Expediting implementation of FFFS in road tunnels

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ABSTRACT

Road tunnel fixed fire fighting systems (FFFS) have made substantial progress in their incorporation. Initially utilized primarily in Asia, they have now become common in Europe and North America. They have been shown to prevent the spread of fire to nonincident vehicles and minimizing the damage to road tunnels. This has a significant benefit particularly to critical transportation corridors. Water application rate continues to be the most important design parameter and yet no guidance is provided, leaving designers to figure it out each time. The determination of this parameter is very important as water usage must be optimized, particularly for restricted water supplies.
The ability of these systems to mitigate flammable liquid tanker (FLT) fires is not as well understood. The general practice has been to restrict their use or stipulate foam suppression. Both of these practices are influenced due to industry increased demand for usage. While there is evidence that the same system can provide reasonable mitigation, there is hesitation about allowing it. In short, FFFS implementation could be greatly enhanced by two considerations.

- Providing prescriptive water application rates that reduce the uncertainty in their criteria and objectives.
- Implementing a test program for FLT performance that would help reduce the uncertainty of system performance on these types of fires and allow greater confidence that these fires can be successfully mitigated without foam systems.

KEYWORD: FFFS, road tunnel, water application rate, tanker

HISTORICAL EXAMPLES OF FFFS IN ROAD TUNNELS

Road tunnel fixed fire fighting systems (FFFS) have made substantial progress in their incorporation. Initially utilized primarily in Asia, they have now become common in Europe and North America. A pair of tunnel fires highlighted their benefit, the Santa Clarita fire in Newhall, California and the Burnley Tunnel in Australia.

Nihonzaka Tunnel Fire

One of the largest tunnel fire incidents occurred in the Nihonzaka Tunnel (1) in Japan on July 11, 1979. The Nihonzaka Tunnel consists of two 2 km-long tubes with unidirectional traffic. There were no restrictions on hazardous materials travelling through the tunnel, although this changed as a result of the fire. The fire was started by a rear-end collision involving four trucks and two cars. The accident caused tanks on the vehicles to leak, and this fuel subsequently ignited.
Seven people died in the fire and two were injured. Of the 230 vehicles in the tunnel, 173 were destroyed by the fire. The tunnel lining and the additional 45 mm (1¾ inch) thick reinforcement of the tunnel walls were damaged for a length of about 1100 meters (3600 feet). The greatest damage occurred in an area of about 500 meters (1640 feet) on either side of the seat of the fire. The road surface melted in places up to a depth of 200 to 300 mm (8 to 12 inches) average, with the maximum depth being 700 mm (28 inches).

It took two days to bring the fire under control and a week to finally extinguish it. The deluge sprinklers located in the tunnel were set off automatically by fire alarm systems. After about 10 minutes the fire appeared to have been extinguished. However, about 15 minutes later the fire flared up again. The water supply reservoir was emptied. Thereafter the fire grew to its maximum length.

Figure 1. Nihonzaka Tunnel fire accident.

Newhall, Mont Blanc and Burnley Tunnel Fires.
In the recent Newhall Tunnel fire in Los Angeles (2), for example, as many as 30 HGV's were involved. While the fire origin was relatively small, it spread to the other vehicles, creating a much higher FHRR (Fire Heat Release Rate). The Mont Blanc Tunnel (3) also involved multiple vehicles. The primary mechanism of this is the heat flux generated by the originating fire. An FFFS system reduces this heat flux preventing the fire from spreading to other vehicles. This was confirmed in the Burnley Tunnel fire in Australia (4) where three vehicles were involved and the fire did not spread past the original three vehicles.

Inferno on the Interstate: What Went Wrong?
Heavyweight traffic, a slick roadway and a narrow tunnel with a blind curve add up to the big-rig version of the perfect storm.

The inferno that consumed 30 trucks and caused three fatalities on the night of Oct. 12 was later fanned by wild Santa Ana winds, with flames leaping 100 ft. into the sky from the tunnel's mouth. (Photograph by The Associated Press)

Figure 2. Newhall Pass Tunnel fire (Santa Clarita).

These examples show that the FFFS provides a significant mitigation in tunnel damage from fire. This is especially important for critical infrastructure routes. Many Agencies require them and one of the leading industry Standards, NFPA 502 considers them conditionally mandatory. In contrast with the building environment, where suppression (sprinkler systems) are often mandated and prescriptive requirements are provided for implementation that allow for compliance enforcement, road tunnels often require a significant performance assessment. In order to make the installation decision easier, can these requirements be simplified?

	
Mont Blanc Tunnel after fire (no suppression system.)	Burnley Tunnel after fire (with suppression system). NB road surface and tunnel walls and services still intact.

Figure 3. Mont Blanc and Burnley Tunnels after fires.

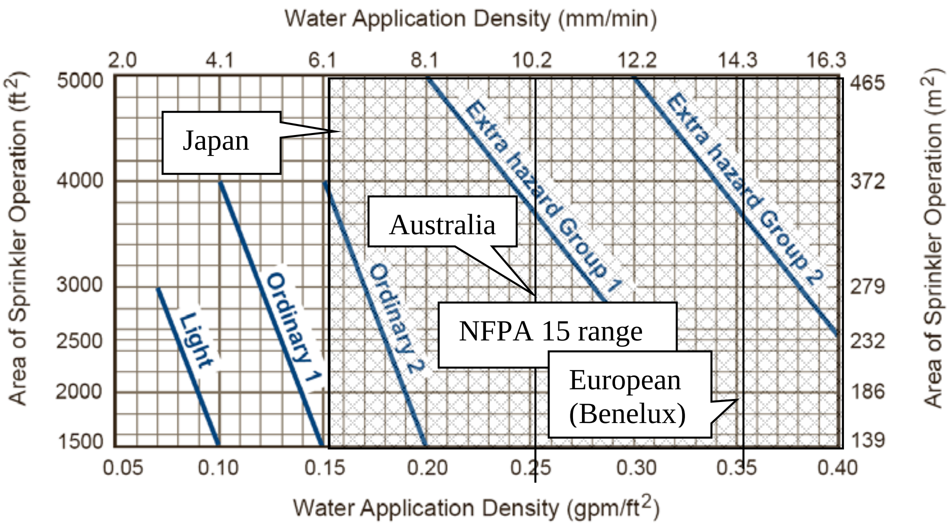
The second major issue to be addressed is their implementation with flammable liquid tanker (FLT) cargoes and with the addition of conventional heavy goods vehicles (HGV). In many cases, FLTs are prohibited or restricted from tunnel usage. This may cause other issues with alternate routes. There is also some discussion as to whether different systems, such as foam or higher water application rates are necessary. Can an FFFS be provided that handles both HGV and FLT incidents, simplifying operational response?

