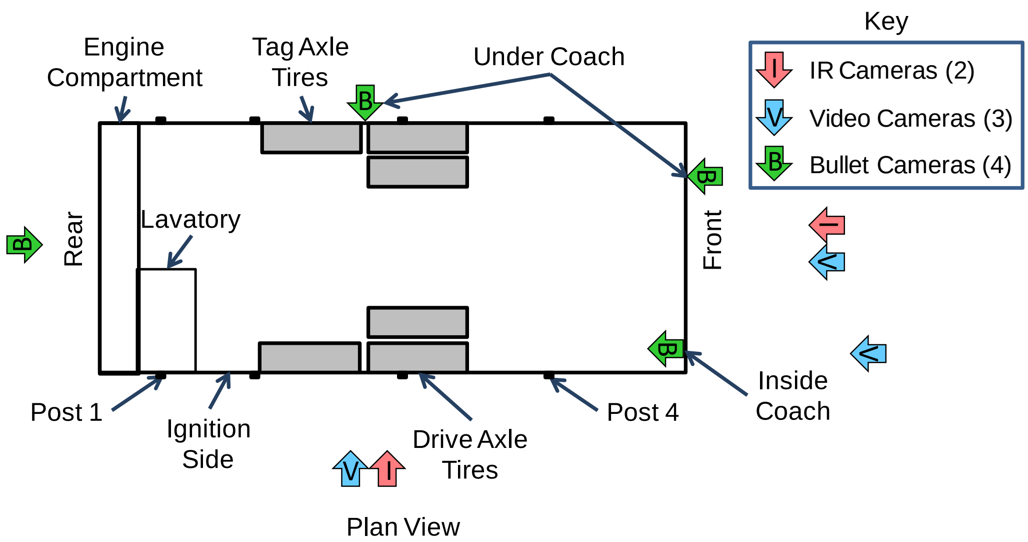


Figure 4. A diagram of the video camera layout showing their general locations and directions faced.

Figure 5. Drive axle wheel heating experiment about 30 s after burner was turned off.

Figure 6. Drive axle wheel heating experiment showing large fire plumes on each tire.

