Fire Technology, 42, 273–281, 2006

DOI: 10.1007/s10694-006-7506-9

Numerical Simulation of the Howard Street Tunnel Fire

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Abstract. The paper presents numerical simulations of a fire in the Howard Street Tunnel, Baltimore, Maryland, following the derailment of a freight train in July, 2001. The model was validated for this application using temperature data collected during a series of fire experiments conducted in a decommissioned highway tunnel in West Virginia. The peak predicted temperatures within the Howard Street Tunnel were approximately 1,000°C (1,800°F) within the flaming regions, and approximately 500°C (900°F) averaged over a length of the tunnel equal to about four rail cars.

Key words: fire modeling, Howard Street Tunnel fire, tunnel fires

Introduction

On July 18, 2001, at 3:08 pm, a 60 car CSX freight train powered by 3 locomotives traveling through the Howard Street Tunnel in Baltimore, Maryland, derailed 11 cars. A fire started shortly after the derailment. The tunnel is 2,650 m (8,700 ft, 1.65 mi) long with a 0.8% upgrade in the section of the tunnel where the fire occurred. There is a single track within the tunnel. Its lower entrance (Camden portal) is near Orioles Park at Camden Yards; its upper entrance is at Mount Royal Station. The train was traveling towards the Mount Royal portal when it derailed. For almost its entire length the tunnel runs beneath Howard Street. The fire erupted under the intersection of Howard and Lombard Streets where a ruptured tank car (52nd out of 60 cars) spilled tripropylene onto the floor of the tunnel. It was unclear how the fire started, but it was speculated that a spark produced when the tank car was punctured could have been the cause. The liquid fuel sustained a fire that lasted several hours. Other materials burned slowly for several days within closed box cars. The other cars on the train were transporting a variety of bulk materials including pulp board, brick, steel, soy oil, paper, and a variety of corrosive acids.

Under the sponsorship of the US Nuclear Regulatory Commission (NRC), the Building and Fire Research Laboratory of the National Institute of Standards and Technology (NIST) undertook a study of the incident to assess the thermal environment within the tunnel during the fire. The National Transportation Safety Board (NTSB) conducted an investigation of the accident and provided NIST with information about the tunnel, the damage to the rail cars, and various other details [1]. Using this information, a series of numerical simulations were performed to predict the temperature of the hot gases and the heat flux to various objects within the tunnel. The results of these calculations were used in a subsequent analysis of the performance of nuclear waste transportation casks under conditions similar to those in the Howard Street Tunnel fire [2].

Technical Approach

In cooperation with the fire protection engineering community, a numerical fire model, Fire Dynamics Simulator (FDS), has been developed at NIST to study fire behavior and to evaluate the performance of fire protection systems in buildings [3]. The model is based on the low Mach number form of the Navier-Stokes equations and uses a large eddy simulation (LES) technique to represent unresolved, sub-grid scale motion. Fire is modeled by solving a transport equation for the conserved scalar quantity known as the mixture fraction, a linear combination of the fuel and oxygen that indicates the mass fraction of the gas originating as fuel. Thermal radiation is modeled by solving the radiative transport equation for a non-scattering gray gas using what is known as the Finite Volume Method.

To ensure that the numerical algorithm was appropriate for the tunnel fire simulations, several past tunnel fire experiments were simulated before work proceeded on the Howard Street Tunnel fire. A series of fire experiments was conducted in a decommissioned highway tunnel in West Virginia from 1993 to 1995 by the firm Parsons Brinckerhoff [4]. The tunnel was 853 m (2,800 ft) long with a 7.9 m (26 ft) ceiling height, a 3.2% upgrade, and a semi-circular ceiling. Various fire sizes and ventilation strategies were tested. Of most relevance to the Howard Street Tunnel fire were tests with fires of 20 and 50 MW and only natural ventilation. The fuel for the tests was No. 2 fuel oil poured on top of water in large pans. The temperatures recorded near the ceiling of the tunnel directly over the fire during the tests were considerably different. For the 20 MW fire, peak temperatures above the fire were measured to be about 320°C (600°F). For the 50 MW fire, peak temperatures above the fire were measured to be about 800°C (1,500°F) in the first few minutes, decreasing to about 700°C (1,300°F) after 14 minutes. The slight reduction in peak temperatures most likely was due to the underventilated environment in the upper layer of the tunnel which prevented the fuel from burning close to the ceiling. For both fires, the difference between measured and predicted temperatures was less than 50°C (100°F), ensuring that the model was appropriate for this application. Further details can be found in Ref. [5].

Tunnel Fire Simulation Parameters

In this section, various model inputs for the Howard Street Tunnel simulations are described. Table 1 lists the major assumptions and sources. A few notes:

- The overall geometry of the Memorial and Howard Street Tunnels was similar. Both have barrel-shaped roofs; both are relatively small in cross-sectional area. The most significant difference was that the Memorial Tunnel has a 3.2% upgrade; the Howard Street Tunnel has a 0.8% upgrade in the section of the tunnel where the fire occurred. The 0.8% upgrade persists until the Mount Royal portal.
- In the simulations, the rail cars in the tunnel were assumed to be blocks 3 m wide and 4 m high, with 1 m of void space beneath to represent the undercarriage. The walls of the cars were assumed to be steel plates with a thickness of 3 mm. Most of the cars were

Table 1
Input Parameters for Numerical Simulation of the Howard Street Tunnel Fire

Tunnel geometry	
Length	2,650 m (1.65 mi)
Height	6.7 m (22 ft)
Width	8.2 m (27 ft)
Grade	0.8%
Grid spacing	0.4 m
Wall properties [6]	
Material	Brick (8 layers)
Depth	0.9 m (3 ft)
Thermal conductivity	0.5 to 1.0 W/m/K
Specific heat	0.8 to 1.0 kJ/kg/K
Density	1,500 to 3,000 kg/m^3
Emissivity	0.85 to 0.95
Fuel properties [7]	
Formula	C_9H_{18} (Tripropylene or nonene)
Molecular weight	126 g/mol
Heat of combustion	44,300 kJ/kg
Heat of vaporization	300 kJ/kg
Boiling temperature	135°C
Density	0.74 kg/L
Soot yield (mass soot per mass fuel burned)	0.2 [8]

centered in the tunnel, but several of the derailed cars were offset based on the diagram of the accident scene provided by the NTSB. The cars in the simulation served as targets of thermal radiation and obstructions limiting the airflow to the fire. Specific damage to the cars was not included in the simulations, nor was the burning within the closed box cars.

- The fire in the Howard Street Tunnel was fueled initially by spilled tripropylene. It was reported by the NTSB that the tripropylene spilled from a 1.5 inch (4 cm) hole near the bottom of the cylindrical tank [1]. The car carrying the tripropylene held approximately 110,000 L (28,700 gal). The flow from the hole was estimated to have been about 1,000 L/min initially, gradually decreasing over time as the car emptied. The time required for the car to empty its contents was bracketed from two to four hours. If the spilling fuel had burned immediately upon its release without forming a pool, the heat release rate of the fire would have been about 500 MW. Rough calculations were performed initially that indicated that a fire of this size could not have been sustained in the tunnel due to the lack of sufficient oxygen to consume the fuel. Thus, it was assumed that the spilling tripropylene soaked into the roughly 1 ft (30 cm) layer of ballast (fist-sized rocks) between and below the ties of the railroad tracks.
- Burning rates for liquid hydrocarbon fuels are reported for deep, unobstructed pools under fully-ventilated conditions [7]. However, the tripropylene probably did not form a deep pool, and the heat fed back from the hot brick would have increased the burning rate to some extent. To simplify the analysis, the area of the pool was varied while the burning rate per unit area was fixed. As a baseline, the burn area was assumed to have

been 12 m^2. The burn area was then increased and decreased to determine the sensitivity of the tunnel temperatures to the size of the pool.

Approximately three hours after the fire started, a water main crossing just below the tunnel ceiling and running perpendicular to the tunnel at Lombard Street, ruptured, and water poured into the tunnel. Estimates of the amount of water spilled varied, but it was substantial. It was observed by Baltimore City Fire Department (BCFD) officials that water filled the intersection of Howard and Lombard Streets to a depth of about 1 ft (30 cm). The water had a significant effect on the fire below because 40 min after the pipe ruptured, BCFD officials commented that there was a noticeable change in the color of the smoke pouring from the Mount Royal portal, from dark black to gray. Preliminary calculations showed that the velocity of the smoke and hot gases near the ceiling of the tunnel flowing towards the Mount Royal portal was on the order of 1 m/s. At this rate, it would have taken on the order of 30 min for the smoke to have traversed the 1,900 m between Lombard Street and Mount Royal. Because some time would have been required for the water to affect the fire, plus a weaker fire would not have driven the smoke as quickly, the appearance of whiter smoke approximately 40 min after the pipe rupture was attributed to the introduction of a substantial amount of water into the tunnel near the fire.

It was not known to what extent the water reduced the size of the fire. NTSB interviews indicated that when fire fighters were able to approach the tripropylene car twelve hours after the fire started, it was not burning. It could, thus, be assumed that the fire burned at full strength for three hours, potentially burned for several more hours but at a reduced rate due to the introduction of water, and exhausted itself either due to a lack of fuel or extinguishment by water after twelve hours. Smoldering fires continued in the closed box cars for several days during which time emergency responders pulled the cars from the tunnel.

Calculation Results

The calculations simulated the first hour of the fire. The predicted gas and surface temperatures reached a steady-state in this amount of time, allowing for an assessment of the thermal environment for the time period before the water main break.

Shown in Figure 1 are the predicted gas temperatures at various heights near the fuel spill. These temperatures were subsequently used as boundary conditions for a detailed thermo-structural analysis of a waste transportation cask [2]. Initially, the simulated fire was well-ventilated; that is, it had access to a supply of oxygen comparable to the outside. However, as the tunnel filled with smoke and other combustion products, the fire becomes oxygen-limited, especially on the up-slope side of the fire. Figure 2 shows the predicted near-floor and near-ceiling oxygen concentrations an hour after the fire erupted. Since the air movement in the tunnel would have been biased towards the uphill portal (Mount Royal Station), the fire's oxygen supply came mainly from the Camden Portal, which was downhill of the spill. The flow bias was more pronounced in the Memorial Tunnel experiments, where the air flow through the tunnel was uni-directional uphill. The Howard Street Tunnel was about one-fourth as steep as the Memorial Tunnel, and as a result, smoke was observed at both portals. The simulation predicted oxygen concentrations uphill of the fire that would have been too low to sustain combustion. Downhill, the predicted oxygen concentration was

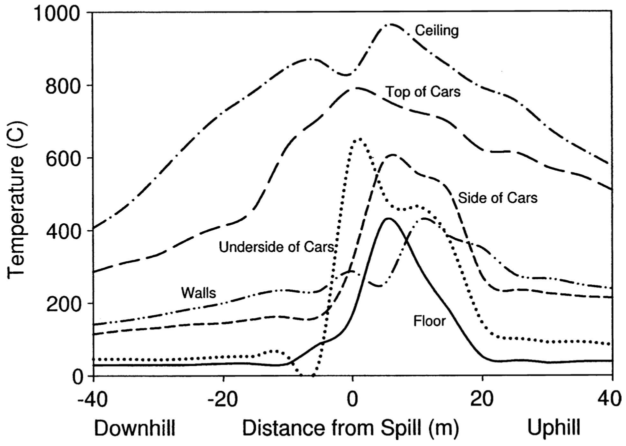

Figure 1. Predicted gas temperatures near the tunnel ceiling, walls and floor, plus the gas temperatures near the top, side and underside of the rail cars, as a function of the distance from the fuel spill.

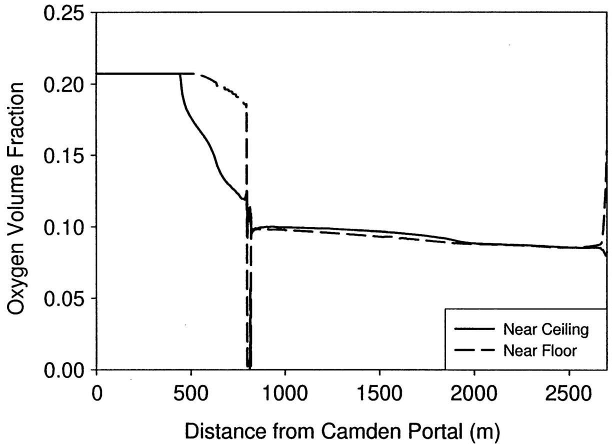

Figure 2. Predicted oxygen concentration near the tunnel ceiling and floor.

high enough (greater than 15%) to sustain the fire, but it certainly limited its heat release rate. The (predicted) net flow of air through the tunnel was about 24 m^3/s, meaning that, on average, oxygen was flowing through the tunnel at a rate of about 6.6 kg/s. Not all of this oxygen was consumed by the fire because a concentration of about 10% was predicted uphill of the fire. Thus, the fire consumed about half the available oxygen, at a rate of 3.3 kg/s. For most hydrocarbon fuels, the heat released per unit mass of oxygen consumed is about 13,000 kJ/kg. Thus, the fire size was limited to about 3.3 × 13,000 kJ/kg $\approx$43,000 kW. The exact values of the various flow rates differed from calculation to calculation, but

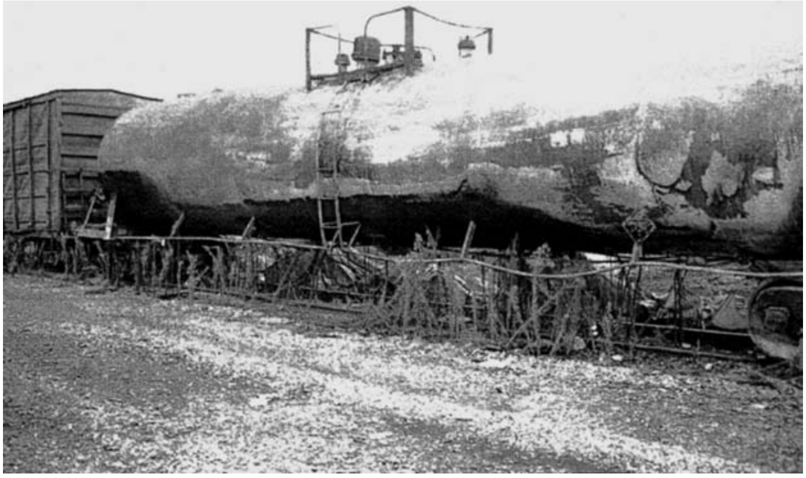

Figure 3. Tripropylene tank car (#52) after the fire, shown from the left side. The fuel spilled out of hole near the bottom of the tank at the right. The car in front is a box car carrying paper (car #51 out of 60). Courtesy Nancy McAtee of the National Transportation Safety Board.

regardless of the specific parameter choices, the heat release rate of the fire was limited by the net flow of oxygen to about 50 MW.

The results in Figure 1 were for a small fraction of the overall length. The entire tunnel volume was included in the calculation so that the mixing of fresh air and hot smoke along the entire tunnel length was simulated (the pressure at the portals was assumed ambient). The mixing process dictated where the boundary between the hot upper layer and cooler lower layer was located. This was an important finding because train cars that were pulled from the tunnel a few days after the initial derailment showed discoloration above a height of a few meters. The level at which the discoloration began varied, depending on how far from the fire the car was. Figure 3 is a photograph of a tank car with damage roughly two-thirds of the way down, while Figure 4 displays a car with damage one-third of the way down. These damage patterns were consistent with the smoke layer height predicted by the model.

The extent of the damage to objects within the tunnel was a function of the gas temperature surrounding the object and the radiative heat flux to the object from nearby hot objects or fire. Objects closer to the ground were subjected to less direct heating from hot gases, but they did absorb radiant energy from the hotter gas layer above. For the simulations of the Howard Street Tunnel fire, the temperature and heat flux was estimated at the tunnel ceiling and floor, to bracket the range of temperature and heat flux to which objects in the tunnel may have been exposed. The estimates indicated that surfaces that were exposed to direct flame impingement were subjected to heat fluxes in a range from 100 to 150 kW/m^2. These surfaces included the tunnel ceiling above the fire and the sides of the rail cars directly within the fire. This magnitude of heat flux has been measured at Sandia National Laboratories in fire experiments involving large objects suspended in large, open hydrocarbon pool fires

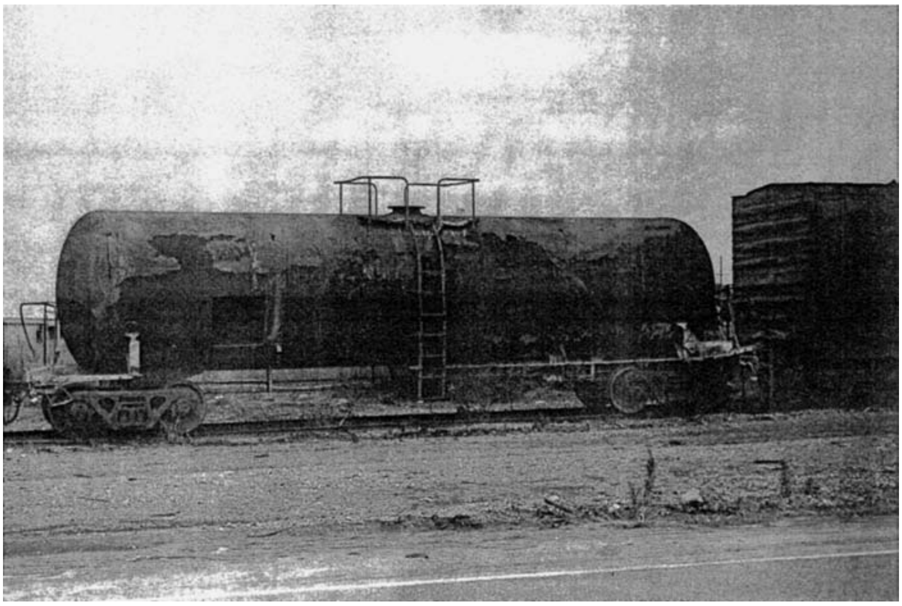

Figure 4. Right side of car #53, a tank car carrying hydrochloric acid. Courtesy Nancy McAtee of the National Transportation Safety Board.

[9]. Surfaces that were exposed to the hot, smoke-laden gases flowing near the tunnel ceiling, like the tops of the rail cars, were estimated to have seen heat fluxes in the range of 40 to 80 kW/m^2, depending on the proximity to the fire. Ultimately, the steel rail cars heated up to a temperature very near the gas temperature. After the tripropylene had been consumed, the closed rail cars containing smoldering paper products probably maintained a temperature on the order of 300°C (570°F), consistent with the temperature at which paper undergoes thermal degradation into pyrolyzates. The basis of this speculation was the fact that several cars burst into flames when they were opened up in the course of extinguishing the smoldering materials inside. The introduction of oxygen to the closed cars caused the transition from smoldering to flaming combustion.

Sensitivity Analysis

Several dozen simulations of the Howard Street Tunnel fire were performed to assess the sensitivity of the results to uncertainties in the condition of the train cars, the tunnel geometry, the ventilation, and the fuel spill. An examination of photographs taken by the NTSB during and after the incident helped to narrow down the range of potential fire scenarios. The calculations showed small variations in results, but nothing that would significantly affect the overall conclusions.

The various simulations performed as part of a sensitivity analysis suggested that the heat release rate was limited to about 50 MW. In some calculations, only the pool area was specified, and the fuel was allowed to evaporate based on the thermal heat flux impinging on the fuel surface. In others, a fixed heat release rate was used, based on the estimated size of the pool and the properties of the fuel. The heat release rate was limited to about 50 MW, regardless of the assumed evaporation rate.

An important consideration in the analysis was the absorption of heat by the tunnel lining. Given the length of the tunnel, most of the fire's heat was absorbed by the walls. The temperature of the smoke exiting the tunnel at both ends was very nearly ambient, based on the results of the calculations. Various sources in the heat transfer and fire literature [6, 10] report a range of thermal properties of brick (see Table 1). Because the thermal properties of the brick used in the Howard Street Tunnel were unknown, calculations were performed to assess the sensitivity to these inputs, particularly the thermal conductivity. The baseline calculation was run with a value of 0.7 W/(m · K), followed by calculations using 0.5 W/(m · K) and 1.0 W/(m · K). The peak surface temperature at the ceiling for the baseline case was approximately 700°C (1,300°F); whereas it was approximately 800°C (1,500°F) with the lower value and 600°C (1,100°F) with the higher value.

Conclusion

The Howard Street Tunnel fire in Baltimore in July, 2001, was modeled using the Fire Dynamics Simulator, a computational fluid dynamics fire model developed by the National Institute of Standards and Technology. The objective of the calculations was to quantify the peak gas and surface temperatures that were likely reached over a several hour period during which the spilled tripropylene burned. As a validation of the numerical model, several fire tests conducted in a decommissioned highway tunnel in West Virginia were simulated and the results compared favorably with the model.

The simulations of the Howard Street Tunnel fire addressed the behavior of the fire from its ignition until the rupture of a water main three hours later. The simulations suggested that during this time period the fire was oxygen-limited, that is, the heat release rate of the fire was limited to about 50 MW by the amount of oxygen that could reach the fire. Between three and twelve hours after ignition, the tripropylene fire self-extinguished either due to a lack of fuel or suppression by water. Beyond twelve hours, the combustible products within the closed box cars continued to smolder for several days, but at temperatures far less than those experienced during the flaming combustion of the liquid fuel.

The peak calculated temperatures within the tunnel during the first three hours (before the water main rupture) were approximately 1,000°C (1,800°F) within the flaming regions or about half of the length of a rail car, and approximately 500°C (900°F) when averaged over a length of the tunnel equal to the length of three to four rail cars. Because of the insulation provided by the thick brick walls of the tunnel, the temperatures within a few car lengths of the fire were relatively uniform, consistent with what one would expect to find in an oven or furnace. According to the calculations, the peak calculated wall surface temperature reached about 800°C (1,500°F) where the flames were directly impinging, and 400°C (750°F) over the length of three to four rail cars. The steel temperature of the rail cars were similar to the surrounding gas temperature because of the long exposure time and high thermal conductivity of steel.

A sensitivity study was undertaken to ensure that variations in the physical parameters of the model and the accident scenario would not lead to dramatic changes in the overall results. The fact that the fire within the tunnel would have very soon become oxygen-limited reduced the possibility for wide variations in the outcome of the study.

Acknowledgment

This work was sponsored by the US Nuclear Regulatory Commission Office of Nuclear Material Safety and Safeguards, and undertaken with the cooperation of the National Transportation Safety Board. The authors would like to thank Chris Bajwa at NRC, and Jay Kivowitz and Nancy McAtee at NTSB for many useful discussions of the accident.

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