DETERMINATION OF A PRESCRIPTIVE REQUIREMENT

Can a prescriptive requirement be established that meets the objective and allows these beneficial systems to be easily implemented? In order to answer that question it is necessary to understand how water interacts with fire. In general, the discussion of performance vs. prescriptive requirements involves the trade-off of relatively straight-forward (and sometimes very arbitrary) rules to be followed vs. analysis of the controlling factors of the situation and developing mitigations necessary to meet the intended requirements. In many cases, especially if the requirements are extremely arbitrary and have little basis other than fiat, performance-based design can offer significant advantages. On the other hand, prescriptive requirements can make implementation relatively easy.

Background

Prescriptive requirements do exist in many areas, but their variation and arbitrariness is clearly evident. Japan and Australia each have their own water application rates of 6 mm/min (0.15 gpm/sf) (5) and 10 mm/min (0.25 gpm/sf) (6)respectively. In European system tests (Benelux), a water application rate of 14 mm/min (0.35 gpm/sf) (7)has been tested. These values have been added to Figure 4 which shows a range of water application rates that are prescribed and accepted by local codes or standards within specific fire department jurisdictions. There is a significant variation and more importantly, little has been done to compare these under similar conditions.



Current practice in the United States generally follows NFPA 502 where system installation and its performance requirements are not mandated, as stated in Article 9.3.5.

Figure 4. NFPA 13, NFPA 15, and other international water application rates.

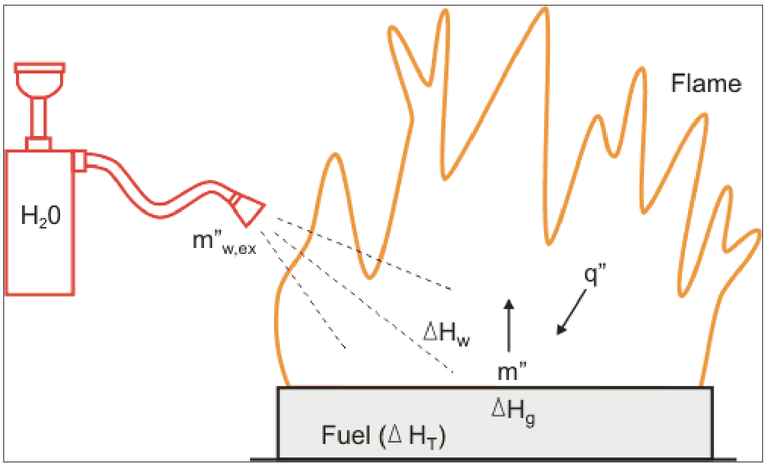
9.3.5 Layout Parameters. To achieve the design objectives in accordance with 9.2.1, discharge device coverage, spacing, positioning, spray characteristics, working pressure, and flow rates shall be determined by use of applicable codes, standards, or accepted practices, or where necessary, by an engineering analysis considering relevant available data resulting from full-scale tunnel fixed water-based fire-fighting tests of the type of fixed water-based fire-fighting system being used.

The problem with this article is that no applicable codes, standards or accepted practices have been defined for the water application rate. Therefore either an engineering analysis or full-scale testing is required to develop the key design parameters. In contrast NFPA 13, the standard for sprinkler systems and NFPA 15, the standard for water spray systems both prescribe water application rates for buildings. While it may be tempting to impose a "safe" rate that is probably excessive, this must be balanced against the duration of the fixed or restricted water supply. Restricted supplies can occur in remote areas where municipal supplies are limited. In such cases tankage may be required. For example, the Nihonzaka Tunnel in Japan had a FFFS system. Deluge sprinklers located in the tunnel were set off automatically by fire alarm systems. After about 10 minutes the fire appeared to have been extinguished. However, about 15 minutes later the fire flared up again. The water supply reservoir was emptied. Thereafter the fire grew to a length of more than 1100 meters (3600 feet). Therefore an optimum prescriptive water application rate should have been balanced with the available water supply.

Fire/Water Physics

Fire point theory as first described by Rasbash (8) relates to the effectiveness of the suppression agent (water), and to the fundamental fire properties. This model is based on the interaction between the heat required to vaporize a solid or liquid fuel and the effect that water has on the prevention of this vaporization. This interaction is illustrated in Figure 5. It is important to note that a solid or liquid fuel itself will not burn. A fuel will burn only after it is converted to a gaseous state by vaporization, which requires energy. A heat source (q") is required to vaporize the fuel. This heat source may either be radiated from the flame itself or radiated from an external source, such as an object burning nearby. The rate of conversion from solid or liquid to gas is the mass loss rate of the fuel (m"). The magnitude of the heat required to vaporize the fuel is ΔH_g. The heat that is generated by the burning of the fuel source (ΔH_T) times the total amount of fuel gives the fire's total energy potential.

The primary way in which applied water suppresses a fire is by cooling, which occurs when a portion of the fire's energy is used to evaporate the water instead of vaporizing the fuel.



Cooling a fire by applying water causes the mass loss rate of the fuel to be reduced below a critical value, preventing vaporization of the fuel. This cooling occurs at the solid/gas interface. The measure of water's potential to suppress a fire is its heat of gasification (ΔH_w). The minimum rate of water application to extinguish a fire per unit area is known as the critical water application rate or critical application density ($m''_{w,ex}$).

Figure 5. Dynamics of fire and extinguishment.

Generally speaking, the amount of water required to extinguish a fire ($m''_{w,ex}$) depends on the net heat flux on the fuel surface, which is the combination of:

- The amount of radiation emitted by nearby burning objects, plus
- The amount of radiation emitted by the flame itself.

Solving for the water application rate, m''_w, gives Equation 1.

$$m''_w = \frac{q''_e}{\varepsilon_w \Delta H_w + \delta_w} + \frac{\Phi \Delta H_T m''_{cr} - q''_r - m''_{cr} \Delta H_g}{\varepsilon_w \Delta H_w + \delta_w} \tag{1}$$

noting that at flame extinction $m'' = m''_{cr}$, the critical fuel mass loss rate, q''_e is the heat flux at flame extinction, and Φ is the maximum fraction of combustion energy flame reactions may lose to the surface by convection without flame extinction, described as the kinetic parameter.
The heat fluxes are external (q''_e), reradiated from the fuel surface (q''_r), and that removed from the surface or flame (by an extinguishing agent) as the flame extinction condition is reached. When water is the extinguishing agent, then the heat flux removed from the surface of a burning material by water evaporation, ε_w is the product of water application efficiency and ΔH_w the heat of gasification of water (2.58 kJ/g). In addition, δ_w is the energy associated with the blockage of the flame heat flux and fuel vaporization at the surface per unit mass of fuel vaporized.

The first term on the right is the external heat flux component and the second term is the critical water application rate for flame extinction, which is related to the fundamental fire properties of the material. In contrast to the second term, the first can be considered to account for general fire effects such as shape and arrangement of materials. It is not dependent on the particular materials used.

Water as a suppression agent acts by preventing fuel vaporization, thus preventing these fuel vapors from mixing with oxygen and combusting. How effective is a water spray at doing this? For non-flaming fuel sources, i.e. target fuel piles that could be ignited by an incident, the energy equation can be modified from Equation 1 by considering only the external heat flux. This becomes Equation 2.

$$m''_w = \frac{q''_e}{\varepsilon_w \Delta H_w + \delta_w} \tag{2}$$

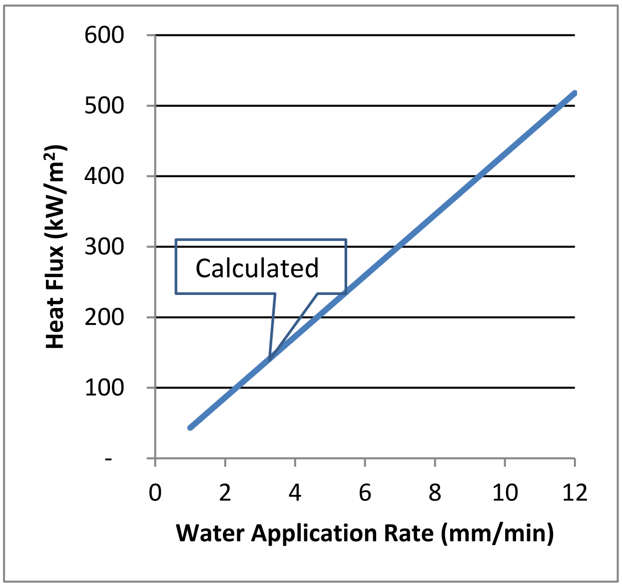


Figure 6. Vaporized water heat flux.

Setting δ_w equal to 0, ε_w equal to 1 and solving for q''_e as a function of $m''_{w,ex}$ gives the calculated water-vaporized heat flux results shown in Figure 6. These can be compared to common heat flux levels as shown from Quintere (9) as shown in Table 1 to estimate the amount of water necessary to mitigate heat flux and its resulting fuel vaporization. It should be remembered that the purpose of this work is to develop a spray system that meets a particular objective. Fire point theory shows that heat flux is the key parameter for predicting water effectiveness and that understanding this allows for better predicting water spray performance.

Table 1. Common heat flux levels.

Source	**kW/m^2**
Irradiance of sun on the earth's surface	≤1
Minimum for pain to skin (relatively short exposure)	~1
Minimum for burn injury (relatively short exposure)	~4
Usually necessary to ignite thin items	≥10
Usually necessary to ignite common furnishings	≥20
Surface heating by a small laminar flame	50-70
Surface heating by a turbulent wall flame	20-40
ISO 9705 room-corner test burner to wall 100 kw	40-60
ISO 9705 room-corner test burner to wall 300 kw	60-80
Within a fully-involved room fire (800-1000 C)	75-150
Within a large pool fire (800-1200 C)	75-267

PRESCRIPTIVE REQUIREMENTS

Having a prescriptive requirement in the governing Standard, such as NFPA 502, simplifies the process. From a risk perspective standpoint, it sets a ceiling on design requirements. More sophisticated methods can be used for improving on the design, but reasonable prescriptive requirements can make implementation less cumbersome. As always, what make sense for the situation is the primary objective.

Occupancy Hazard Classification

The Ordinary Hazard Classifications of NFPA 13 would appear to define the physical characteristics of HGV cargo loading. Use of these could automatically trigger prescriptive water application rates for FFFS.

5.3.2.1 Ordinary hazard (Group 2) occupancies shall be defined as occupancies or portions of other occupancies where the quantity and combustibility of contents are moderate to high, stockpiles of contents with moderate rates of heat release do not exceed 12 ft (3.66 m), and stockpiles of contents with high rates of heat release do not exceed 8 ft (2.4 m).

Table 2. Mitigated heat fluxes for water application rates and design areas.

Occupancy	372 m^2 (4000 ft^2) (mm/min/gpm/ft^2)	Mitigated Heat flux (kw/m^2)	139 m^2 (1500 ft^2) (mm/min/gpm/ft^2)	Mitigated Heat flux (kw/m^2)
Ordinary 2	6.1/0.15	259	8.1/0.20	345
Ordinary 1	4.1/0.10	173	6.1/0.15	259

The mitigated heat fluxes from Table 2 are greater than the values for solid and liquid fuel fires as shown in Table 1.

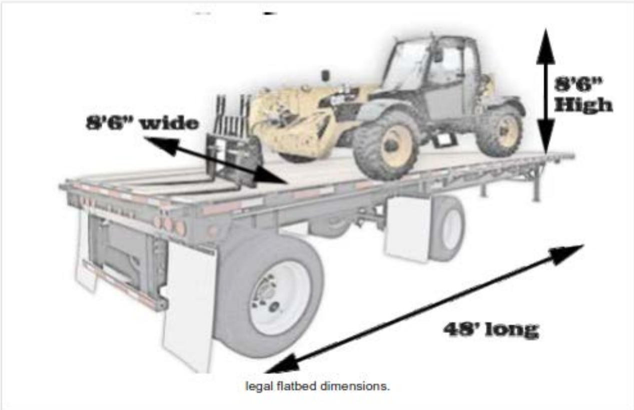


Figure 7. Flatbed trailer dimensions

Since the large fire incident is often dictated by HGVs, it is important to understand the physical limitations of trailers and fuel loads. The load height is set by legal restrictions. The dimension shown in Figure 7 is the minimum in the United States. In many states it is 150 mm (6 in.) higher. In one state, Alaska, it is 300 mm (1 ft.) higher. It should be emphasized these are legal maxima and in most cases, cargo, especially open cargo is stacked slightly less. This cargo arrangement would certainly comply with the limitations of Ordinary 2 Occupancy Hazard Classification and is just over the height limitation for Ordinary 1 Occupancy Hazard Classification. While Ordinary 1 would probably handle the situation, Ordinary 2 provides some additional safety factor for uncertainty. If it was strongly agreed that a lower water application rate would be beneficial, particularly for locations with supply limitations, then the more detailed performance analysis could be performed.

Discussion

FFFS have been shown to significantly reduce the damage caused by major fires in road tunnels. The code requirements often stipulate modelling or testing in all cases and do not include the most critical element, the water application rate. As a result, significant effort is spent developing a conceptual program, its justification methodology, and the implementation of developed results. This is in contrast to the general industry practice of defining a hazard classification and then applying a prescriptive water application rate to that arrangement.

A default prescriptive requirement eliminates this uncertainty and standardizes the water application rate for relatively easy implementation. A prescriptive stipulation of Ordinary 1 Hazard Classification would mitigate the heat fluxes generated, controlling the fire, while Ordinary 2 would provide greater heat flux mitigation and allow a safety factor for usage.

FLAMMABLE LIQUID TANKERS

This is the next logical step in these systems. For various reasons this aspect has more uncertainty.

Define Requirements for Flammable Liquid Tankers

FLTs are often restricted from tunnels. FFFS for tunnels that include FLTs are usually either foam systems or water systems of the prescribed rates from NFPA 13 and NFPA 15. Testing programs have shown that standard water sprays can reduce the FHRR. Adding foam systems to FFFS increases both system complexity and operational complexity. Other testing programs have shown similar fire control mitigation with plain water sprays and foam water sprays. This objective can be described as comparing effectiveness of water sprays with and without foam.

Foam

Foam is often thought to be the optimum suppression agent for flammable liquid fires. However, it does add complexity in functionality and implementation. The key question is does it provide any significant benefit for road tunnel spill scenarios as opposed to the pool scenarios for which foam is generally used. Testing has shown there may not be much difference.

Water

NFPA Standards (13 and 15) already stipulate a Commodity Hazard Classification (Extra Hazard 2, 12 mm/min, 0.30 gpm/sf) prescriptive water application rate, so this implies foam is not necessary for flammable liquid fires. Again testing has shown significant mitigation with lower water application rates for the thin-film fires expected in road-tunnel applications.

Flammable Liquid Fire Suppression

While much is known about how water reacts with solid fuel fires, the process of flammable liquid suppression with water is less well known. The mechanisms of how additives, such as foam, suppress these fires are better understood. In the case of foam, under the right conditions, it floats on the liquid surface and prevents the mixing of fuel vapors and oxygen necessary for combustion. It should be noted that these tests are usually based on flat contained liquid pools, not necessarily the situation on a highway tunnel. Recent testing has shown that water mists of very fine droplets can also control these fires without foam. Table 3 shows some tests performed by Lemaire (10) to compare the performance of various suppression agents. Note there was very little difference between the 1%AFFF (VerTest2) and plain water (PerTest1).

Table 3. Suppression of solid and liquid fuel fires.

Test	SCENARIO		ACTUAL CONDITIONS			
	Fire load	Additives	Initial ventilation speed	Start of suppression after ignition	Burning period	Nominal HRR
			m/s	s	s	MW
VerTest1	Solid: 180 pallets (80% wood, 20% plastic.)	1% AFFF	3.7	335	1140	50
VerTest2	Pool: 100 m^2 diesel oil	1% AFFF	4.0	96	150	200
PerTest1	Pool: 100 m^2 diesel oil	no additives	4.0	125	180	200
PerTest2	Pool: 100 m^2 diesel oil	1% Bioversal	~ 4	160	420	200
PerTest3	Solid: 720 pallets (80% wood, 20% plastic.)	no additives	~ 4	439	2100	200

Tests of Water Spray in Flammable Liquid Fires

Numerous tests and studies have been done that show water spray does suppress flammable liquid fires. Rasbash (11) investigated the effect of cooling by water sprays for flammable liquid fires with fire points higher than the water temperature. Experiments with burning kerosene showed that water spray effectively cooled the fire to extinction, and even for tests without extinction, the temperature-time record showed that the water spray maintained a steady temperature after 12 minutes. This seemed to indicate that the heat entering the fire and the heat leaving the fire reached equilibrium. Other experiments by Rasbash (12) investigated the effect of various water spray pressures and flow rates on flammable liquid fires. He found that higher flow rates were needed for extinction of larger liquid fires, but that there was no advantage in increasing pressure for these type of fires. The application of spray however does have to meet certain conditions, particularly with regard to droplet size. Rasbash and Rogowski (13) conducted a series of tests in 300 mm diameter open vessels with flammable and combustible liquids of 50-60 mm thickness.

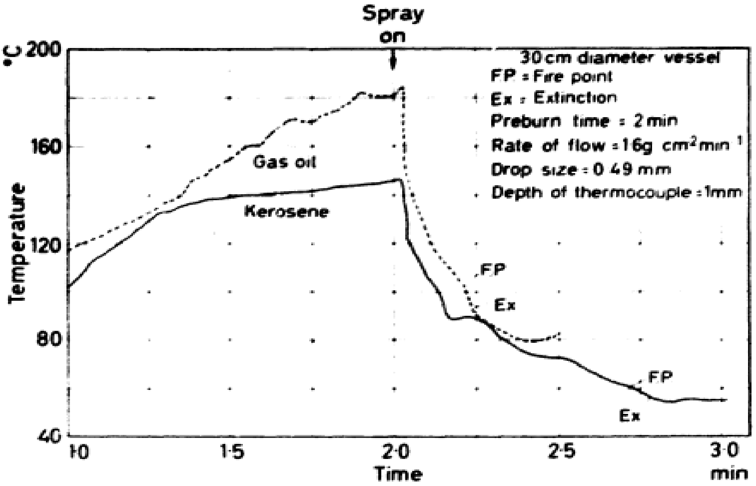


Figure 8 shows the plots of the gas/oil mixture and kerosene indicating significant control and extinguishment within one minute of spray application. Of significance in road tunnel applications is the approximately 50% drop in temperature below the surface of the burning liquid within 15 seconds after activation.

Figure 8. Temperature/time records below surface of burning liquid extinguished by water sprays.

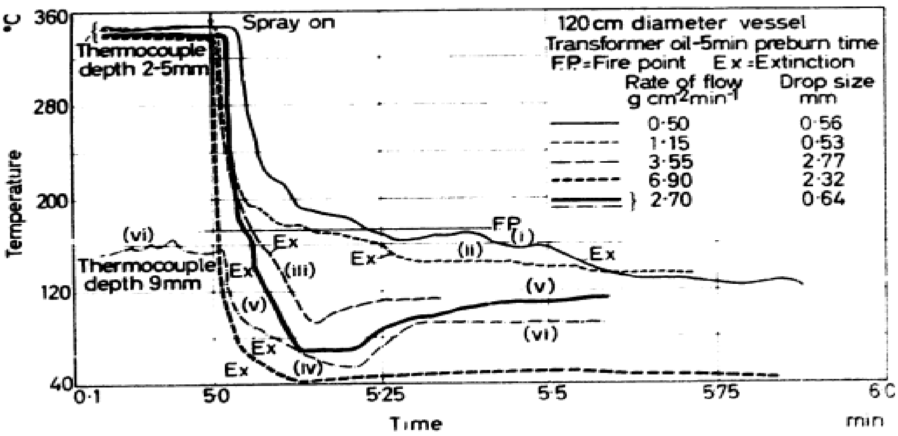


Figure 9 shows the results of tests of transformer oil in a 1.2-meter diameter vessel, again showing a relatively sharp initial temperature drop and later on control and extinguishment.

Figure 9. Further temperature/time records below surface of burning liquid extinguished by sprays.

Oil thickness varied from 50-60 mm thickness. The correlation of the critical parameters is established in the extinction time formula, Equation 4. The terms are defined as shown.

$$T = 34{,}000 * \left(\frac{D}{M}\right)\left(\frac{Y}{\Delta T^{1.75}}\right) \quad (4)$$

T	Extinction time.
D	Median drop size
M	Flow rate
ΔT	Temperature difference between ambient and liquid fire point.
Y	Preburn time

One of the difficulties with this method is that it requires the difference between ambient temperature and the fire point. For Class I flammable liquids such as gasoline, the fire point is below ambient temperature.

Rasbash, Rogowski and Stark (14) conducted tests of additional liquids including alcohols and gasoline. Since gasoline is the most common liquid transported, attention will be focused on that. The tests were similar with 50-60 mm (2.0-2.4 inch) thick pools involved. Equation 5 and Equation 6 for gasoline and kerosene respectively were developed from regression analysis of the various tests. The additional term A is the entrained air velocity cm/sec.

Purtori (15) used particle tracking and laser-induced fluorescence to measure droplet sizes in standard sprinklers. Data showed a median droplet diameter range of 0.261 mm (0.010 inch) to 0.212 mm (0.008 inch). For purposes of this example, 0.261 mm (0.010 inch) will be used. Entrained air current is not a common value. Rasbash, Rogowski and Stark measured this for several sprinklers and the lowest value was approximately 160 cm/second (5.2 fps).

Gasoline

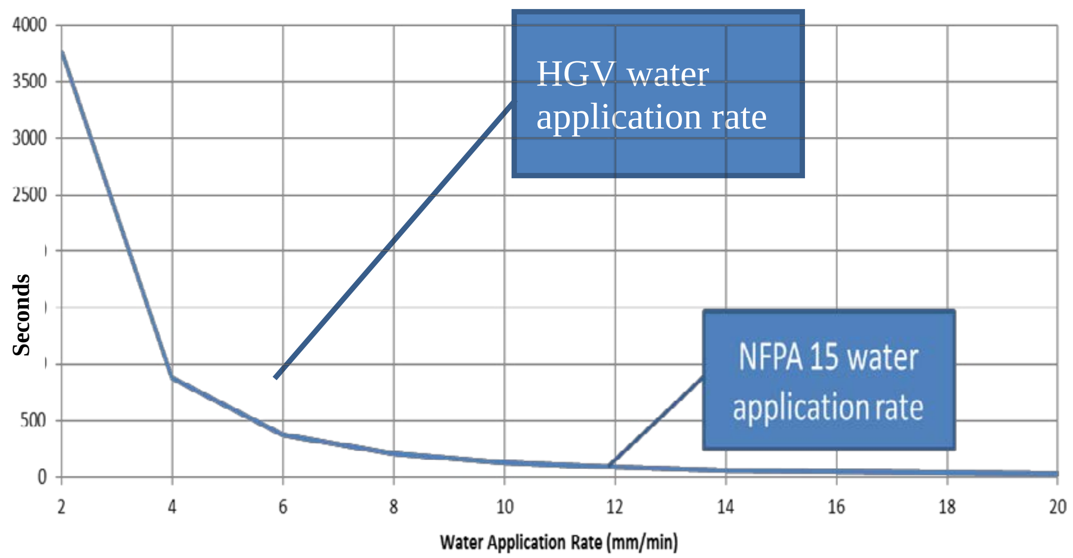
$$t = 6.1 * 10^{12} * \left(\frac{D^{4.5}}{M^{2.1} * A^{3.0}}\right) \tag{5}$$

Kerosene

$$t = 2.6 * 10^{5} * \left(\frac{D^{6.9}}{M^{0.5} * A^{3.2}}\right) \tag{6}$$

The context of this previous work has been to extinguish flammable liquid fires quickly, typically in less than one minute. However, road tunnels are different.

Figure 10 shows a significant drop in the time to extinguish a gasoline fire with a water application rate of 4 mm/min. At 6 mm/min., a reasonable design value, it is in the seven to eight minute range, consistent with expectations for solid fuel fires. Figure 10 also shows the points identified for two water application rates, one typical of that used for HGV fires and the other stipulated by NFPA 15 for flammable liquid fires. It should be noted that the prescriptive requirement of NFPA 15 is about double the HGV rate.



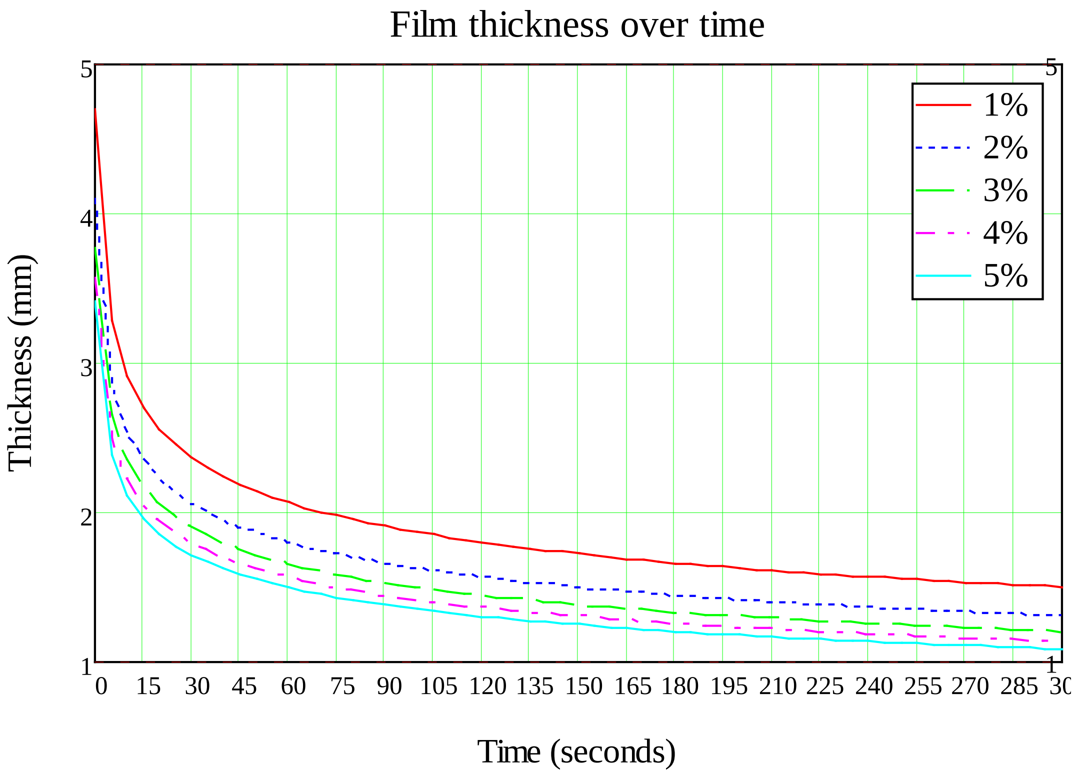
Note: Refer to Figure 4 for conversion of mm/min to gpm/square foot.
Figure 10. Time in seconds to extinguish a gasoline fire for various water application rates.

POOL-SPREAD CHARACTERISTICS

Like all fires, the heat release rate is dependent on the rate of fuel vaporization to mix with available air. Liquid fuels in contrast to solid fuels do not have an inherent surface area available for vaporization but conform to the surrounding boundaries. For roads, this means the liquid will follow the slope and will be limited by elements such as curbs, drainage channels, etc. that define the liquid surface boundary area. For this reason, an understanding of how a liquid fuel spreads on a surface is extremely important.

Pool spread and depth

The above referenced tests were done on liquid pools of 50-60 mm (2.0-2.4 inch) thickness. Most of the research has been performed on these relatively thick pool fires. A tanker incident in a road tunnel is more likely to cause the liquid to flow from the tank onto the roadway surface, more accurately described as a spill of much thinner thickness. Mealy (16) has shown that flammable liquid spills reaching their spread limits have a nominal thickness of about 0.7 mm (0.03 inch).



Note: 0.003m is approximately 0.12 inches.
Figure 11. Film thickness for one to five percent slopes.

The typical design tanker fire is considered to consist of a tank rupture either from a penetration or nozzle removal. This causes the liquid to flow through the nozzle and onto the roadway. An analysis of gasoline spilling onto a slope was performed to determine liquid thicknesses. The initial flow from the tank was considered as a flow through an opening and was determined for a series of circular openings. A 1-meter static head was assumed as the starting condition. These conditions were used to establish the flow and fluid velocity. The Navier-Stokes equations were used to determine the flow velocity based on gasoline fuel. Five increasing slopes were calculated, starting with one percent. This is a common roadway slope that allows surface water to drain. The maximum was five percent, one that can define a superelevation as well as a steep general road slope.
Figure 11 shows these film thicknesses over time. Note that they drop fairly quickly from the spill to

less than 2 mm (0.08 inch) after 75 seconds. Given the previous water application rates in Figure 10, the proportion of water to gasoline rises rapidly. A spill will flow out from the source. Assume for this exercise that the spill flows in two directions and forms a quarter circle of radius l meter, with area as shown in Figure 12.

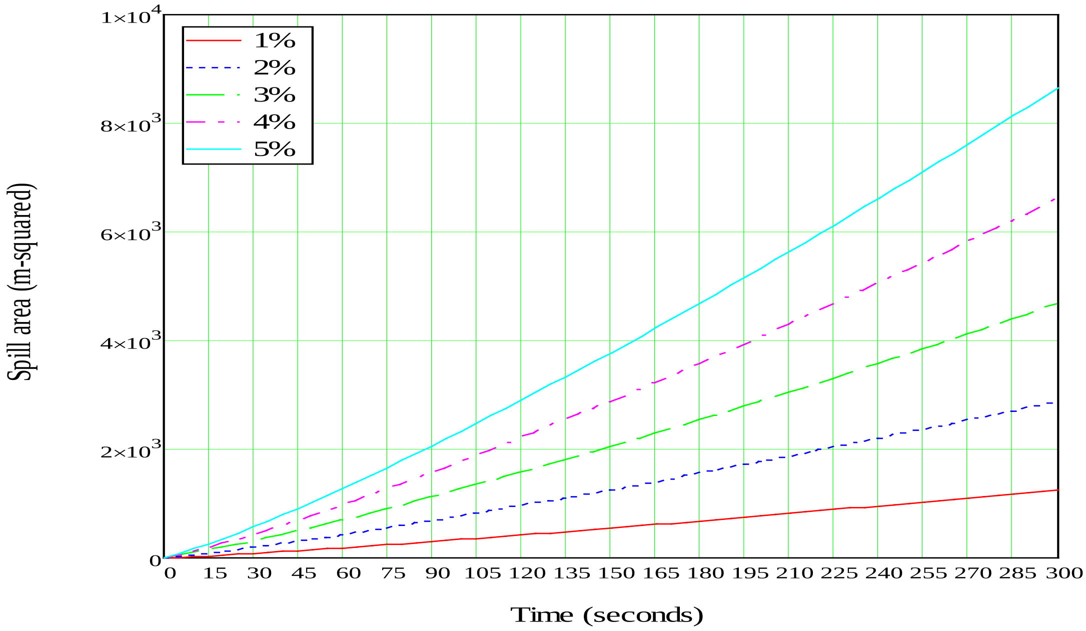


Figure 12. Spill area for one to five percent slopes.

By understanding the dynamics of liquid fires, mitigation effects can better be understood. Because liquids are unconfined, they can easily spread increasing the surface area and vaporization, leading to potentially very high heat release rates. Therefore, a mitigation can be to limit the pool spread by providing frequent drainage that limits the pool area.

TEST COMPARISON

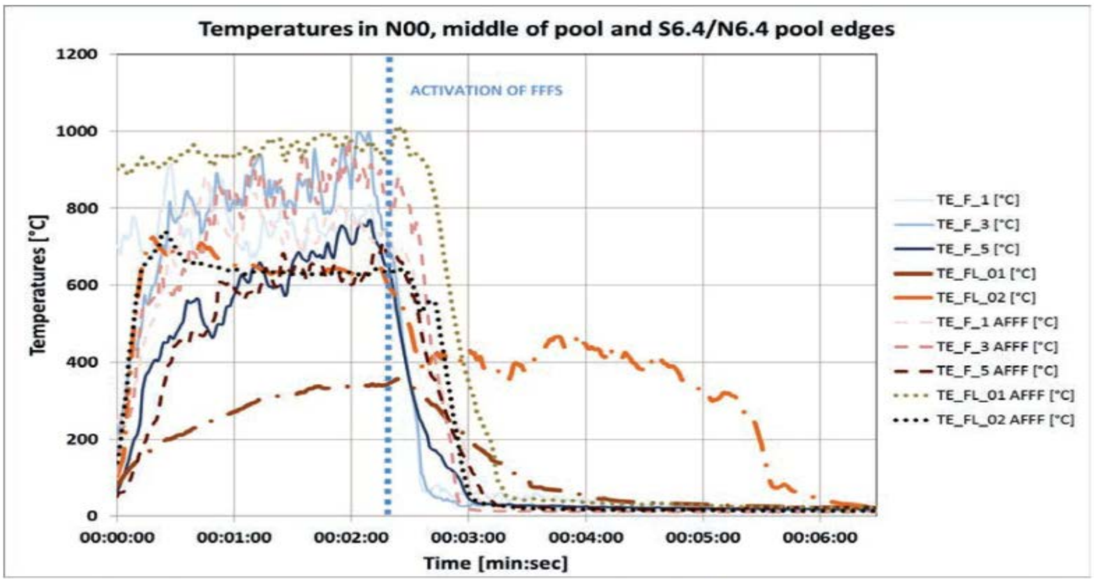
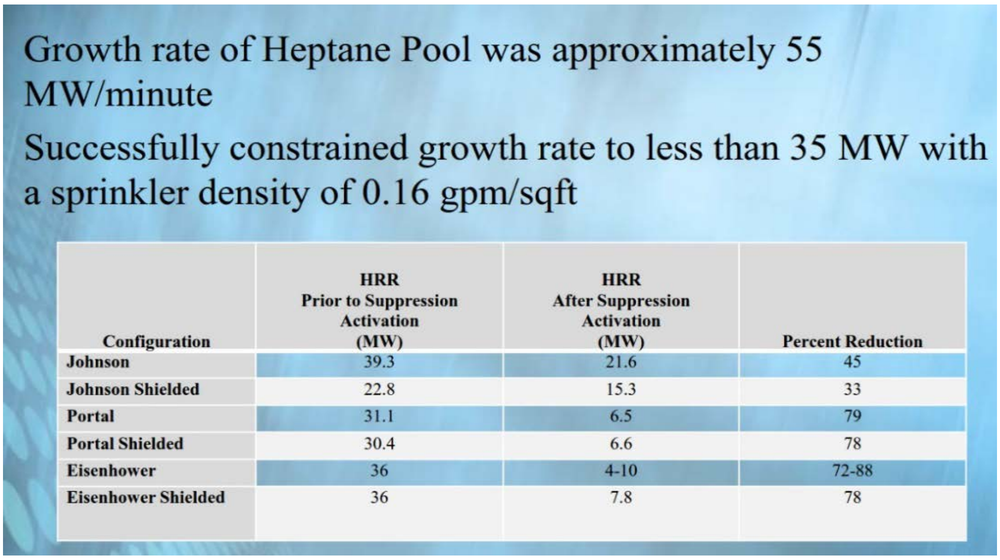


Figure 13. Temperature measurements using fine water spray with and without foam.

One key piece of information that had been missing until recently was a comparison of plain water and the foam additive. Recent testing by Lakkonen (15) has provided that information. Figure 13 shows that once the spray is applied, the temperature starts dropping almost immediately and is in the tenable range in less than a minute, no matter what medium is used.

Eisenhower Johnson Tunnel Testing.

Rondinelli (18) presented results from concept testing for a water-only FFFS for the Eisenhower-Johnson Tunnels in Colorado. As part of this project, a proof-test was conducted of the ability for water-only to mitigate flammable liquid fires. Figure 14 shows the compliance with a goal to constrain the FHRR to less than 35 MW. The growth rate of the heptane pool was approximately 55 MW/minute. However, in all cases, the FHRR was substantially reduced after application of the FFFS. This shows that early activation is the most important factor.


Growth rate of Heptane Pool was approximately 55 MW/minute

Successfully constrained growth rate to less than 35 MW with a sprinkler density of 0.16 gpm/sqft

Configuration	HRR Prior to Suppression Activation (MW)	HRR After Suppression Activation (MW)	Percent Reduction
Johnson	39.3	21.6	45
Johnson Shielded	22.8	15.3	33
Portal	31.1	6.5	79
Portal Shielded	30.4	6.6	78
Eisenhower	36	4-10	72-88
Eisenhower Shielded	36	7.8	78

Figure 14. Reduction in FHRR for various tests.

Figure 15 shows one Colorado fire test in more detail. As soon as the water spray is applied, the FHRR significantly decreases. It is not known why the data stops at 350 seconds. It could have stopped recording, been manually extinguished, or burned all the fuel.

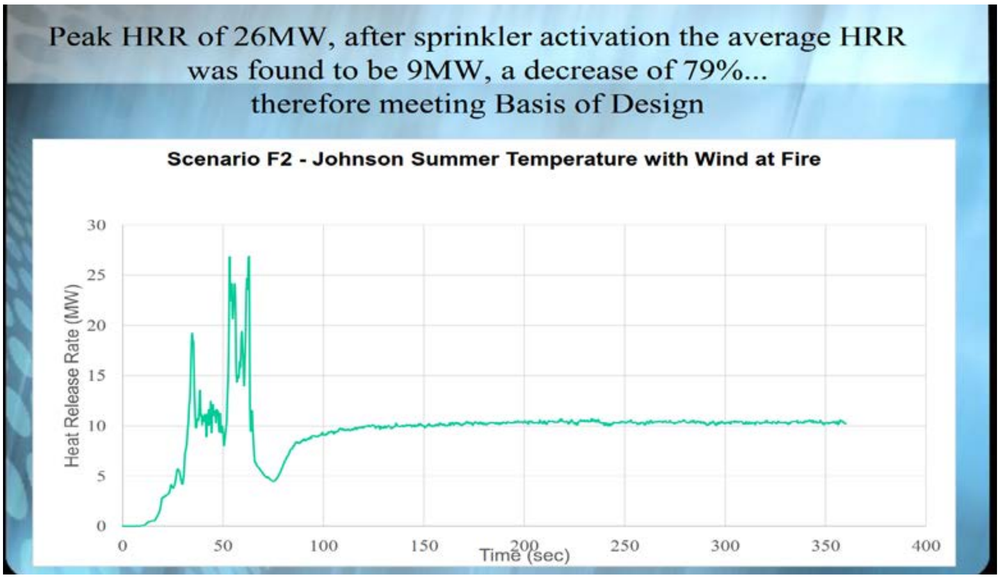


Figure 15. Detail of scenario F2.

Figure 16 shows the suppressed condition as the fire is much less intensive than it would be otherwise as evidenced by flame height.

Figure 16. Pan test with the water spray activated.

Figure 17 provides a more direct comparison with unsuppressed fires on the left and the reduced flames on the right with the water spray. While these tests were not a direct comparison of foam, they are another indication that water spray alone is a significant mitigation for flammable liquid fires. What is also significant is that they reinforce two important points.

- The fire growth rate is much faster than the 20 MW/minute criterion for this Project.
- The rapid detection and application is more important than the suppressant.

Figure 17. Fires before and after FFFS application.

SP Test of Flammable Road Tunnel Spill

Ingason (19) tested a spill configuration for gasoline and E85 conditions for the following scenarios:

- Free burn test determined the amount of time it took for a 6-square meter spill to be consumed.
- 10 mm/min-foam provided for a continuous fuel flow for two minutes and the application of a 10-mm/min foam and water mixture.
- 10-mm/min water provided for a continuous fuel flow for two minutes and the application of a 10-mm/min water spray.

Figure 18 shows the use of foam resulting in a significant reduction in peak fire heat release rate. However, the duration was only a small amount longer for the water application case. A similar test was done with 5 mm/min water application rate that showed little difference between the two.

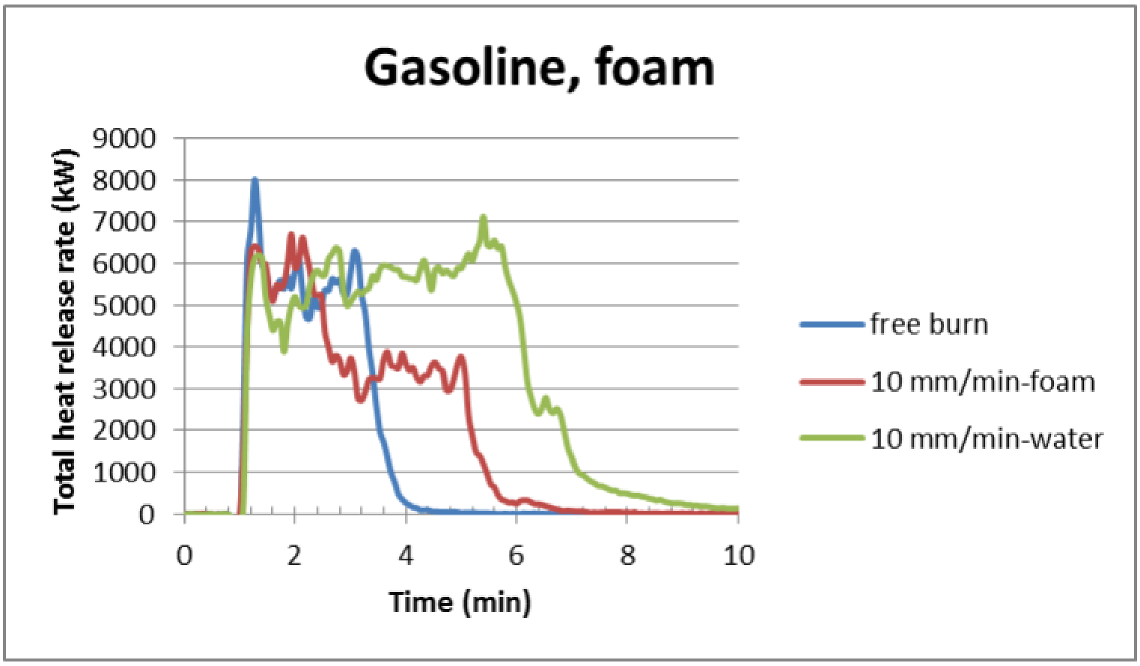


Figure 18. The measured total heat release rate for tests with gasoline fuel.

Discussion

Unlike solid fuel fires, there is much more uncertainty with regard to flammable liquid fires. The application of water sprays does mitigate the effects of these fires. The question has always been how much. The other factor that should be addressed is operational complexity. These fires are extremely rare, even among fire incidents and the hard question needs to be addressed if the benefit is worth the operational complexity of foam systems in addition to that of plain water?

CONCLUSION

There are significant benefits in providing FFFS for road tunnels. They have been shown to prevent the spread of fire to non-incident vehicles and minimizing the damage to road tunnels. This has a significant benefit particularly to critical transportation corridors. Water application rate continues to be the most important design parameter and yet no guidance is provided, leaving designers to figure it out each time. The determination of this parameter is very important as water usage must be optimized, particularly for restricted water supplies. The ability of these systems to mitigate FLT fires is not as well understood. The general practice has been to restrict their use or stipulate foam suppression. Both of these practices are facing pressure due to industry increased demand for usage. In short, FFFS implementation could be greatly enhanced by two considerations.

- Providing prescriptive water application rates reducing uncertainty in criteria and objectives.

- Implementing a test program for FLT performance that would help reduce the uncertainty of system performance on these types of fires and allow greater confidence that these fires can be successfully mitigated without foam systems.

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