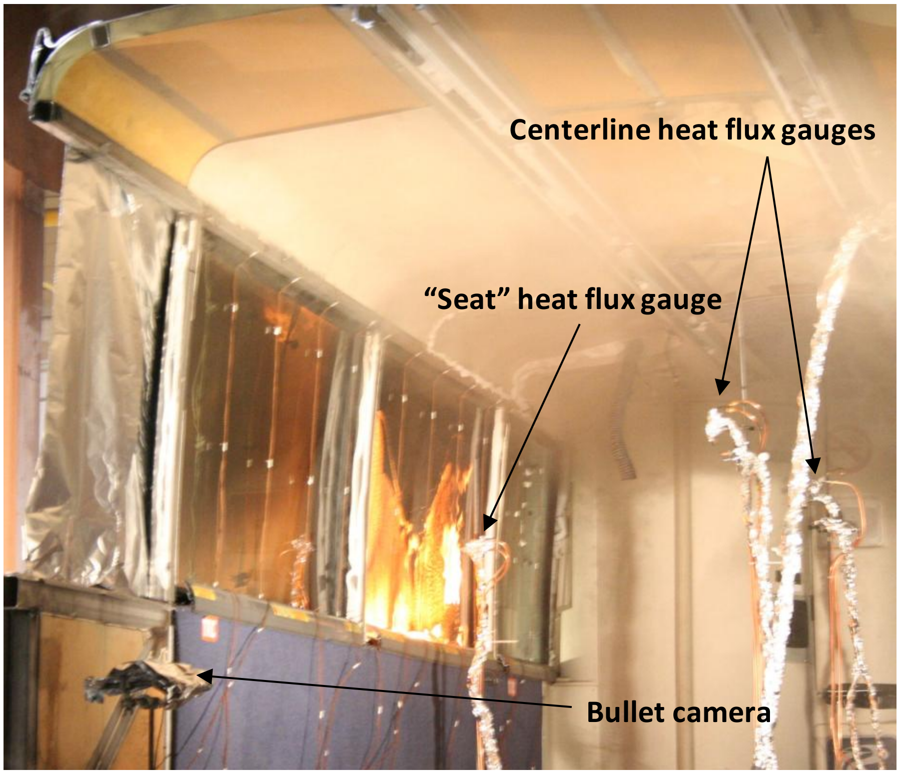
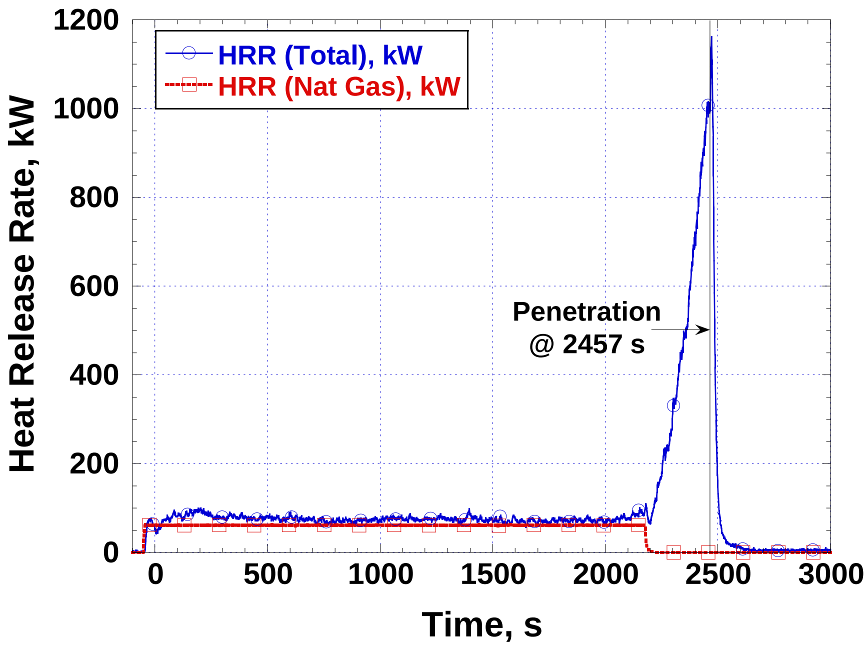


Figure 7. Tag axle wheel heating experiment at fire penetration.



