Chapter 16
Fire Suppression and Detection in Tunnels

Abstract The basic concepts of fire suppression systems are depicted. There are mainly two water-based fire suppression systems used in tunnels, that is, water spray systems and water mist systems. The main differences are the water density, pressure, and droplet size. The extinguishment mechanisms are explored and the critical conditions at extinction are discussed. Further, suppression of realistic fires is discussed considering both the water flow rate and the total water flow rate used for fire suppression. A summary of fire suppression tests carried out in tunnels is presented followed by a short discussion of tunnel fire detection.

Keywords Fire suppression · Deluge · Water spray · Water mist · Surface cooling · Gas cooling · Extinction · Critical water flow rate · Fire detection · Fire tests

16.1 Introduction

Sprinkler systems in buildings and warehouses have now been used for over 100 years. The definition of a sprinkler system for buildings is found in NFPA13 [1]. The use of sprinklers in tunnels began in Japan in 1963 [2], however, there is still confusion about how to design sprinkler systems in tunnels. The most common system to date used in tunnels is the Fixed Fire Fighting Systems (FFFS), which includes all types of fixed *water-based systems* and *foam-based systems*. This classification depends on what the main extinguishing medium is. If the system uses a foam agent as the main extinguishing medium (light water foam, compressed air foam) it is referred to as a 'foam system'. On the other hand, if the system uses water as the main extinguishing medium (even with a small amount of foam additives), it is referred here to as a "water-based system".

The nomenclature used also depends on how the systems are constructed, activated, and operated. The most common systems applied in tunnels nowadays operate in zones (*deluge systems*), however, a few systems are activated by individual bulbs (*automatic systems*) which are the same as those used in buildings.

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For clarification, when discussing “FFFS” or “sprinklers” in this chapter it means all types of water-based FFFS by default.

Water-based systems can be divided into *water spray systems* and *water mist systems*, depending on the operating pressure and the water droplet size. If the system operates under low pressure (generally several atmospheric pressure), it is usually called a ‘water spray system’, whereas if it operates under high pressure (generally over 10 atm) with very small droplets it is referred to as a ‘water mist system’. Water mist systems can be subdivided into low pressure water mist systems (around 10 atm) and high pressure water mist systems (For example, 80 atm). Water spray systems and water mist systems (that is, water-based systems) are usually operated in zones that are remotely controlled by valves. More details on different types of systems are given in Sect. 16.2.

Depending on the performance in relation to a given fire, FFFS can be classified in different ways, however, there are no standard design fires against which the performance of the FFFS in tunnels can be tested or classified. Usually, one discusses the performance of water based FFFS in tunnels in terms of

- suppression of the fire,
- control of the fire, or
- thermal management of the fire.

The word ‘fighting’ from the acronym FFFS can be misleading in terms of performance of the system. The first priority is activation of the system (if necessary), then to protect the tunnel structure, reduce and prevent further development of the fire, and to mitigate the hazardous situation for tunnel users. It also should be a complement to firefighting operations.

Fire suppression, according to NFPA13 [1], is defined as “sharply reducing the heat release rate (HRR) of a fire and preventing its regrowth by means of direct and sufficient application of water through the fire plume to the burning fuel surface”. In the road tunnel standard NFPA 502, Standard for Road Tunnels, Bridges, and Other Limited Access Highways [3], suppression is explained in the informative part of the standard as “Fire suppression systems are designed to arrest the rate of fire growth and significantly reduce the energy output of the fire shortly after operation”. This text is more general than that written in NFPA13 [1].

Fire control is defined in NFPA 13 as “Limiting the size of the fire by distribution of water so as to decrease the HRR and pre-wet adjacent combustibles, while controlling ceiling gas temperatures to avoid structural damage”. NFPA502 [3] reads “Fire control systems are designed to significantly reduce or stop the rate of fire growth, but not necessarily to reduce the energy output of an established fire”. Here again, the text in NFPA13 is more detailed and specific.

The term *thermal management* could be related to the term “volume cooling systems” described in the Annex of NFPA502: “Volume cooling systems are designed to reduce the temperature of heated products of combustion, and of systems and tunnel structures, but may not have any direct effect on fire size or fire growth rate.”

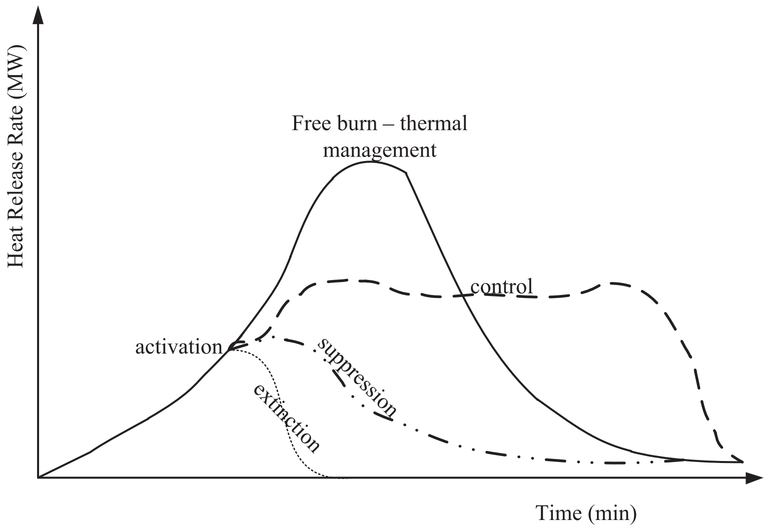

Fig. 16.1 A schematic of the performance objectives of water-based FFFS

There is one more performance possibly achieved by sprinkler systems, namely *extinguishment* or *extinction*. This means, a complete elimination of the fire HRR and protection of all the surfaces shortly after the system is activated. However, in tunnels extinguishment is mostly not the FFFS design objective. Further, most systems work in deluge mode, that is, operate in zones with a given water density. In contrast, in buildings extinguishment is much more easily obtained because most sprinkler heads operate automatically. This means that at the early stages of a fire the sprinklers right above the fire can operate with a very high water density. In Fig. 16.1, a sketch explaining each of the terms is given.

The terminology of "suppression" commonly used in tunnel fire safety may be slightly misleading as it is generally not meant to extinguish the fire or suppress it completely or efficiently. The idea is to arrest the flame volume so that the heat feedback is reduced immediately. At the same time, there is a need for delivery of water to cool the fuel surface to such a degree that the pyrolysis process is reduced significantly, although not completely. Usually, fires in solids are deep-seated and in order to extinguish the fire additional water density is required. The main difference between suppression and extinction is therefore the amount of water that reaches the fuel surfaces per unit area. When automatic sprinkler heads activate at an early fire stage in buildings they usually have an overcapacity in relation to their design criteria whereas deluge systems in tunnels do not. They simply deliver the designed amount of suppression media in each zone. On the other hand, they can cover larger areas and the risk that the fire will escape is significantly reduced. The idea of controlling fires instead of suppressing them comes from the awareness that a sprinkler system is designed to cover a certain area when all the nozzles have activated. In

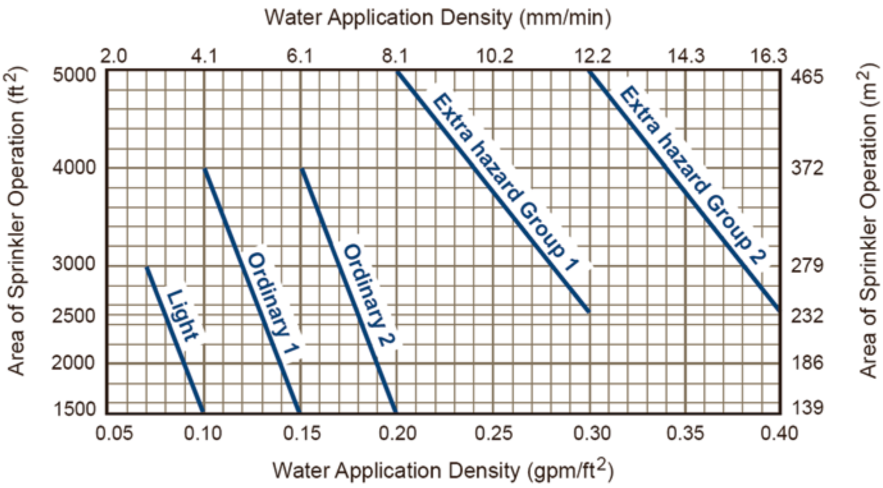

Fig. 16.2 A graph of necessary water density for sprinkler systems given in NFPA13

any case, the applied water density should be enough to control the fire, that is, control the rate of burning, and protect the structure.

The terminology of water density is related to the fuel that should be protected, however, it has been adapted to tunnels without any clear correspondence to the type of fuel. Numerous experiments were conducted in 1960–1990 with pool fires (sometimes referred to as Class B fires), and cars, small trucks and buses [2] (sometimes referred to as solid material or Class A fires). These results provided a basis for designing tunnels with 6 mm/min (6 l/(min m^2)) water density, which implies that a water density of 6 mm/min for a deluge system should be enough to control and prevent fire spread. In Australia, the water density in deluge systems is in the range of 7.5–10 mm/min, although tests using deluge systems with that density were not carried out in tunnels when adopting it. Large-scale tests using 8 and 12 mm/min have been conducted by the Land Transport Authority (LTA) in Singapore with good results [4, 5]. In the Benelux tests [6], water density of 12 mm/min were used. Most water mist systems use much lower water density, on the order of 1–4 mm/min.

It is interesting to compare these water densities with the NFPA13 standard for buildings. Figure 16.2 shows the water design area of the sprinkler system as a function of the water density. As the design area increases the water density requirement decreases, although the total applied water flow rate increases. The choice of a design line is based on the classification of the expected fuel load and activity in the building. The hazard groups are divided into different categories, see Fig. 16.2. Examples are given of different occupancy groups (three examples for each group are given here, for others see NFPA13):

- light hazard occupancies
  - churches
  - hospitals
  - restaurant areas
- Ordinary hazard occupancies (group 1)
  - Automobile parking
  - Electronic plants
  - Laundries
- Ordinary hazard occupancies (group 2)
  - Chemical plants
  - Machine shops
  - Paper process plants
- Extra hazard occupancies (group 1)
  - Plywood and particle board manufacturing
  - Saw mills
  - Upholstering with plastic foam
- Extra hazard occupancies (group 2)
  - Flammable liquid spraying
  - Plastic processing
  - Solvent cleaning

It is clear from this classification that there is a correlation to tunnel occupancy in the form of vehicles and other types of fuel load, for example in the cargo of a heavy goods vehicle (HGV). The sprinkler systems are designed to control the fire within a given design area (area of operating sprinklers). According to NFPA13, this area varies from 140 to 465 m^2, as shown in Fig. 16.2. If we assume that we have a tunnel that is 10 m wide, this would correspond to a zone length of about 15–50 m, which is within the size of zone lengths designed for tunnels today. In Sect. 16.2, these zone lengths will be discussed in more detail. In tunnels, the average fuel density over the protected zone is usually much lower than in buildings, although the local fuel density in tunnels could be higher. Further, the ventilation conditions are very much different in tunnels and can play an important role. It is, however, clear that the water density design for tunnels has a reasonable correspondence with building water density.

16.2 Basic Concepts of Fire Suppression Systems

In the following text, a detailed description of different types of FFFS is given. As mentioned earlier, the fire suppression systems in tunnels can be categorized into water-based FFFS and foam systems. Water-based FFFS can be subdivided into deluge water spray systems and water mist systems, both with and without the use of foam additives. All of these systems have been applied to tunnels, although deluge systems without additives represent the vast majority of the installed systems.

16.2.1 Deluge Water Spray System

16.2.1.1 General Description

Deluge water spray systems consist of open sprinklers[1] or water spray nozzles[2] attached to pipework at the tunnel ceiling. The pipework consists of mains pipes, manifold pipes, feed mains, and branch pipes. The sprinklers or nozzles are attached to the branch pipes, which are typically arranged in a uniform pattern at the ceiling to distribute spray to all sections of the roadway. The branch pipes are connected to a feed main which is connected to a deluge valve. The deluge valve is mounted on a manifold attached to a mains pipe that is supplied by one or more water reservoirs or fire pump stations. Mains pipes are normally water-filled up to the point of connection to the deluge valve. Therefore, the mains pipe and the deluge valves must be protected against freezing. The deluge valve separates the water-filled mains pipe from the empty (dry) feed main and branch pipes supplying the sprinklers or spray nozzles. When the deluge valve is opened, water flows into the feed main and branch pipes and discharges from the open sprinklers.

The branch piping is divided into deluge zones, typically 25–50 m in length, each served by its own deluge valve. An independent fire detection system that is capable of locating a fire accurately is required, so that the deluge valve serving the zone where the fire is located can be released. The deluge valve can be opened either automatically by the detection system, or manually by a signal from the tunnel operator. If an incident occurs on the boundary between two deluge zones, both zones may need to be activated. When the deluge valve opens, water flows into the feed main and branch piping and discharges from all sprinklers or nozzles in that deluge zone. As the water spray nozzle (or sprinkler head) orifices are open, the branch piping is at atmospheric pressure until water is introduced. A water spray system has a time delay between detection of a fire and the discharge of water from the sprinklers or nozzles due to the time required to operate the valve (which depends on whether activation is automatic or manual) and to fill the branch piping network with water and reach the desired operating pressure.

According to recommendations provided in NFPA 502 [3], standard water spray nozzles should be spaced such that the coverage of the water spray extends to the roadway shoulders and, if applicable, maintenance and patrol walkways. The system should be designed with sufficient water capacity to allow simultaneous operation of at least two consecutive deluge zones, but depending on the precision provided by the detection system, it may be necessary to design for three operating zones, one in the incident area, and the adjacent upstream and downstream zones.

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[1] An open sprinkler is a sprinkler that does not have actuators or heat-responsive elements.

[2] An open spray nozzle is an open water discharge device that will distribute the water in a specific, directional pattern. Spray nozzles are typically used in applications requiring special water discharge patterns, directional spray, or other discharge characteristics.

The length of the deluge zones should be coordinated with the pumping capability as well as the fire detection and ventilation zones. Piping should be designed to allow drainage of water from all piping between the deluge valve and the sprinklers or nozzles after the flow is stopped.

16.2.1.2 Specific Technical Information

The length of deluge zones typically varies from 25 to 50 m. Standard water spray nozzles, which typically require a minimum operating pressure of 1.5–5 bar are used and they discharge a uniform pattern of water droplets over the protected area with droplet sizes less than 2 mm in diameter. The water discharge density over the length of the deluge zone or predefined area commonly in tunnel fires is in the range of 6–12 mm/min (l/(min m^2)). The K-factor of the nozzles is typically 80 L/(min $bar^{1/2}$). Tests with fires having potential free burning HRRs in the order of 25–140 MW have been conducted with deluge water spray systems.

The most suitable length of the deluge zones must be based on the width of the tunnel and the capacity of the water supply. Large zones will reduce the number of control valves but require a higher total water demand [7]. The typical application rates and zone sizes can result in flow demands in the range of 7500–15,000 L/min, which can have a significant impact on supply and drainage system requirements [8]. This value is very much dependent on the tunnel width. For example in a 15 m wide tunnel, a density of 10 mm/min, and a two operating deluge zones each having a length of 50 m would require 15,000 L/min. If the tunnel width is 10 m instead, the corresponding flow would be 10,000 L/min, which is significantly lower.

The type of fire detection device is selected, mainly, based on the hazard (For example, smoke detectors, heat detectors, CCTV, or optical flame detectors). The initiation device signals the fire alarm panel, which in turn signals the deluge valve to open. Activation can also be manual, depending on the fire protection objectives of the system. Manual activation is usually done via an electric or pneumatic fire alarm pull station, which signals the fire alarm panel, which in turn signals the deluge valve to open. According to the SOLIT guidelines [9], water spray systems may be activated and operated manually or automatically depending on the availability of trained personnel, the risks expected, the type of water spray system, the control systems used, and applicable legislation. NFPA 502 [3] recommends that the time delay should not exceed 3 min in order to prevent the development of a major fire. NFPA 502 also say that automatic fire detection system should be able to detect a tunnel fire incident of 5 MW or less within 90 s or better in testing environment of 3 m/s. More information on fire detection in tunnels is presented in Sect. 16.5.

The UPTUN [10, 11], and SOLIT [9] guidelines recommend that the installation of pumps shall comply with the manufacturer's documented requirements. Pumps shall be installed in a dedicated pump room or other designated area. Adequate ventilation and drainage shall be provided. The pump room shall be lockable to prevent access of unauthorized personnel. Deluge water spray systems shall be designed to provide at least 110 % of the nominal flow rate required for the most demanding protection area in the tunnel. This flow rate shall be calculated at the minimum nozzle pressure as tested in large-scale fire tests and shall be provided by one or more pumps.

According to the SOLIT guidelines [9], the duration time shall be determined in a specific risk analysis for every individual tunnel. The system shall be capable of a minimum activation time of 30 min, although longer activation times are normally required. A minimum of 60 min shall be used for tunnels longer than 500 m, however, in practice 90–120 min are probably necessary to account for the response capabilities of the fire department.

Deluge water spray systems are mostly installed in Australia and Japan.

Australian Deluge Systems Australia has installed FFFS systems into its road tunnels since the Sydney Harbour Tunnel was opened in 1992. Currently, there are 19 tunnels with water spray systems in operation. A deluge valve station is generally located every 120 m along the tunnel length. This location coincides with the location of cross passages or egress passages and therefore the valves are located inside a fire rated space. The deluge valves are designed and timed to open and close automatically as the valves are at a considerable distance from the tunnel operations control room. This means that the operator can open and close deluge valves as required during a fire scenario, especially if the fire moves or spreads.

The deluge zone length can vary but has generally been designed around a deluge zone area of 300 m^2 which covers the full width of the roadway. Consequently, the length of the deluge zone can vary according to tunnel width. The system is designed for simultaneous activation of, however, many zones are required to provide complete coverage of the maximum length vehicle that uses the tunnel plus allowance to cover the possibility that the vehicle may be at the boundary of two zones. Currently, common practice is to provide a water discharge density of between 7.5–10 mm/min in road tunnels. Australia also has some tunnels which are only used by buses. The water discharge density for these tunnels is generally 6 mm/min. In a fire scenario, the system flow rate is designed to operate for 60 min at full flow while a number of hydrants operate simultaneously. Pumps and tanks (if required) are duplicated so that no single failure can affect the water spray system performance.

Activation of the water spray system is usually by manual operation from a remote Control Room. The operator receives an alarm from one or a number of detection systems such as a Video Automatic Incident Detection (VAID) system, linear heat detection system, other Closed Circuit TV (CCTV) cameras and/or manual alarm calls. On receipt of the alarm, the operator confirms that there is a fire event and activates the water spray system. Most systems are configured so that on alarm, unless the operator intervenes, the water spray system activates. However, the operator can initiate the system prior to automatic operation. The operational intent is to activate the FFFS as soon as possible while the fire is still small, that is, less than 10–20 MW [12].

Japanese Deluge Systems Japan introduced deluge systems into its high risk urban tunnels 40 years ago, and currently there are over 120 systems in operation. Different technical solutions are applied, depending on the owner of the tunnel. The Japanese deluge water spray systems are designed for 6 mm/min. The pressure at the nozzle location is between 3 and 3.5 bars. There are either 50 m spray zones or 100 m spray zones. Depending on the owner there are different distances between nozzles in each zone. Water reservoir capacity should be designed as 40 min for the operation time for two deluge zones (50 or 100 m) [14]. System design and operation is as follows [13]:

1. Flame detectors are located on tunnel side walls at 1.1–1.3 m height with 10–13 m spacing within the whole section for initial detection of the fire
2. The fire location is confirmed in the Control Room by CCTV, at which time the deluge system is manually activated for a 50 m zone around the seat of the fire until the fire brigade arrives to the fire site
3. To minimize the risk of fire spread, one additional deluge zone will be activated.

Technically, the Japanese water and foam sprinkler systems are automatic in design in combination with fire detector and automatic valve control. However, as automatic operation of sprinklers could cause a traffic accident, the tunnel operator must recognize the fire and confirm its existence by CCTV, before starting the sprinkler system. Once the fire has been visually confirmed, the sprinkler system is started manually as quickly as possible [13].

Swedish Simplified Deluge Water Spray System In 2012, the Swedish Traffic Administration started to install a simplified deluge water spray system in the tunnel of the Northern Link. An improved version of the concept is also planned to be used in the Stockholm Bypass when it will open in 2020. In total, the system will be installed in 50 km of tunnels.

The design considerations were: simplicity, robustness, investment cost, and maintenance issues. To meet these design requirements the system consists of:

- A single pipe in the centre line of the tunnel ceiling, fitted with two extended coverage nozzles (large K-factor nozzles) directed horizontally toward each of the tunnel walls. The entire cross section of the 14 m wide tunnel is covered with only one pipe. The nozzles used for the Northern Link have a K-factor of 240 (L/(min·bar$^{1/2}$)) and the nozzles for the Stockholm Bypass have a K-factor of 360 (L/(min·bar$^{1/2}$)).
- Long sections of 50–75 m are used and they are designed to deliver 5–10 mm/min without the use of any water additives. A lower water density is acceptable if two sections are activated due to a fire between them,
- The deluge water spray system is combined with the fire hydrant system, reducing the need of water mains in the tunnel to only one,

- The water supply is obtained by connection to the public water supply, and no additional pumps are required. This means that the duration time of the water supply is virtually unlimited.
- Thermoplastic-coated steel pipes and clamp couplings instead of welded stainless steel pipes have been used.

The main purpose of the system is to limit the fire size and prevent fire spread during the evacuation period in congested traffic situations. When the traffic is flowing freely the need for the system is regarded as minor. The system can be manually operated from the Traffic Control Centre based on detection by CCTV, or from the tunnel escape routes where the deluge valves are located. The system also starts automatically if a heat sensing cable detects high temperatures from a fire. The sprinkler pipes are self-draining due to the risk of freezing. In winter, the temperature in the traffic space is expected to drop below −20 °C.

16.2.2 Water Mist Systems

Water mist systems are fundamentally similar to deluge water spray systems, that is, the pipework consists of a water-filled mains pipe, manifold, deluge valves, dry feed main, and branch pipes to which the nozzles are attached. The mains pipe is connected to a water supply and the pressure is generated by pumps. Water mist deluge systems may vary with respect to their working pressures, that is, low and high pressure mist systems. The piping or tubing utilized in the system must be designed for the corresponding operating pressure. To protect against plugging of small orifice nozzles, water mist systems utilize corrosion resistant materials such as stainless steel pipe or tubing. The primary difference between the systems are the percentage of smaller droplet sizes (as a rough estimation the droplet size is inversely proportional to the pressure applied), and the momentum of the spray ejected from the nozzles (for a given water flow rate the spray from a high pressure nozzle has a higher momentum than that from a low pressure nozzle).

According to the definition given in UPTUN guidelines [10] the general principle of the low pressure water mist system is to produce a fog (or mist) of small water droplets at a nozzle pressure of 3–10 bar. The high pressure water mist system produces a fog (or mist) with a mix of different sizes of water droplets at a nozzle pressure of 60–120 bar.

According to the Annex table in the UPTUN document [11], the total water flow rate per 25 m zone for low pressure systems (without additives) is in the range of 221–683 L/min, and for high pressure systems, 140–550 L/min. Note, however, that the total water flow rate depends on the tunnel width, zone length and the number of zones operating. One zone of 25 m in a 10 m wide tunnel, at 2.3 mm/min, would require 575 L/min. Designing for two zones would require a pumping capacity of 1150 L/min (+ 10 % of the nominal flow required), and for three 25 m zones, 1725 L/min (+ 10 %). If the tunnel is more than 10 m wide and the zones longer than 25 m, the hydraulic demand and pump capacity is much higher. The discharge rate for low pressure systems is in the range of 1.1–3.3 mm/min and for high pressure systems 0.5–2.3 mm/min. Note that the design application densities are based on a density per unit area of coverage (l/(min m^2) or mm/min). They are sometimes converted to another measure often used when discussing water mist systems, namely a volumetric density expressed as a flow rate per volume (L/(min m^3)) by dividing mm/min by the ceiling height of the tunnel in meters. This means that for two tunnels with the same width but different tunnel heights, the water spray densities are identical when expressed in terms of tunnel area, but very different when expressed in terms of volume. The K-factor for a high pressure system can vary between 4.0–5.5 L/(min bar$^{1/2}$). The length of each zone can vary from 20 to 25 m and up to three zones can be used at once.

The water mist systems use significantly less water than deluge water spray systems. On the other hand, they require significantly higher pressure, especially the high pressure system. As a result, pipes, tanks, and pump capacities can be smaller, and the water demand be lowered. Likewise, drainage volumes can potentially be lowered [12].

According to the SOLIT guidelines [9], a high pressure water mist system applies nozzle pressures above 35 bars. Low pressure water mist systems apply nozzle pressure of less than 12 bars. The medium pressure water mist systems apply nozzle pressure between 12–35 bar. Water mist systems apply small water droplets as the firefighting agent. The diameter of drops contained in a volume of spray from a water mist nozzle, that is, the "Dv0.90" value (meaning that 90 % of the volume of the spray is contained in drop sizes of less than 1 mm) is measured in a plane 1 m from the nozzle at its minimum operating pressure [9]. NFPA 750 uses a "Dv099" value instead of a "Dv0.90" value to define a "water mist". The NFPA 750 definition ensures that almost no drops are larger than 1 mm in diameter.

Centrifugal pumps are typically used for low pressure and medium pressure systems, whereas positive displacement (PD) pumps (or assemblies of PD pumps) are typically used for medium and high pressure systems. For the pump capacity, the same rule should be applied as for water spray systems. The minimum output capacity for positive displacement pumps, or assemblies of PD pumps, shall be 90 L/min. The minimum capacity for centrifugal pumps shall be 750 L/min. The water tank shall be suitable for providing water for all simultaneously activated sections (typically two or three) with the required flow rate based on the defined minimum period of operation [9].

16.2.3 Foam Systems

There are mainly three types of foam systems. A foam water spray system with injected foam concentrates into the water supply, a high expansion foam system (Hi-Ex), and compressed air foam (CAF).

A foam water spray system is a specific application system, discharging low expansion foam, resulting in a foam spray from the sprinkler. Foam water spray systems are effective in controlling fires involving flammable liquid spills in tunnels, but they are also effective against conventional lorry fuel load fires [15]. Systems using injected foam concentrates can be both deluge water spray systems and water mist systems, as described in Sect. 16.1.

The discharge density needed in order to extinguish or control flammable liquid fires using water with a film forming additive is reasonably well established. Information is given in NFPA 16, which recommends an average discharge density of 6.5 mm/min. Large-scale fire suppression tests in tunnels show good performance for foam-water sprinkler systems. In tests conducted by Arvidson in 2010 [16] water and foam additives (3 % AFFF) were pumped from a container to the deluge zone with nozzles. The tests showed that the effectiveness of the deluge foam-water spray system was not negatively affected by a longitudinal ventilation velocity of 4.2 m/s. The test fires were extinguished in less than 30 s.

Technology involving CAF [17] or Hi-Ex [18] has been tested against both solid and liquid fuel fires. These foam system tests demonstrated a good degree of fire control. As pointed out by Mawhinney [15] neither the CAF nor Hi-Ex systems have been widely accepted for use in tunnels. One reason is uncertainty about the potential loss of visibility for firefighting and rescue operations, particularly with Hi-Ex foam.

16.2.4 Mode of Operation

There are different types of operation modes presented by different manufacturers. The most common is the deluge mode. Mawhinney and Telles [19] presented three modes of operation: the deluge mode, the sprinkler mode, and the hybrid mode. The major difference between the modes is the amount of water discharged outside the immediate fire region. This forms the basis for the attempt to reduce costs without weakening firefighting performance.

In the deluge mode, all nozzles are open. Opening the zone valve leads to water discharge from all the nozzles in the zone as soon as the piping is filled and pressurized. This mode applies the highest total amount of water compared to the other two modes.

In the sprinkler mode, automatic nozzles are used, meaning each nozzle is individually activated by heat from the fire. Water flow into the branch pipes serving the automatic nozzles is controlled by a zone control valve. Under normal conditions, the nozzles are covered with protective caps that protect the heat sensitive glass bulbs from dirt and mechanical impact and, in case of fire, prevent bulbs from breaking by heat in inactive zones further away from the fire. The branch piping does not contain water unless the zone control valve is opened, either manually or automatically by an independent fire detection system. At activation, the branch piping in the zone is filled with water, and the protective caps within the pressurized zone are hydraulically released. Nozzles will begin to activate in areas with sufficient heat. Even if heat spreads beyond the fire zone, water will only be released from nozzles where the zone control valve has been opened. The sprinkler mode applies the lowest total amount of water of the three concepts.

The hybrid mode is a combination of deluge and sprinkler modes, with half of the nozzles being automatic nozzles and the other half open nozzles. Open nozzles and automatic nozzles are spaced sequentially along each branch pipe. Opening the zone valve leads to immediate discharge of water from the open nozzles as well as removal of the protective caps from the automatic nozzles. This approach ensures that only the automatic nozzles closest to the seat of the fire discharge water, such that the maximum water discharge density is focused on the actual fire region while additional cooling is obtained remotely from the fire region within the activated zones. The hybrid mode of operation could use significantly less water than a deluge system.

There are water-based FFFS available which are designed to share the pipe and pump units with a hydrant system.

The operation of foam systems is similar but not discussed further here.

16.3 Tunnel Fire Suppression Tests

There have been many FFFS tests conducted in full-scale or large-scale tunnels. Several tests were carried out in Japan, for example, Futatsugoya tunnel fire tests in 1969 [14], Kakeitou Tunnel fire tests in 1980 [20], and New Tomei Expressway tests in 2001 [14]. However, these tests were not well documented and technical information was very limited. After 2000, several series of large-scale fire suppression tests have been conducted in tunnels, most of which were performed in Europe. These reasonably well documented tests are summarized in Table 16.1, and the results are briefly discussed below. There are also some model-scales tests that have been conducted, for example [21, 22], but not included here.

16.3.1 Second Benelux 2000–2001

During 2000 and 2001, 14 large-scale fire tests were conducted in the Second Benelux Tunnel near Rotterdam in the Netherlands [6].

The test tunnel had a rectangular cross section with the width 9.8 m, the height 5.1 m, and a length of 980 m. The intended traffic direction was unidirectional. The slope of the tunnel was maximum 4.4 % and its lowest point was in the middle of the tunnel. The tube had two traffic lanes. Six fans were installed in the upstream tunnel opening to create longitudinal ventilation air flows up to 6 m/s. The test area was located 265 m from the downstream portal. Measurements were taken in an area ranging from 50 m upstream to 200 m downstream of the fire.

Table 16.1 A summary of tunnel fire tests with water-based fire suppression systems

Test	Year	Number of suppression tests	Fire suppression	Tunnel length (m)	Tunnel width (m)	Tunnel height (m)	System configuration	Water flow rate (mm/min)	Activation time or type	V (m/s)	Fire source	HRR Free-burn (MW)
2nd Benelux, Netherland	2000–2001	4	Water spray	980	9.8	5.1	17.5 m + 20 m	12.5	4–21 min	0–6	Simulated truck load	5–30
IF tunnel, Norway, UPTUN	2002–2004	19 low, 56 high[a]	Low pressure mist High pressure	100	8	6	24 m 36 m	1.1–3.3	Mostly 2 or 3 min	3	Pool, pallets, vehicle	2–25
IF tunnel, Norway, Marioff	2004	24	High pressure	100	8	6	24 m (1 zone)	1.4–3.7	2 or 3 min	3	Pool, pallets	5–25
VSH Hagerbach, Marioff	2005	10	HI-FOG	200	9.3	2.55	NA	NA	10 min	3	Automobile car	5–30
San Pedro de Annes, Spain, Marioff	2006	40	HI-FOG	600	9.5	5.2	72 m (3 Zones)	3.7–4.3	Hybrid Most 5–7 min	3.5	Pallets	75/90
Runehamar, SINTEF and Effectis	2007	5		1600	9	6	75 m (3 Zones)	NA	1.5–7	3–4	Pallets, pool	200

Table 16.1 (continued)

Test	Year	Number of suppression tests	Fire suppression	Tunnel length (m)	Tunnel width (m)	Tunnel height (m)	System configuration	Water flow rate (mm/min)	Activation time or type	V (m/s)	Fire source	HRR Free-burn (MW)
San Pedro de Annes, Spain, SOLIT	2008	50	Water mist	600	9.5	5.2	NA	NA	NA	NA	Pallets, pool	200
San Pedro de Annes, Spain, SOLIT2	2011–2012	30	Water mist	600	7.5	5.2	60 m	NA	3 min	2–3	Pallets, pool	5–160
Singapore tests	2011–2012	7	Water spray	600	7.2–9.5	5.2	50 m	8–12	4 min[b]	3	Pallets	150
Runehamar, SP	2013	6	Water spray	1600	9	6	30 m	10	2–12 min[b]	3	Pallets	100

NA Not Available

[a] 19 Low pressure mist tests and 56 high pressure mist tests with 8 free-burn reference tests

[b] delay time after "fire detection"

The performance of open deluge water spray systems was tested in four fire tests with simulated truck loads, tests 11–14. Test 11 consisted of one van loaded with 18 wood pallets having a total weight of 400 kg (18) pallets, with three tyres placed on top. Tests 12 and 13 had an aluminum covered truck load and test 14 had an open truck load. The open truck load consisted of 72 wood pallets and six tires having a total weight of 1600 kg. The aluminum covered truck loads consisted of 36 wood pallets with four tires on top and had a total weight of 800 kg stacked under an aluminum cover with the rear side open.

The open deluge system was designed with a water discharge density of 12 mm/min and consisted of two sections. Section 1 was directly above the fire and contained two parallel rows of sprinklers along the tunnel. Each row had a length of 17.5 m. Section 2 contained two rows of sprinklers, each with a length of 20 m, and was placed downstream of the fire next to Section 1.

In tests 11, 12, and 13, both sections were activated after 14, 4, and 10 min, respectively. In test 14, Section 1 was activated after 21 min and Section 2 was delayed by 10 min, that is, it was activated after 31 min. The chosen activation time was determined based on the objective of the test. The purpose of test 11 was to examine steam production by heating the van as much as possible before activation of sprinklers. The purpose of tests 12 and 13 was to determine the visibility reduction due to water droplets, steam, and smoke. The systems were activated as soon as possible after detection or after the time required to stop the traffic and evacuate the tunnel. In test 14, the effects of heating a tanker or truck near the fire and then cooling it with sprinklers were investigated. For all the tests, the systems were activated manually.

In test 11, the fire reached approximately 7.2 MW at 14 min when the two sections of spray systems were activated. After activation, the HRR decreased to 5 MW at around at 20 min and to 1.6 MW at 25 min. In test 12, the fire reached 6.3 MW at around 4 min and the two sections of water sprays were activated. After activation, the HRR was not measured. In test 13, the HRR reached around 13.5 MW at 10 min and then the two sections of water sprays were activated. After activation, the data were again not available. However, it can be seen from the temperature measurements that all the thermocouples measured ambient temperatures. Therefore, the fire should have been effectively suppressed, that is, extinguishment was achieved. In test 14, the fire reached its peak value of 26 MW at 11.5 min and started to decrease from 18 min. Section 1 was activated when the HRR decreased to 14 MW and the HRR continued to decrease. The fire was 1 or 2 MW at 30 min when Sect. 2 was activated. Note that based on the fuel types and configurations, one may estimate the peak HRRs for tests 11 to 13 to be 7.2, 14, 14 MW. Therefore, in all the tests except test 12, the water sprays systems were activated after the fires had approximately reached their peak HRRs.

Further, the water spray systems reduced gas temperatures significantly and the risk of fire spread was also reduced. The temperature downstream did not attain lethal tenability and steam production was insignificant. However, the visibilities in these tests were reduced so that escape routes were difficult to detect.

16.3.2 IF Tunnel, UPTUN 2002–2004

In the framework of the UPTUN project [23], two series of fire suppression tests were carried out in the IF tunnel, primarily a training tunnel, located the south of Oslo in Norway, including 19 low pressure water mist tests and 56 high pressure water mist tests. In each series of tests, eight free-burn tunnel fire tests were conducted for reference.

The fire sources were mainly diesel pool fires in pans. This creates a relatively thick fuel bed and the mass burning rate per square meter fuel will be much higher compared to thin fuel layers that float on a road surface. Further, the water sprayed into the fire source is contained in the pan along with the fuel, rather than washing the flammable liquids away as in a realistic leakage fire. Therefore, these types of liquid pools cannot simulate realistic fire sources in tunnels. Besides the pool fires, in each series of tests, two tests were carried out using 80 wood pallets as the fire sources and one test using small vehicles.

The low pressure water mist system had one row of nozzles below the ceiling with a length of 20 m, and two rows placed in the corner between the floor and the tunnel wall, with a length of 16 m. The high pressure mist systems had three rows of nozzles at the ceiling level.

The low pressure water mist systems had an operating pressure ranging from 5 to 9 bar, and the high pressure systems had an operating pressure ranging from 60 to 120 bar. It was reported that the water droplets produced by the nozzles used in both systems were much smaller than 1000 μm (1 mm). The applied water flow rates were in a range of 1.1–3.3 mm/min for low pressure water mist systems, and in a range of 0.5–2.3 mm/min for high pressure water mist systems. In most of the tests, the fires were only controlled but not extinguished.

16.3.3 IF Tunnel, Marioff, 2004

In 2004, Marioff [24] conducted 24 fire suppression tests in the IF tunnel in Norway. The tunnel cross-section has a shape of a horse shoe. Three rows of sprinklers were installed consisting of one at the center line of the tunnel and right below the ceiling, and the others placed on sides of the wall. The spacing between the nozzles, that is, spray heads, was 3 m in most of the tests and 4 m for the last five tests.

Trays of diesel and/or different numbers of wood pallets were used as the fire sources. Each tray had a dimension of 1.4, 1.6, and 0.4 m. There was always a 1.1 m high wall vertically placed in the front of the first two pools to simulate a blocking effect. Further, in some tests, a steel plate was placed at a short distance above the pool fires and covered 75 % of the pool area. The HRRs ranged from 5 to 25 MW. The water flow rate can be estimated to be in a range of 1.4–3.7 mm/min.

In most of the tests, the fires were controlled but not extinguished. However, gas temperatures were reduced significantly.

16.3.4 VSH Hagerbach, Marioff, 2005

Mawhinney [25] and Tuomissaari [24] described a series of tests involving passenger automobiles in a tunnel with a low ceiling height, carried out in 2005 at the Versuchstollen Hagerbach (Hagerbach) tunnel research facility in Sargans, Switzerland. The test tunnel was representative of the "A86" passenger vehicle tunnel on a highway encircling Paris, France. The A86 passenger vehicle tunnel was approximately 9 m wide and 2.5 m high. The tunnel sloped upward in the direction of travel at approximately 2 % slope, with a transverse gradient from left to right. Fuel from ruptured fuel tanks drained downhill and across the tunnel floor. The tests simulated the fire scenario in the tunnel involving a collision of two or more passenger cars.

Instrumentation was installed near the tunnel discharge to measure oxygen depletion in order to estimate the HRR. These tests showed that fires in passenger automobiles in a tunnel (before activation of the water mist system) typically exceeded the peak HRR from NFPA 502 of 5 MW per automobile. With tunnel ventilation at approximately 3 m/s, a group of three passenger cars created fires with peak HRR between 25 and 35 MW. The HRR for three vehicles would have been approximately 15 MW. With a peak HRR two times larger than the design fire, the additional heat and buoyancy may overwhelm the ventilation system and the time available for egress and rescue decreases. The risk of fire propagation to additional vehicles in the tunnel increases.

The fire scenarios consisted of a three-automobile fire in a two-lane and three-lane configuration. The primary differences included the number of vehicles surrounding the group involved in the fire and the relationship of the vehicles to the overhead lines of nozzles. In the "two lane" scenario, there were no vehicles to the right of the fire group.

The water mist system consisted of two zones of 33 m length with three lines of nozzles attached to the ceiling. The water mist system was activated manually based on a visual assessment of the size of the fire. All nozzles were 90° spray cone nozzles operating at approximately 80 bar pressure. The distance between the lines of nozzles was 2.8 m. The system operated as a deluge system with all nozzles flowing.

In the tests, the longitudinal velocity was initially 6 m/s, and then reduced to 3 m/s over a 4 min period after ignition. The tests results show that the fire spread to adjacent vehicles was prevented after activation of the fire suppressions system.

16.3.5 San Pedro de Anes tests, Marioff, 2006

Marioff Corporation conducted a series of full-scale fire tests in the San Pedro de Anes Test Tunnel facility in Asturias, in northern Spain, between February 2 and 27, 2006 [24, 25]. The objective of the tests was to evaluate the performance of a HI-FOG water mist system against very large fires in fuel packages similar to HGV trailer loads. Eleven tests were conducted—most using standard European wood pallets placed on a platform to simulate the elevated load of a HGV trailer. These were referred to as "standard severity" fire packages. Two of the fire tests were conducted using wood pallets interspersed with high density polyethylene pallets (16 % by weight); these are referred to as "high severity" fire packages.

The fuel packages with wood-pallets only could potentially reach 75 MW under unsuppressed conditions. Similarly, the high severity-fire fuel packages with polyethylene pallets were estimated to have a potential peak HRR of 95 MW under unsuppressed conditions. In addition to the type of fuel package, the wind conditions in the tunnel, the location of the fuel load relative to the lines of nozzles, and water pressure were varied. The longitudinal wind-speed varied from less than 2–3.5 m/s; the fuel load was placed under the middle line or between two lines; and the water mist system was operated at nominally 100 bar or 80 bar end nozzle pressure. In addition, the fuel load was tested with and without a wind-break panel on the rear face of the fuel package—intended to simulate the effect of the solid rear doors and solid forward cab that are typically found on HGV trailers.

The water system consisted of three consecutive sections of 24 m each. Each section was equipped with three lines of sprinklers with a horizontal spacing of 4 m and longitudinal spacing of 3 m. Three modes of activation were tested, that is, the deluge mode, sprinkler mode, and the hybrid mode. The sprinkler mode used a dedicated protective cap for each section. After a section valve was opened all the protective caps in that section were released and the sprinklers were exposed to the hot gases. The hybrid mode was a mixture of deluge and sprinkler systems. Every other sprinkler was a closed sprinkler nozzle. The nominal volumetric flux density in all cases was nearly constant, ranging between 3.7 and 4.3 mm/min.

In every test, the fires were prevented from achieving their full potential by the water mist system. The water mist system reduced the HRR of the "standard severity" fires to between 20 and 37 % of their peak potential HRR of 75 MW. For the two high severity tests, the water mist system reduced the fires to 68 and 29 % of the peak potential HRR of 95 MW.

The thermal management of the water mist system was evaluated based on the ceiling temperatures at the end of the water mist zone, and in the 15 m section directly over the fuel package. The temperatures at the ceiling at the end of the water mist zone were typically as low as 80 °C, although in one test the temperature was as high as 213 °C. At an elevation of 1.5 m above the roadway and from 8 to 15 m downstream from the end of the mist zone, the average temperatures were below 65 °C.

In five out of 11 tests, between 28 and 60 % of the available fuel remained unburned after the test. In the remaining 6 tests, all available fuels on the platform burned. The high severity fuel packages were entirely consumed in both tests.

The water mist system prevented the ignition of target arrays in all but one fire. In that fire (T14, between two lines), the top three pallets on the target located 4 m away ignited. No ignition occurred in any targets located more than 4 m away from the end of the fuel package [24, 25].

16.3.6 SINTEF Runehamar Tunnel 2007

SINTEF, together with Efectis Nederland BV [26], conducted several fire suppression tests during December 2007 and January 2008 in the Runehamar tunnel in Norway. The fire scenarios were pool fires and solid fuel fires, each with a nominal HRR of up to 200 MW. The prime objective of these tests was to determine the suppression and extinguishing effect of a water mist system on fully developed fires. These tests were carried out by SINTEF NBL and Aquasys upon request of Rijkswaterstaat, the department within the Ministry of Public Works of The Netherlands that is also responsible for tunnel safety. These tests were designed to serve as a unique opportunity to obtain experimental data on the risk of a BLEVE (Boiling Liquid Expanding Vapor Explosion) in the area immediately downwind of the fire, and also to perform measurements on the tenability conditions along the first few 100 m downstream of the fire.

The largest solid fire load consisted of 720 pallets, configured to represent a loaded HGV. The fire pool consisted of diesel fuel and had a surface area of 100 m^2. The BLEVE-risk and the tenability conditions were investigated. However, no data about the HRR in the fire suppression tests are available.

16.3.7 SOLIT 2008 and SOLIT2 2012

In the SOLIT project [27], more than 50 fire tests were carried out in the San Pedro de Anes test tunnel with water mist systems. The tests included 25 truck fires with a potential HRR of almost 200 MW and pool fires with surfaces partly covered creating a HRR of up to 35 MW. The HRRs of two tests were presented. The water mist systems in both tests were activated 4 min after ignition, when the HRR was less than 10 MW. After activation, the covered fire increased slowly to around 50 MW and was extinguished manually, and the uncovered fire increased to 30 MW at 11 min and then decreased gradually. The data have shown that the fires in these two tests had been effectively controlled, however, the technical information is not available.

In the SOLIT2 project [9], more than 30 tests were conducted in the San Pedro de Anes test tunnel with water mist systems. In the vicinity of the fire, additional walls were installed resulting in a tunnel width of 7.5 m. Wood pallets and diesel pools were used as fire sources. The peak HRRs for the wood pallet fires was estimated to be 150 MW. The nominal HRRs for the pool fires were 5, 60, and 100 MW. The water mist system was installed over a length of 60 m. Two rows of nozzles were installed along the tunnel. Both longitudinal ventilation and semi-transverse ventilation systems were tested. The semi-transverse ventilation is designed to deal with free-burn fires of approximately 30 MW. Data of five tests were presented in the report. Under longitudinal ventilation, the fire size was restricted to 30 MW for a wood pallet fire with a PVC tarpaulin cover and 15 MW for a wood pallet fire without cover. The activation time was around 7 and 3 min in the tests and the corresponding activation HRRs were around 8 and 5 MW, respectively. For the pool fires with longitudinal ventilation, the activation time was also 3 min, and the corresponding activation HRR was approximately 25 MW. The peak HRR was approximately 70 MW. Note that in this test the nominal HRR was 60 MW. Therefore, the fire was not controlled except that the gas temperature was lowered due to gas cooling.

In the two pool fire tests with semi-transverse ventilation and flow rates of 120 and 80 m^3/s, the activation time was approximately 4 and 3 min, and the corresponding HRRs were approximately 15 and 35 MW, respectively. The peak HRRs in these two tests were approximately 65 and 70 MW, respectively. The nominal HRRs in these two tests are unknown. However, from the HRR curves it can be expected that the nominal HRRs were also 60 MW in these two tests. In summary, the water mist system effectively controlled or suppressed the wood pallet fires but had limited influence on the fire development of pool fires. It should be kept in mind that the water flow rates used in these tests are unknown.

16.3.8 Singapore tests 2011–2012

In 2011, Land Transport Authority (LTA) Singapore commissioned Efectis to conduct a fire test programme [4, 5] to investigate the effect of fire suppression on the HRR and tunnel ventilation, to reduce the risk of vehicular fire spread, and to acquire information on the appropriate design parameters to adopt. A total of seven large-scale fire tests were conducted in the San Pedro de Anes test tunnel with water spray systems.

The fire sources consisted of 228 wooden (80 %) and plastic (20 %) pallets. The HGV mock up was 2 m wide, 3 m high, and 7.5 m long covered by a tarpaulin. The tunnel had a ventilation velocity of around 3 m/s. Two piles of pallets were placed 5 m behind the edge of the HGV mock-up to investigate the possibility of fire spread to adjacent targets.

The water spray systems consisted of three rows of nozzles were used in these tests. The nozzles had a K-factor of 80 and an operating pressure of 1–2 bar. The water flow rate was 8–12 mm/min. The system was activated 4 min after the “fire detection”, corresponding to 60 °C gas temperature measured below the ceiling.

The test data showed that the peak HRRs were below 40 MW if the deluge system was activated 4 min after detection. Note that the HRR in the free-burn test stayed near 115 MW for about 5 min period and had a peak HRR of 150 MW during a short period (1–2 min). The reason for the peak has not been given, but one can speculate that it has to with a sudden collapse of parts of the fuel stack. This will increase the exposed fuel surface directly, and consequently the HRR may rise. The reduction of the HRR from 115/150 to less than 40 MW shows that the system controlled the fire effectively. However, the duration time was prolonged and most of the fuels were consumed in the tests. If the deluge system was activated 8 min after detection, the HRR was as high as 100 MW and the curve was similar to the free-burn test. The ceiling gas temperature in test 1 was reduced to 300 °C, compared to 1200 °C in the free-burn test, and the heat flux can also be expected to be reduced significantly although the measurement could fail while being exposed to the water sprays.

16.3.9 SP Runehamar Tunnel Fire Suppression Tests 2013

In 2013, SP Sweden [28] carried out a series of fire suppression tests in the Runehamar tunnel in Norway to investigate the performance of the Swedish simplified deluge water spray system before its application in the Stockholm Bypass. A total of six tests were carried out. Wood pallets were used as fuel with an estimated peak HRR of 100 MW. A total length of 30 m was covered by the fire suppression system equipped with TN (Tunnel Nozzle)-25 manufactured by TYCO (Prior to the notation it was called T-Rex). A 1.1 bar water pressure at the nozzles with K-360 (L/(min bar$^{1/2}$)) yielded a water flow rate of 375 L/min. The coverage area was 37.5 m^2, which corresponds to a water density of 10 mm/min. The criterion for the "fire detection" was a ceiling gas temperature of 141 °C. The activation of the fire suppression system was delayed by 2–12 min after the "fire detection".

The results showed that the HRR upon activation ranged from approximately 10–30 MW. The HRR was controlled after activation for a period of 10–20 min. After that the fire was suppressed over a period of 10–30 min, which means that the system prevented further fire spread inside the fuel. The FFFS resulted in peak HRRs lower than 50 MW in all five cases, which was one of the original questions postulated by the LTA. The maximum temperatures at the ceiling were never higher than 400–800 °C after activation. In all experiments, the fire was controlled in the first period after activation and then suppressed with a considerable amount of fuel still remaining. A target consisting of a pile of pallets stood 5 m from one end of the fire. It was used to assess the risk of fire spread to adjacent vehicles. In all cases with the FFFS operating, the target was unaffected by the main fire.

The experiments also showed the importance of early activation of the FFFS. Despite this, it was clear from the experiments that the system has a sufficient safety margin to allow delayed response while retaining the ability to fight the more severe fires produced by such a delay. The system was able to prevent the spread of the fire beyond the main fire load, and was clearly able to lower the gas temperatures in the tunnel. This has important implications for the design and safety of the evacuation. The tests show that the design fire of 100 MW as originally planned can be reduced to lower than 50 MW by the presence of a FFFS, which translates into significant savings in investment costs for the ventilation system. The experiments show that if the system activates late, an increase of toxic substances and smoke is produced, but the impact of this effect can be mitigated by activating the system early.

16.3.10 A Short Discussion

Water spray systems normally use a water flow rate of 10–12.5 mm/min. Water mist systems normally use a water flow rate of 1–4 mm/min. The ratio of the water flow rates used in these two systems is in a range of 3–4. However, these values of water flow rate are mainly applied from fire suppression in residence and industrial buildings. The main mechanisms of fire suppression using these two types of systems are different. A deluge water spray system suppresses a fire mainly by fuel surface cooling; a water mist system suppresses a fire mainly by dilution and gas cooling.

Compared to normal building fires, the fuel load density for a HGV tunnel fire is much higher. Further, ventilation reduces the dilution effect significantly. Therefore, in suppression of fires in tunnels with longitudinal ventilation, the systems with low water flow rates and small droplets, which extinguish fire mainly by dilution, cannot perform as well as in building fires in a quiescent environment.

In most of the tests discussed here, the fires were neither extinguished nor suppressed, and instead were only controlled, especially for the water mist systems tested. There have been some popular arguments that fire suppression systems cannot suppress tunnel fires, but only mitigate the fire effect. However, we can only conclude that most of the systems tested cannot successfully suppress or extinguish the tunnel fires. The main problem is that the design of fire suppression systems used in buildings has been applied to tunnel fires, which corresponds to low water flow rate, especially for the water mist systems. In other words, in order to successfully suppress tunnel fires, the performance of fire suppression systems needs to be improved.

There are also arguments that the performance of a water mist system is better than a water spray system. However, under the tested water flow rates, the performance of the water sprays systems was much better than the water mist systems. Further, it should always be kept in mind that the water spray systems and water mist systems discussed here use significantly different water flow rates. Therefore, it is apparently not fair to make the comparison so simply.

The use of fire suppression systems in a tunnel is always a cost-effectiveness issue. The capability of fire suppression systems needs to be improved to effectively suppress the fires, rather than only control the fires. However, the cost will definitely increase. Research on the minimum capacity to suppress the fire is of special interest from an economic point of view.

16.4 Theory of Fire Suppression

16.4.1 Extinguishment Mechanism

The mechanism of extinguishment of fires using water-based fire suppression systems can be classified into two types: condensed phase suppression and gas phase suppression. In the condensed phase, surface cooling is the main mechanism. In the gas phase, the extinguishment mechanisms can be categorized into gas cooling, heat capacity and dilution effects, and kinetic effects.

16.4.1.1 Surface Cooling

The water droplets arriving at the fuel surfaces evaporate and take the heat away, which results in lower burning rates or extinction of the fire. This process is called surface cooling. Note that 1 kg of water can take away around 2.6 MJ heat by evaporation to water vapor at a temperature of 100 °C. For water-based fire suppression systems in tunnel fires, fuel surface cooling can be regarded as the primary mechanism of suppression of solid fuel fires.

For surface cooling to be effective the water droplets must be able to penetrate the fire plumes. During this process, both the momentum and the evaporation of the water droplets dominate. Further, the flow rate of the water droplets surviving in this process and arriving at the fuel surfaces must be great enough to suppress the fire. For exposed solid fuels, traditional water spray systems could have better performance due to the large water flow rate and large water droplets. The amount of water required for fire suppression only needs to approximately equal the heat absorbed by the fuel surface, rather than the total HRR.

In a tunnel fire, surface cooling delays the fire growth rate by pre-wetting the nearby un-burnt fuels. Further, the nozzles away from the fire source discharge water to the surface of the nearby vehicles, inhibiting vehicular fire spread. Surface cooling can easily delay or prevent ignition. Many tests have shown that even a small amount of water is capable of preventing fire spread to neighboring targets.

Water sprays discharged to the tunnel walls also provide protection for the tunnel structure. As a consequence, the requirement for passive protection could be lowered.

16.4.1.2 Gas-Phase Cooling

The water discharged from the nozzle is atomized into a large number of water droplets, and the total droplet surface areas are very large. Droplet evaporation results in efficient cooling of the flame and hot gases. The cooling of the flame raises the lower flammability limit of the oxygen and reduces combustion intensity. Further, heat feedback to the fire source is reduced. In a tunnel fire, the cooling of hot gases could increase the tenability conditions for evacuations, although the vapor introduced slightly lowers down the tenability limit for the respiratory gas temperatures. For large tunnels fires the HRR is very high so extinction purely by gas phase cooling would require a very large amount of water, which is almost impossible. Therefore, this is not the main mechanism of fire suppression in tunnel fires.

The nozzles upstream of the fire source also contribute to fire suppression by cooling the gases flowing to the fire source if back-layering exists, and a small amount of the injected water droplets could also be blown to the nearby fire source.

16.4.1.3 Dilution Effects and Heat Capacity

Dilution effects in water-based fire suppression systems are created by the evaporation of water drops. Note that due to the evaporation, the volume of water droplets expands by a factor of around 2700 at a temperature of 300 °C, which dilutes the concentration of both fuel and oxygen in the vicinity of the fuel surfaces and in the flame. At the same time, the higher heat capacity of water vapor compared to air reduces the gas temperatures.

Dilution effects could be the key mechanism of suppression of gas and liquid fires, especially for water mist systems. However, in tunnel fires with forced ventilation, the water vapour could be blown away and the dilution effect could be significantly reduced.

16.4.1.4 Radiation Attenuation

Similar to soot, water sprays and water vapors also absorb radiation. The radiation attenuation due to the water sprays depends on the water flow rate and the droplet sizes. For a continuous water curtain, the radiation attenuation could be very effective due to the high absorptance of the water. It is known that water vapor has a low absorptance, however, it could still play a key role due to the large volume.

Radiation attenuation reduces heat feedback to the fuel surface and lowers the HRR. It can also delay the fire growth rate and prevent fire spread to nearby vehicles in a tunnel fire.

On the other hand, water vapors produced by evaporation perform as a radiation medium, which absorbs heat from flames and hot gases, and also re-radiates the heat at a lower radiation intensity.

16.4.1.5 Kinetic and Other Factors

Kinetic effects include the impingement of water droplets on the fuel surface, turbulence induced by the water sprays, the interaction between the nozzles, and the effect of droplets on the flame temperature limit.

Other factors could include the effect of tunnel ventilation on the movement of water droplets and water vapors and the effect of tunnel walls.

These are only secondary effects and are not expected to significantly affect the performance of water spray fire suppression systems in tunnels, and therefore are not discussed further.

16.4.2 Critical Conditions for Extinction

16.4.2.1 Condensed Phase Extinction

The fire point equation is widely used in fire suppression theories, which in reality is the energy equation applied to the fuel surface and can be expressed as:

$$\dot{q}''_{net} - \dot{m}''_f L_g - \dot{m}''_w L_{v,w} = 0 \tag{16.1}$$

where $\dot{q}''_{net}$ is the net heat flux absorbed by the fuel surface (kW/m^2), L_g is the heat of gasification of the fuel (sum of heat of vaporization and increase of heat enthalpy, kJ/kg), $\dot{m}_f''$ is the fuel mass burning rate (kg/(m^{2}s)), $\dot{m}_w''$ is the water flow rate per unit fuel surface area (kg/(m^{2}s)), and $L_{v,w}$ is the heat of vaporization of the water (kJ/kg).

The terms on the left hand side are the net heat flux absorbed by the fuel surface, heat absorbed for gasification, and the heat absorbed for evaporation of water droplets, respectively.

The heat flux absorbed by the fuel surface can be divided into two parts, that is, the heat flux from the self-sustained flame itself (no external flux) and the heat flux from other flames (at other locations) or heat sources. The heat flux from the self-sustained flame could be expressed in the form of the local HRR by multiplying a kinetic parameter, φ. Therefore, the above equation can also be expressed as:

$$\dot{m}_f''(\varphi \Delta H_{c,eff} - L_g) + \dot{q}_e'' - \dot{q}_l'' - \dot{m}_w'' L_{v,w} = 0 \tag{16.2}$$

where $\dot{q}_e''$ is the radiation from external sources or other flames (kW/m^2) and $\dot{q}_l''$ is the radiation loss (kW/m^2). The kinetic parameter, φ, in the above equation is defined as the ratio of heat absorbed by the fuel surface to the HRR [29]:

$$\varphi = \frac{\Delta H_g}{\Delta H_{c,eff}} \tag{16.3}$$

where ΔH_g is the heat of the self-sustained flame transferred to the fuel surface per unit mass of fuel gasified (kJ/kg), and $\Delta H_{c,eff}$ is the effective heat of combustion (kJ/kg). It should be noted that the kinetic parameter, φ, is not constant. However, the equation expressed in such a form is useful when analyzing the critical fire point equation.

In the following text, we discuss the critical conditions for extinction, that is, the critical fuel mass burning rate and the critical water flow rate that are required for fire extinction.

Note that for a self-sustained flame at extinction, we may assume that no radiation loss exists and the fuel surface obtains heat for gasification only by convective heat transfer from the small burning flame. Therefore, the critical fire point equation is expressed as:

$$\dot{m}_{cr}''(\varphi \Delta H_{c,eff} - L_g) = 0 \tag{16.4}$$

where $\dot{m}_{cr}''$ is the critical fuel mass burning rate for a self-sustained burning material (kg/(m^{2}s)).

The critical mass burning rate at extinction for a self-sustained flame is determined by convective heat feedback. According to Spalding's B number theory, it is given by [30]:

$$\dot{m}_{cr}'' = \frac{h_c}{c_p} \ln(1 + B_{cr}) \tag{16.5}$$

The critical B number at extinction, B_{cr}, is defined as [30]:

$$B_{cr} = \frac{Y_{O2,\infty} \Delta H_{O2}}{\varphi \Delta H_{c,eff}} \tag{16.6}$$

In the above equations, h_c is the convective heat transfer coefficient (kW/(m^{2}K)), c_p is the heat capacity of the air, $Y_{O2,\infty}$ is the surrounding oxygen mass concentration, ΔH_{O2} is the heat released by consuming 1 kg oxygen (kJ/kg).

Note that the Spalding's B number theory is only an approximate theory. The physical meaning of the above equation is that burning is sustained only by the convective heat transfer, that is, heat conduction to the fuel surface. Here it is assumed that all the oxygen is consumed near the fuel surface, and also assumed that the heat gain from the flame at extinction equals the heat required for obtaining the critical mass burning rate, that is

$$L_g = \varphi \Delta H_{c,eff} \tag{16.7}$$

The critical mass burning rate per unit area for normal plastics at extinction is in a range of 2.5–4.4 g/(m^{2}s) under forced convection and 1.9–3.9 g/(m^{2}s) under natural convection [31]. Tewarson and Pion [32] defined a term called ideal mass burning rate assuming that no heat is lost from the surface or the heat loss has been compensated by the external heat flux. Ingason and Li [33] compared these values to the data obtained from their tests and found they correlate well with each other. The corresponding ideal mass burning rate per unit area for these normal plastics is in a range of 14–35 g/(m^{2}s). The ratio between the critical and ideal mass burning rate per unit area ranges from 10 to 18 %. However, according to the model described above, the critical mass burning rate is a variable and sometimes a very high mass burning rate could be obtained, although it may not be realistic. As a first estimation, considering it as a fixed value or a variable is acceptable.

An expression for the critical water flow rate required for fire suppression can be obtained from Eq. (16.2):

$$\dot{m}''_{w,cr} = \frac{\dot{m}''_{cr}(\varphi \Delta H_{c,eff} - L_g) + \dot{q}''_e - \dot{q}''_l}{L_{v,w}} \tag{16.8}$$

The model presented above is only an approximate solution and the uncertainty is high. However, the model correlates many parameters and is very useful for understanding the mechanism of the fire suppression.

16.4.2.2 Gas Phase Extinction

Beyler [30] assumed that the analogy of flammability limit for premixed and diffusion flames works, and proposed an equation to estimate the fraction of enthalpy of reaction that can be lost before extinction occurs at the stoichiometric limit, φ_{SL}, which can be expressed as:

$$\varphi_{SL} = 1 - \frac{c_p (T_{AFT} - T_o)(1 + 1/r)}{Y_{O2,\infty} \Delta H_{O2}} \tag{16.9}$$

where T_{AFT} is the adiabatic flame temperature for diffusion flames (K), and r is the mass-based stoichiometric air to fuel ratio which can be ignored in most cases.

Beyler [30] proposed the following equation to account for the effect of dilution and heat capacity on fire suppression:

$$\varphi = k\varphi_{SL} = k1 - \frac{c_p (T_{AFT} - T_o) + Y_{ext} \Delta c_p (T_{AFT} - T_o)}{Y_{O2,\infty} \Delta H_{O2} (1 - Y_{ext}) / (1 + 1/r)} \tag{16.10}$$

where k is the correction ration between the actual and stoichiometric limit (closely 1), Y_{ext} is the mass fraction of the extinguishing agent, Δc_p is the difference in heat capacity between the diluents and ambient gas (kJ/(kgK)). Note that the stoichiometric parameter term in the above equation has been corrected based on the original equation [30].

Although Beyler [30] referred to the parameter T_{AFT} as the adiabatic flame temperature at the stoichiometric limit, the temperature of 1700 K was used, that is, the adiabatic flame temperature at the flammability limit. The physical meaning of the parameter also suggests that the latter temperature should be used.

Note that the fraction must be positive to sustain a flame. This in reality suggests the controlling equation for flammability limit for diffusion flames. Both the ambient oxygen mass concentration and the ambient temperature are key parameters.

Note that the introduction of diluents, that is, water vapor or other extinguishing agents, results in a decrease of the oxygen concentration, which is accounted for by the term $(1-Y_{ext})$ in the denominator. The effect of heat capacity is represented by the additional term in the numerator, and the difference in the heat capacity between the diluents and the ambient gas is Δc_p.

The expression of the fraction of enthalpy of reaction that can be lost before extinction could be questionable. Further, the assumptions made in Eq. (16.9) may not work in case of fire suppression.

For water-based fire suppression systems, the inerting gas is water vapor. Given that the fuel mass is normally negligible compared to the total mass in a flame volume, the parameter r can be ignored in Eq. (16.10). Assuming that the concentration of water vapor is Y_w and $k=1$, the fraction of enthalpy of reaction can be expressed as:

$$\phi = 1 - \frac{c_p (T_{AFT} - T_o) + Y_w \Delta c_p (T_{AFT} - T_o)}{Y_{O2,\infty} \Delta H_{O2} (1 - Y_w)} \tag{16.11}$$

The gas phase extinction can be linked to the condensed phase extinction by applying the above equation in combination with Eqs. (16.8), (16.5) and (16.6).

Based on the above equation, the extinction criterion for flames with fire suppression can be obtained, which is expressed as:

$$Y_{O2,\infty}\Delta H_{O2}(1-Y_w) < c_p(T_{AFT}-T_o)+Y_w\Delta c_p(T_{AFT}-T_o) \tag{16.12}$$

The above criterion indicates the oxygen level needs to be higher for possible ignition in case of fire suppression. This criterion is very valuable in determining the combustion conditions for under-ventilated fires and suppressed fires.

Example 16.1 Estimate the critical mass burning rate for a small wood sample under normal conditions. Assume that the heat of combustion is 15 MJ/kg, and heat of vaporization is 2.5 MJ/kg, and the convective heat transfer coefficient is 10 W/(m^{2}K).

Solution: First calculate the critical B number using Eq. (16.6)*, that is,* $B_{cr} = 0.023 \times 13.1/2.5 = 0.12$*. Then calculate the critical mass burning rate using* Eq. (16.5)*, that is,* $\dot{m}''_{cr} = 10/1 \times \ln(1+0.12) = 0.00114$ *kg/(m^{2}s) or 1.14 g/(m^{2}s).*

16.4.3 Fire Suppression

Note that the critical mass burning rate and critical water flow rate correspond to the critical state of fire suppression when the fire is almost extinguished, and the corresponding extinguishment time could be infinite. To effectively suppress a well developed fire the water flow rate needs to be greater to assure either that enough the water droplets are able to penetrate the fire plume and reach the fuel surfaces before evaporation, or that enough water vapor is produced to cool the flame and dilute the combustible mixture.

16.4.3.1 Suppression of Gas and Pool Fires

Rasbash et al. [34, 35] carried out a series of tests on extinction of liquid pool fires. Two groups of extinction processes with water sprays were identified, that is, cooling the burning fuel surface to the fire point and action of spray on the flames causing rapid disappearance of the flames. It was concluded that except for alcohol fires, which were extinguished by surface dilution, the liquid fires were extinguished by fuel surface cooling. The extinction time was reported to decrease with increasing water flow rate and increased with water droplet size. The critical water flow rates associated with fuel surface cooling increased linearly with droplet size.

Kung [36] reported on suppression of hexane pool fires by cooling the flames in a ventilated room where the pool was placed in the corner and the water nozzle was placed at the centre of the room. Extinction occurred when the mole fraction of steam generated immediately after discharge of the water spray was greater than a value that was between 0.3 and 0.39. The water evaporation rate was proportional to the HRR and the water flow rate, and it varied by the −0.73 power of the mean droplet size.

Heskestad [37] conducted a series of water spray tests using liquid pool fires, accounting for the nozzles that are not geometrically scaled. He proposed an equation for gas and pool fires to predict the critical water flow rate, which is exponentially proportional to an effective nozzle diameter, nozzle height, and free-burn HRR. The equation for the critical water density can be expressed as:

$$\dot{q}_w = 0.312 D_{ne}^{1.08} H^{0.4} \dot{Q}^{0.41} \tag{16.13}$$

where $\dot{q}_w$ is the volumetric water flow rate (L/min), H is the clearance height between the nozzle and the pool surface (m), $\dot{Q}$ is the HRR (kW), and D_{ne} is the outlet diameter of the nozzle (mm). For comparison of nozzles with different geometries, an effective nozzle diameter should be used instead of the outlet diameter. Based on the conservation of mass and momentum equations, the effective nozzle diameter, D_{ne} (mm), is defined as:

$$D_{ne} = \left[4\dot{m}_w^2 / (\pi M \rho_w) \right]^{1/2} \tag{16.14}$$

where M is the momentum (N) and ρ_w is the density of water (kg/m^3). Heskestad [37] argued that spray-induced dilution of the flammable gas is a major factor in extinguishing gas fires, and that a liquid pool fire needs higher water rates to be extinguished compared to a gas fire.

It should be kept in mind that Heskestad's equations presented above are only suitable for extinguishment of pool fires using a water spay nozzle directly above the pool.

Example 16.2 Estimate the water density required for one nozzle to extinguish a 5 MW pool fire in a 5.5 m high tunnel. The nozzle has an outlet diameter of 7 mm is placed 5 m above the pool and is designed to cover 25 m^2 of tunnel area.

Solution: The required water flow rate can be estimated using Eq. (16.13)*, that is,* $\dot{V}_w = 0.312 \times 7^{1.08} \times 5^{0.4} \times 5000^{0.41} = 160$ *L/min. The water density can then be calculated:* $q''_w = 160/25 = 6.4$ *l/(m*^{2} *min) or 6.4 mm/min.*

In case of a water mist nozzle with several small outlets, Eq. (16.14) could be used to roughly estimate the effective nozzle diameter, although such a use has not been validated.

16.4.3.2 Suppression of Solid Fuel Fires

The suppression of solid fires normally takes a longer time due to the three-dimensional characteristics of the solid fire source. The time that is required for extinction of a fire is correlated to the water flow rate. A higher water flow rate can reduce the extinguishment time and less fuel will be consumed.

Kung and Hill [38] investigated the extinction of wood crib and pallet fires and obtained some useful empirical equations. They conducted a series of experiments on extinguishment of wood crib fires by water applied directly on the top of the cribs and wood pallets. The water was applied on the top by means of a rake consisting of perforated stainless steel tubes. They presented interesting nondimensional variables which basically account for variations in the preburn percentage and crib height, showing nondimensional fuel consumption and total water evaporated as functions of non-dimensional water flow rate. More specifically, it was shown that a single empirical correlation, for three types of cribs with the same stick size, but different crib height can be established between the ratio of crib mass consumed during the extinction period and combustible material remaining at the beginning of the water application, *R*, and the ratio of true water application rate and the fuel burning rate at the activation of water application, which is expressed as:

$$R = \frac{\Delta m_{f,ex}}{m_{f,a}} = \xi \left[\frac{\dot{m}_w (1-c)}{\dot{m}_{f,a}} \right]^{-1.55} \tag{16.15}$$

where $\Delta m_{f,\,ex}$ is the mass consumed during the extinction period (kg), $m_{f,\,a}$ is the combustible fuel mass at the activation (kg), $\dot{m}_w$ is the applied water flow rate (kg/s), *c* is the fraction of water applied that fell directly through the shafts of the crib, $\dot{m}_{f,a}$ is the fuel burning rate at activation (kg/s), ξ is a correlation coefficient. Note that the factor *c* is introduced into the equation by Ingason [22].

In Kung and Hill's work [38], the correlation coefficient ξ is a variable, which is 0.312 for the center-shaft ignited wood crib fires, 0.26 for the full-bottom ignited wood crib fires, and 0.15 for the wood pallet fires if the factor *c* is set to 0. Kung and Hill [38] also presented a single linear relationship between the ratio of total water evaporated and the total mass consumed during extinguishment and the ratio of the "true" water application rate versus the maximum free burning rate of the wood crib based on wood crib tests:

$$\frac{\Delta m_{w,ev}}{\Delta m_{ex}} = \psi \frac{\dot{m}_w (1-c)}{\dot{m}_{f,\max}} \tag{16.16}$$

where $\Delta m_{w,\,ev}$ is the total water evaporated (kg), $\dot{m}_{f,\max}$ is the maximum burning rate in a free-burn test (kg/s) and Ψ is a correlation coefficient which is determined by Kung and Hill [38] to be 2.5.

Ingason [22] carried out a series of model-scale tunnel fire tests with a deluge system and a water curtain system using hollow cone nozzles, in order to improve the basic understanding of water spray systems in a longitudinal tunnel flow. The water spray system used consisted of commercially available axial-flow hollow cone nozzles. Based on Kung and Hill's work [38], Ingason [22] proposed the following equation to correlate the energy content with the HRR:

$$\frac{\Delta E_w}{\Delta E_{ex}} = \psi \frac{\dot{Q}_w (1-c)}{\dot{Q}_{f,\max}} \tag{16.17}$$

where ΔE_w is the total energy taken by water evaporation (kJ), ΔE_{ex} is the total energy content at the activation (kJ), $\dot{Q}_w$ is the heat flux taken by the water (kW) and $\dot{Q}_{f,\max}$ is the peak HRR in a free-burn test (kW). Ingason [22] correlated the non-dimensional ratio of HRR, excess gas temperature, fuel consumption, oxygen depletion and heat flux downstream of the fire to the non-dimensional water flow variable (the term on the right-hand side in the above equation), and good agreement was found. In Ingason's work [22], a value of 0.89 for the factor c provided a good fit to Kung and Hill's equation [38]. This value is reasonable because in Ingason's work [22] the wood cribs were loosely packed.

Tamanini [39] also investigated the application of water sprays to the extinguishment of wood crib fires. A corrected water flow rate was used to correlate the results. It was also found that the mass consumed during extinguishment varied with a power law of the water flow rate, where the power of −1.55 was used by Kung and Hill and was in the range of −1.86 to −2.18 according to Tamanini [39]. The time to extinction was also correlated with the corrected water flow rate and the activation parameters which suggests that the time to extinction prolongs significantly as the water flow rate decreases.

Yu et al. [9] made a theoretical analysis of extinguishment of rack-storage fires by cooling of the fuel surface. A thin layer of fuel undergoing pyrolysis was treated as a plate where the temperature was evenly distributed, that is, similar to a steel plate. It is also assumed that the energy absorbed by the surface of this "plate" resulted in an increase of the burning area. Despite the simplicity, these assumptions seemed to work well. A fire suppression parameter, k, was identified to correlate the fire suppression results obtained from large-scale tests conducted using two different commodities arranged in steel racks of different height. The estimated critical water flow rate is about 6 g/(m^{2}s) for Class II commodities and 17–20 g/(m^{2}s) for plastic commodities. Note that these values were estimated based on the fuel surface area rather than the injection area at the top of the fuels. The HRR at a certain time after activation can be estimated using:

$$\frac{\dot{Q}(t)}{\dot{Q}_a} = \exp\left[-k(t-t_a)\right] \tag{16.18}$$

where the fire suppression parameter, k, is defined as:

$$k = \frac{C_o(\dot{m}''_w L_{v,w} - \varphi \dot{m}''_f \Delta H_c + \dot{m}''_f L_p)}{\rho_f c_p (T_p - T_o)}$$

where C_o is a coefficient related to the effective pyrolysis thickness, L_p is the heat of pyrolysis (kJ/kg), T_p is the temperature of pyrolysis (K), t is the time (s) and t_a is the activation time (s), $\dot{Q}_a$ is the HRR at activation (kW).

Xin and Tamanini [11] also conducted a series of fire suppression tests using representative fuels to assess the classification of commodities for sprinkler protection. They defined a critical sprinkler discharge flux as the minimum water flux delivered to the top of the fuel array capable of suppressing/preventing further fire development, and obtained it by linear interpolation of the tests data. An empirical correlation was proposed for a ceiling clearance of 3.05 m to estimate the actual water flux discharged to the fuel surfaces, which was correlated with the sprinkler discharge flux and the convective HRR. A similar equation to Eq. (16.14) was proposed to correlate the energy consumed during extinguishment with the water flow rate. The estimated critical sprinkler discharge flux was 6.9 mm/min for Class II commodities, 19.9 mm/min for Class 3 and Class 4 commodities, 25.6 mm/min for plastic commodities, and 26.9 mm/min for the cartoned meat trays. Note that these values correspond to the injection area at the top of the rack storages. It is concluded that classifications based on sprinkler discharge flux represents the fire hazard levels of the commodities of interest.

We can also get some indication from the equation for the critical water flow rate, Eq. (16.8). Note that at activation the local fuels could probably have been fully involved in burning, and the radiation heat flux should be much higher than the convective heat flux. Further, for a three-dimensional fire source, the radiation loss could be very limited for the fuels, most of which are located inside the flame. Therefore, Eq. (16.8) can be simplified into:

$$\dot{m}''_{w,cr} = \frac{\dot{q}''_{net,r}}{L_{v,w}} \tag{16.19}$$

This suggests that the critical water flow rate is proportional to the net heat flux, which mainly consists of radiation heat flux. Further, in order to extinguish such a fire within a short time, the applied water flow rate must be much higher than the critical water flow rate discussed earlier.

In summary, the HRR and the energy consumed during extinguishment have been correlated with either the discharge water flow rate or the actual water flow rate. Some useful equations have been obtained, however, most of these equations are empirical and they must be used with caution.

Example 16.4 Roughly estimate the water flow rate required to effectively suppress a wood pallet fire in a 9 m wide tunnel. The potential fire size is 100 MW but is 20 MW at the activation of the water spray system. Here we define the effective suppression as only 20 % of the fuel mass at activation consumed during the extinction period. The wood pallet piles are 3 m wide and 8 m long, and its heat of combustion is approximately 15 MJ/kg.

Solution: The water flow rate applied on the wood pallets can be estimated using Eq. (16.16). *First we need to estimate the fraction of water applied that not fall onto* *the fuel surfaces c. Given that the wood pallets are densely packed, it is reasonable to assume that all water droplets falling on the wood pallets do not penetrate the fuel and reach the tunnel floor. The parameter c therefore can be estimated as: $c = (9 - 3)/9 = 2/3$. This indicates 2/3 water applied does not have direct effect on the burning of the fuels. Note that the correlation coefficient ξ is 0.15 for wood pallets and the parameter $R = 0.2$ according to this assumption. Now use* Eq. (16.16) *to estimate the water flow rate, that is,* $\dot{m}_w = \dot{m}_{f,a}(R/\xi)^{-0.645}/(1-c) = (20/15) \times (0.2/0.15)^{-0.645}/(1-2/3) = 3.32$ *kg/s or 199 L/min. The tunnel section length with fuels burning can roughly be estimated as:* $20/100 \times 9 \times 8 = 14.4\ m^2$. *Therefore the water density can be estimated:* $199/14.4 = 13.8$ *mm/min or L/(min m²).*

16.4.4 A Short Discussion

In an open fire and a compartment fire, vaporized water vapor can surround the fire and flame, and the dilution effect could be significant enough to behave as the main mechanism of fire extinction. However, in a ventilated tunnel fire, water vapor will be blown away from the fuel surfaces, and thus the dilution effect is reduced significantly. Small droplets can also be blown away. In any case, the models and equations developed for suppression of open fires and enclosure fires must be verified in tunnel fires. Further, research on the mechanisms of fire suppression in tunnels is highly recommended.

16.5 Tunnel Fire Detection

All the fire suppression systems used in tunnels need fire detection systems for activation. The only exception is a system solely consisting of automatic sprinklers in which thermal heads are embedded.

In the following sections, different types of fire detection systems used in tunnels are shortly summarized, and then a summary of tunnel fire detection tests is presented.

16.5.1 Types of Fire Detection

The fire detection systems used in tunnels include line type heat detection, smoke detection, flame detection, visual image fire detection, CCTV system, spot heat detection, and/or CO2/CO sensing fire detection.

Line type heat detection (LTHD) have been used in road tunnels for fire detection for approximately 40 years. Line type heat detection detect fires by absolute temperature value or temperature changes. There are four types of line type heat detection systems used in tunnels, that is, electrical cable, optical fiber, thermocouple, and pneumatic heat detection systems. The electrical cable heat detectors are subdivided into four types, that is, thermistor type, analog integrating circuit, digital circuit, and semiconductor circuit. Optical fiber cable detects cable deformation due to exposure to heat through a change in light transmission or a change in back scattering. Line type thermocouple detection has the measuring junction unfixed and when it is subjected to an increase in temperature it becomes concentrated at the hottest point anywhere along the sensor's entire length. Pneumatic heat detection systems detect the pressure rise due to gas expansion after the tube is exposed to flames or hot smoke flows. Among these systems, the fiber optic heat detection is the most widely used LTHD system in tunnels. These systems respond differently but this topic has not been systematically studied except for the spot heat detector which will be discussed in the following text.

Smoke detectors detect smoke particles either by light extinction sensors, light scattering sensors, or by ionization attenuation sensors. A light extinction smoke detector detects smoke by measuring extinction of the light due to absorption of the smoke particles, while a light scattering smoke detects smoke by measuring light signals caused by scattering due to the smoke particles. An ionization smoke detector uses a radioisotope to produce ionization and the difference over a certain level caused by smoke can be detected, however, it has been found that it is not sensitive to smouldering fires. