Comparison of Fixed Fire Fighting System Effectiveness in Road Tunnels- High-Pressure Mist vs. Standard Sprinkler

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As part of an ongoing effort to improve overall life safety in road tunnels, PB has performed a study of the relative effectiveness of the competing fire suppression systems in a road tunnel environment. This study examines the effect of sprinkler spray droplet size on fire suppression performance in very well-ventilated environments with emphasis on suppression of vehicle fires in road tunnels. Several well-publicized fires involving heavy loss of life in European tunnels have brought to the forefront the importance of fixed fire suppression (sprinkler) systems in tunnels. The question then is which type is most effective. Historically, fixed fire suppression systems in tunnels have more or less standard (traditional) sprinkler systems, either automatic or deluge. More recently, high-pressure mist-type deluge systems have been suggested as a more effective alternative.

The major functional difference between traditional sprinkler systems and high-pressure mist systems is spray droplet size. Droplet size affects the cooling performance of water-based suppression systems—smaller droplets have greater surface area per unit volume, absorb more heat, and are, therefore, more effective. In a traditional sprinkler system, water spray mean droplet size is typically in the range of 700 to 800 microns; 1,200-1,400 microns for large-drop systems; and 30 to 100 microns for high-pressure mist systems. Note that these are mean droplet diameters. The deviation from the mean can be quite large, especially for traditional and large-drop sprinkler systems.

There has not been extensive study comparing the performance of mist systems with more traditional types in a road tunnel environment. Several studies have been performed for mist systems evaluating their performance in confined spaces with relatively little ventilation. Road tunnels are equipped with ventilation systems designed to remove smoke and products of combustion in the event of fire. Ventilation rates can be quite high. The effect of the movement of such large volumes of air on the performance of various sprinkler systems is a component of this study.

An important variable in sprinkler systems is the amount of water delivered per unit of coverage area (design density). It is usually dependent on density of combustibles. Based on a previous study, current practice in road tunnel design, and a review of NFPA 13, a design density of 0.20gpm/ft^2 is used for traditional sprinkler systems. High-pressure mist systems use less water. Based on review of mist system vendor data from full-scale tunnel tests, a design density of 0.075gpm/ft^2 is used.

This study assesses sprinkler system performance using computer simulation techniques and a review of full-scale test performance data. To provide the desired rigor, computational fluid dynamic analyses were performed using the NIST Fire Dynamic Simulator (FDS) program. FDS uses a form of the Navier-Stokes equations to solve numerically for fire-driven fluid flow. It has the capability of modeling lifelike fire scenarios in three-dimensional space for many common building materials and fuel sources. It produces three-dimensional simulations of the development of fires, including movement of heat, thermal radiation, products of combustion, gas currents, and the effects of fire suppression.

In addition to the CFD simulations, full-scale test data was gathered from the various tunnel fire suppression test programs conducted over the years. Earlier test programs were performed on traditional deluge sprinkler systems. More recent testing has been on high-pressure mist systems. Unfortunately, none of the test programs compared the two directly.

Criteria

This study examines the ability of fire suppression systems to both control deleterious tunnel environmental conditions and to suppress fire, with the ultimate goal of extinguishment. The two are analyzed separately. “Tunnel environmental conditions” refers to the degree to which, for a given fire size, conditions in the tunnel will be improved by activation of the suppression system. For this study, we evaluate one specific fire heat release rate (FHRR). The effect of fire suppression on life safety, fire spread, and tunnel structural integrity are the primary areas of concern. System effectiveness is determined by observing the change in temperature, radiated heat levels, and visibility after suppression is activated. The observed effect of the fire suppression system on tunnel environment is independent of whether any actual reduction in FHRR takes place. For example, as in the case where a fire grows large and suppression has relatively little effect on FHRR or growth rate, such as a well-shielded fire of fast-burning commodities with high heat of combustion.

Ultimately, it would be ideal to extinguish a fire developing in a tunnel. If complete extinguishment is not possible then a reduction in its growth rate and ultimate FHRR are desirable. A separate model was developed for this study to assess the extinguishing capability of various systems. In evaluating extinguishing capability, “fire suppression” refers to the ability of a fire suppression system to reduce fire size, limit growth rate, or limit ultimate size.

Tunnel Environmental Conditions Model

The first series of simulations deal with the effect of suppression on conditions in the tunnel in the event of a fire. For these simulations the fire is modeled using a function in FDS that simulates a fire burning as a constant heat source producing thermal radiation and products of combustion as specified in the input files. Suppression does not reduce the quantities generated. A deluge sprinkler array is located directly above a simulated truck cargo bed and is activated after some time is allowed for the fire to develop and conditions to reach a relatively steady state. Simulated instrumentation is located throughout the tunnel to measure temperature, thermal radiation and visibility.

The tunnel is modeled as a 394-foot-long (120 meters) section of tunnel with concrete construction. Modeling a longer section of tunnel would be difficult because of the computation time required to perform simulations on very large volumes. The section is 50ft (15.2m) wide by 21ft (6.4m) high. The ends of the section are open to allow ventilation and smoke and heat transport out of the tunnel (see Figure 1). Temperature thermocouples are arranged throughout the tunnel to measure the change in temperature resulting from ignition of fire and cooling effects of suppression water. Thermocouples labeled TC-H# are located near tunnel ceiling and those labeled TC-L# are located at head level in the tunnel. The suppression array is arranged in a 100-foot-long by 50-foot-wide grid pattern with nozzles spaced in rows 12ft apart longitudinally by 10ft apart transversally. This same pattern is used for all three of the suppression systems studied. The three systems differ only in the mean diameter of the water droplets produced, the trajectory of the droplets, the design density and the pressure required to achieve the density. The tunnel FHRR specified for the environmental conditions model is 100MW. This is a typical value reflecting normal vehicle traffic through a tunnel including cargo trucks but excluding bulk transport of flammable liquids. Simulations of both shielded and unshielded fires are performed. Shielded fires have a flat structure built above the fire platform simulating the roof of a truck trailer. Suppression is activated 110 seconds into the simulation.

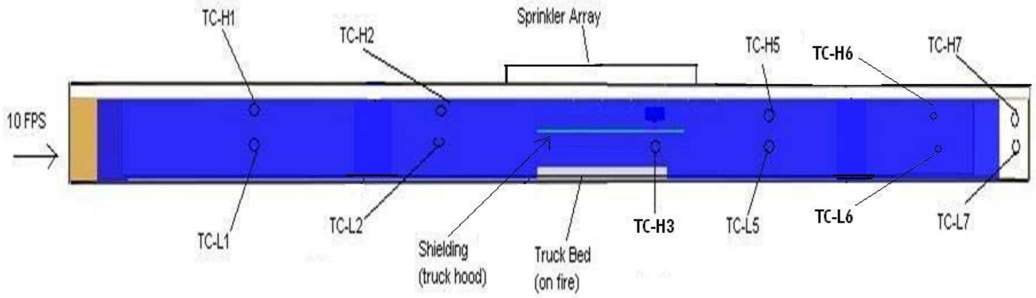

Figure 1. Typical Arrangement of FDS Model

FDS output is organized in several ways. Temperature is recorded in data files, which are then graphed for presentation. Thermal radiation is recorded in “slice files,” which are sections of the tunnel, cut at prescribed locations, showing the change in radiation over time throughout the simulation. The level of radiated heat being indicated with a color chart. Visibility is shown in the simulations similarly to thermal radiation. Slices are taken at various locations describing the distance that one can see through the smoke layer. In the simulations this would be the distance at which a reflective sign could be seen. In the interest of brevity, visibility and radiation slices are not presented here but rather in the full report and presentation.

Figure 2 shows temperature data at ceiling level 98ft downstream of fire. This is and important location because it is heat moving downstream that is likely to ignite additional combustibles and cause fire to spread. Following the activation of suppression at 110 seconds, temperatures levels are shown to drop rapidly for all three systems. Performance of the standard and mist systems are nearly identical. While the similarity is largely a coincidence of water application density it also reflects the fact that the standard drop spray contains a significant percentage of finer droplets. These are able to become entrained in the fire plume and remain in contact with the heated air allowing for the maximum temperature reduction. Larger droplets provide some cooling while falling through the fire, but most of the volume falls to the ground providing no further benefit.

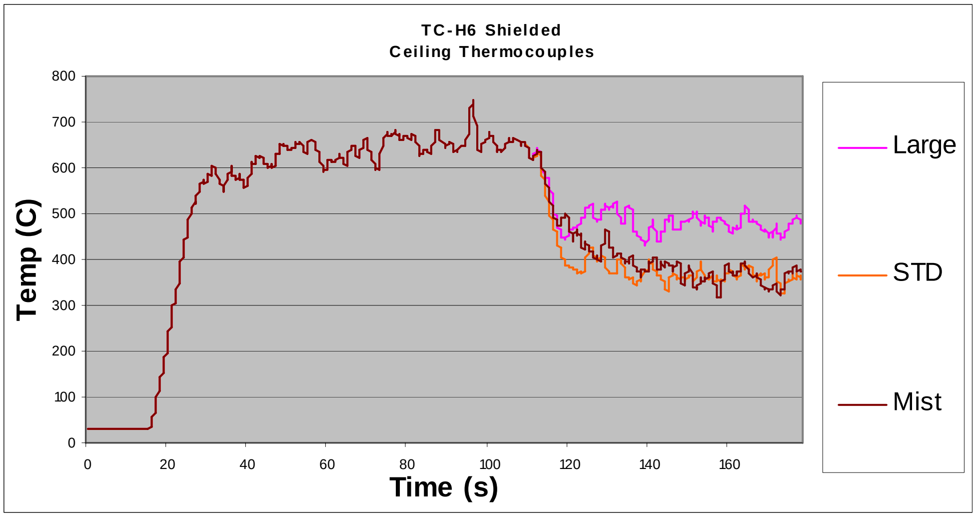

Figure 2. FDS Temperature Graph at Ceiling Level, Downstream of Shielded Fire

Table 1 summarizes temperature and visibility output data for both shielded and unshielded fires. As seen above, temperature performance is generally similar for traditional and mist systems. The large-drop system is least effective. There are some interesting anomalies. Suppression actually increased temperature levels at head level downstream of fire. This is a result of the breakdown in smoke layer stratification. The highest performing suppression systems also caused the greatest smoke destratification and increase in temperature. Also, the mist system was not able to reduce temperature directly above the fire in the unshielded simulation. Apparently, mist droplets are too light to penetrate the fire plume and are simply swept away. All the systems significantly reduced upstream temperatures. This is more a result of reduction in backlayering than direct heat transfer. As backlayering is reduced the smoke front eventually recedes past the location of the thermocouple resulting in an immediate temperature reduction. The systems that most effectively reduced temperature also reduced backlayering the most.

Table 1. Summary Results for Environmental Conditions

		Temperature				Visibility	
Unshielded	Spray Type	Ceiling Downstream (725 C)	Ceiling Above Fire (800 C)	Ceiling Upstream (600 C)	Head Level Downstream (60 C)	Upstream	Downstream
	Large Drop	525	450	200	60	Unaffected	Largely Unaffected
	Standard	425	500	75	70	Unaffected	Significantly Reduced
	Mist	375	850	75	80	Unaffected	Completely Eliminated
Shielded	Spray Type	Ceiling Downstream (650 C)	Ceiling Above Fire (725 C)	Ceiling Upstream (450 C)	Head Level Downstream (60 C)	Upstream	Downstream
	Large Drop	475	425	150	75	Unaffected	Largely Unaffected
	Standard	360	300	60	110	Unaffected	Significantly Reduced
	Mist	360	100	60	125	Unaffected	Completely Eliminated

Table 1. Summary Results for Environmental Conditions

Again looking at Table 1, before suppression is activated there is some degree of visibility, although poor. After activation of the large-drop sprinkler visibility is somewhat reduced. For the standard sprinkler it is much more reduced and for the mist system completely eliminated. This is consistent with what was seen in the temperature graphs. As temperature falls the smoke layer is destratified and drops. Systems that absorb the most heat, such as mist, cause the greatest reduction in downstream visibility. It should be noted that in none of the cases could visibility have been considered to be in the tenable range prior to suppression.

Airborne water droplets are good absorbers of radiated heat. The smallest droplets absorb the most. Water in the gas state is also an efficient radiation absorber. Radiation data from the simulations show that unsuppressed fire generated large areas of radiated heat measuring over 60kw/m^2. As suppression water is added to the fire area, levels of radiated heat measured adjacent to the fire drops. As droplet size is reduced the level of radiated heat also drops, the mist system showing the greatest reduction. Radiated heat drifting downstream is significantly reduced with the standard drop and almost completely eliminated with the mist system.

Suppression of Growing Fires Model (Extinguishment)

The models used to assess the affects of suppression on heat release rate and fire growth are different from that described above. Rather than specifying a known heat release rate, a stack of combustibles is modeled in the tunnel and ignited with a small seed fire. The selection of a combustible material affects the ultimate heat release rate of the fire, the intensity of the fire and fire growth rate. It is desirable to generate a fire that can reach around 100MW if unsuppressed and grow at a rate that will allow multiple simulations to be carried out in a reasonable time. A material with very fast growth rate is needed. After several simulations, acrylic upholstery (polyurethane) was selected. It gives a sufficiently fast growth rate and reaches a suitable maximum heat release rate.

Figure 3 illustrates the suppression of a well-shielded growing fire under longitudinal ventilation at 10ft/s. Suppression is activated just prior to flashover of the fire at 240 seconds. Large drop is not included in these simulations. In this case, the introduction of suppression has little effect on FHHR compared to the unsuppressed fire. This likely results from the fact that heavier droplets are shielded from the fire and lighter ones are mostly carried away with the ventilation flow. They are not able to collect in the seat of the fire in sufficient concentration to significantly cool the combustibles or dilute oxygen concentration.

Figure 4 illustrates the suppression of an unshielded growing fire under longitudinal ventilation at 10ft/s. Suppression is activated just prior to flashover, in this case at 120 seconds. As with the shielded fire, mist system droplets are unable to affect a significant reduction in FHRR. The standard drop system, having a good distribution of both fine and larger droplets is able to dramatically reduce FHHR because the larger droplets penetrate to the seat of the fire. For technical reasons, FDS has difficulty showing complete extinguishment of a fire. Published data from full scale tunnel test programs has shown that unshielded fires burning at similar heat release rates can be completely extinguished with traditional sprinkler deluge systems.

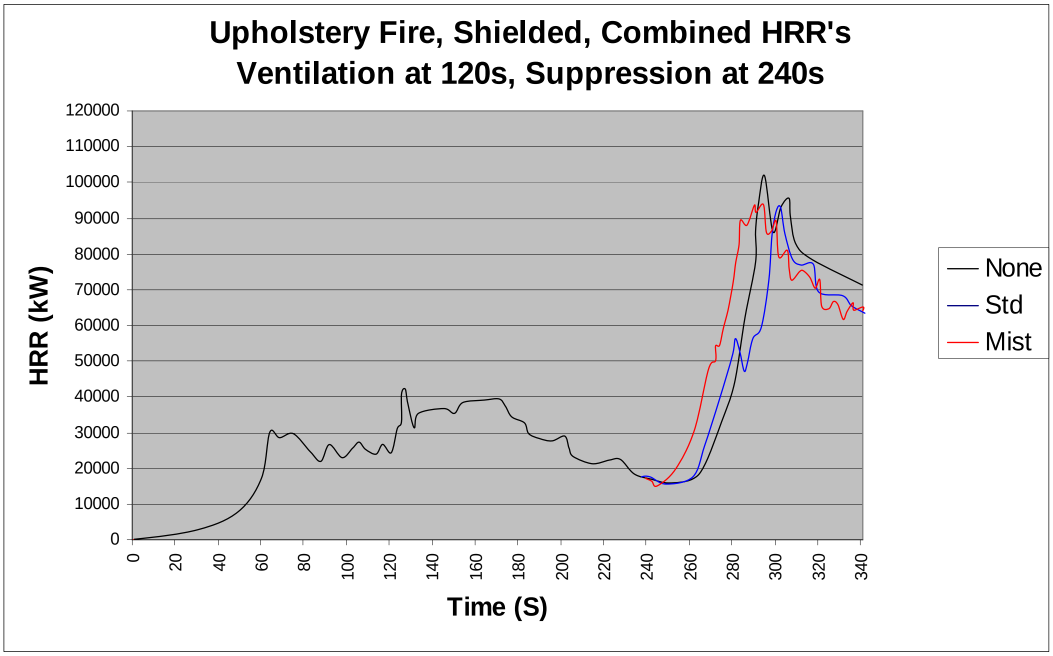

Figure 3. Suppression of Growing Shielded Fire

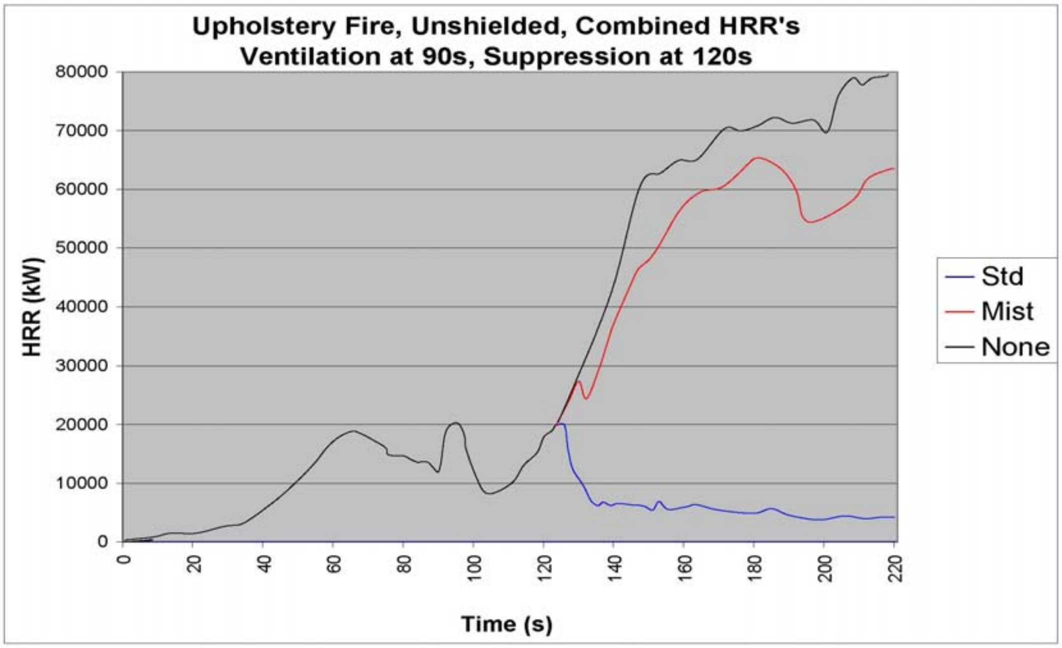

Figure 4. Suppression of Growing Unshielded Fire

Conclusion

Temperature reduction resulting from fire suppression was consistently good with both the standard drop sprinkler system and the high-pressure mist system. Performance shown in the FDS models was roughly equal for the two systems. Full-scale test programs carried out in various tunnels show similar results. In all the FDS simulations suppression reduced temperatures to manageable levels and would have successfully prevented the spread of fire. The large-drop system was less affective at reducing temperature.

In the simulations and in full-scale test programs, downstream visibility was seen to be reduced when suppression was activated. This was expected as it is known that reducing temperature will drop the smoke layer. The mist systems seemed to drop the smoke layer the most but only slightly more than the standard system. This was shown in both the FDS models and in full-scale tests programs.

The most significant reduction in thermal radiation is found in the high-pressure mist system. Performance of the standard drop system is also found to be quite good. In both cases the level of reduction is sufficient to prevent the spread of fire to adjoining combustibles. Full-scale testing showed that decrease in radiated levels would allow the approach of fire fighting personnel. No significant advantage was seen in one system over the other.

FDS simulations of shielded growing fires performed for this study showed roughly equal reduction in FHRR due to suppression by standard drop sprinklers and high pressure mist. FDS simulations performed by the Swedish National Testing and Research Institute found similar results. Full-scale testing by mist system vendors reportedly found reduction in FHRR of wood crib fires to be in the range of 40 to 80 percent. Worst-case performance was for suppression of commodities with very high heat of combustion and with strong ventilation. In these cases, reduction in heat release rate was as little as 20 percent. These are similar conditions to those used in FDS simulations performed here except that the tunnel height was significantly greater. An effective reduction in FHRR of only approximately 10 percent for the simulations was therefore not unexpected.

Based on the results of this study, no significant advantage is seen for high-pressure mist fire suppression systems over traditional systems in improving environmental conditions within a tunnel in the event of fire. Traditional systems are much more effective at reducing fire size and at achieving extinguishment of unshielded fires. It should be noted that the traditional suppression system used nearly three times more water over the same area as the mist system. Also note that this study is performed for a tunnel with high ceilings (21 ft). For shorter tunnels and those with significantly less ventilation flow rate it would be expected that mist concentration could be increased to levels that would allow for better performance. Unfortunately, full-scale test programs carried out to date have not compared traditional and mist systems directly.