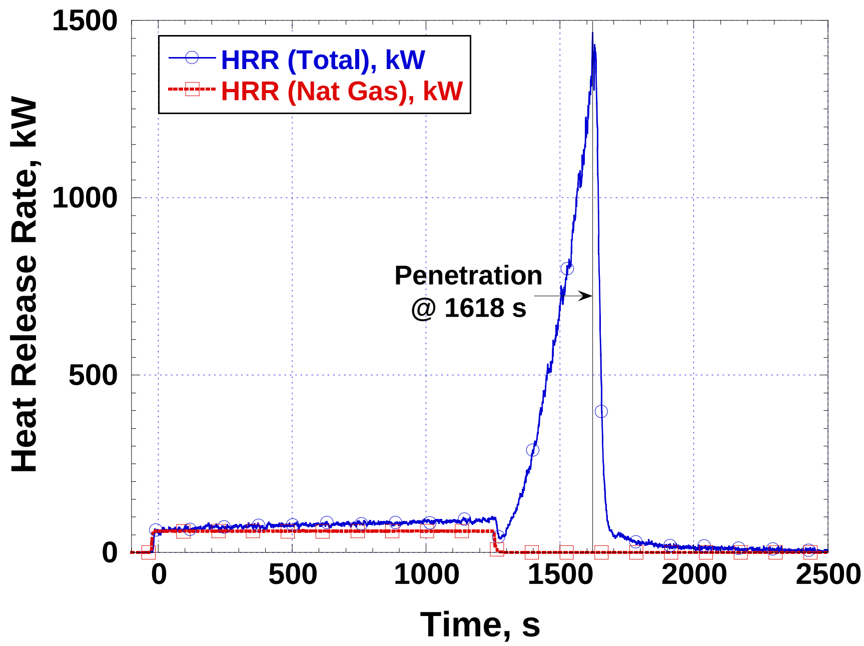
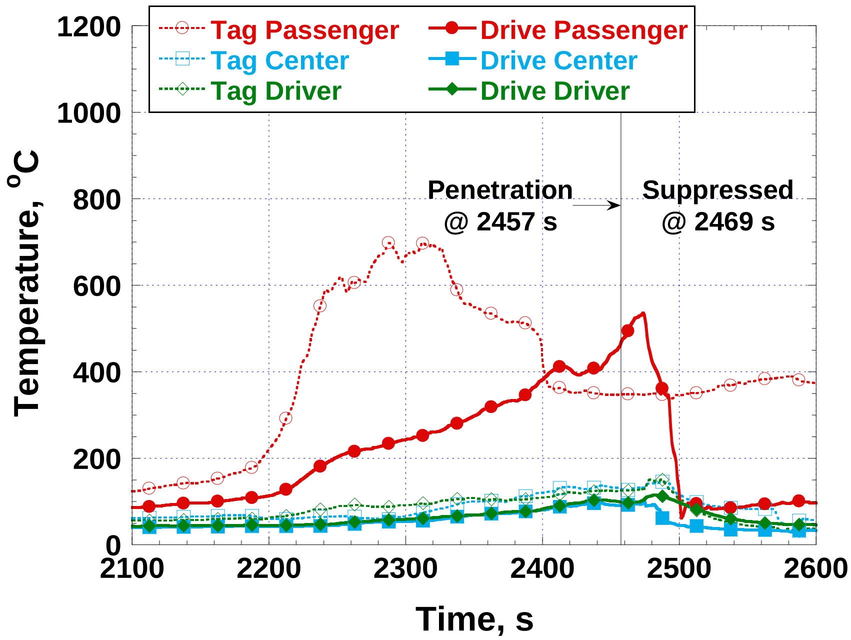


Figure 8. Heat release rate plotted versus time for test 1, the heated tag axle wheel experiment (upper), and test 2, the heated drive axle experiment (lower).



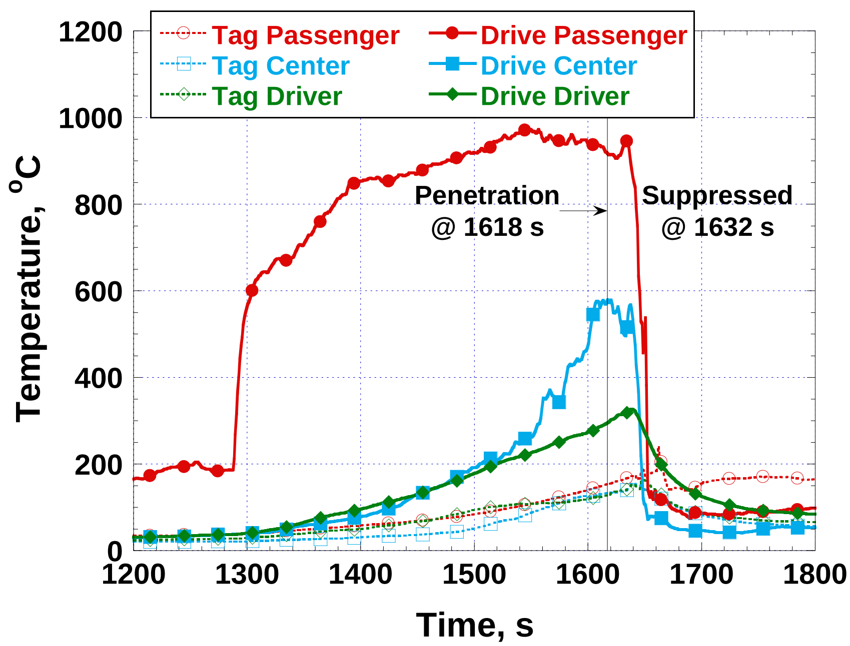


Figure 9. Plots of axle temperatures versus time for test 1 (tag axle) (upper) and test 2 (drive axle) (lower).

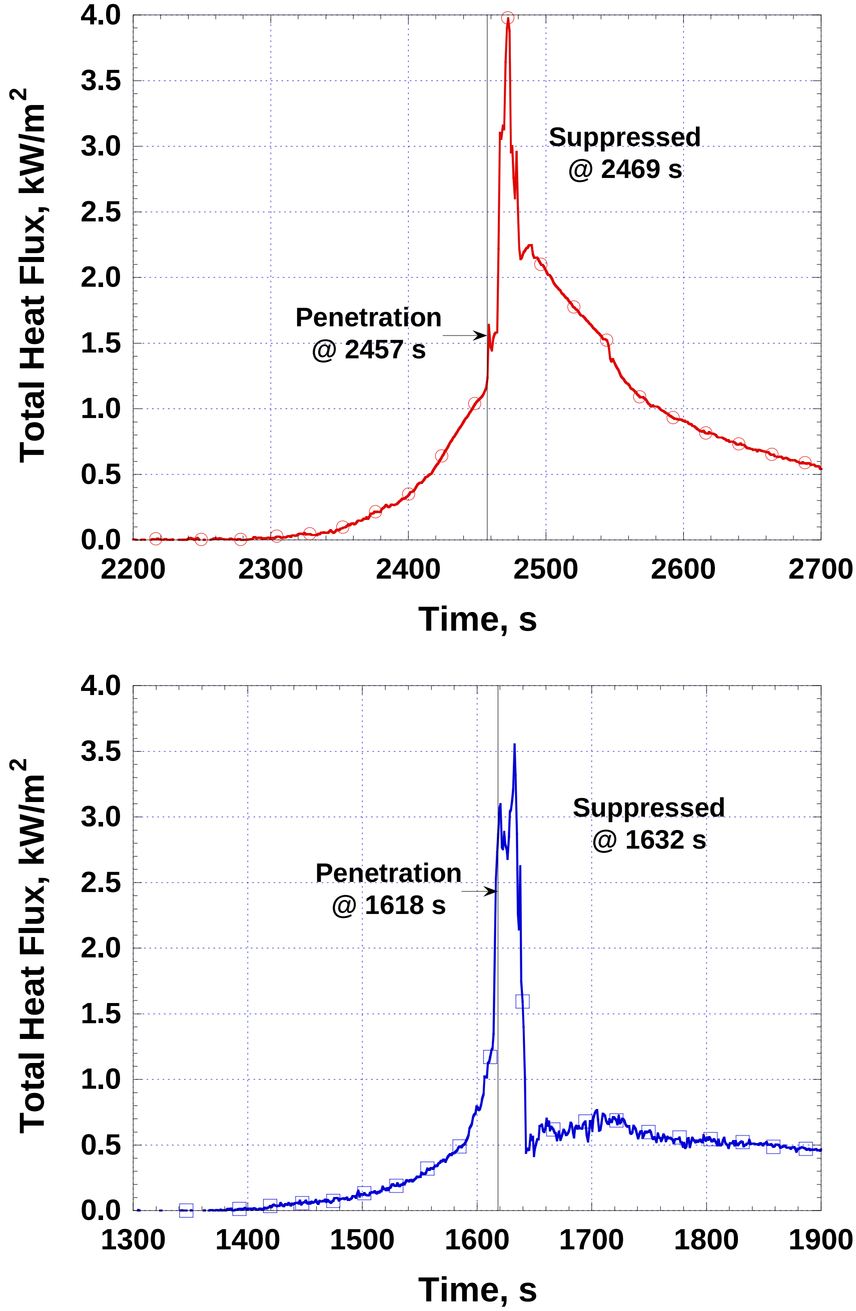


Figure 10. A plot of the seat total heat flux versus time for test 1 (tag axle) (upper) and test 2 (drive axle) (lower).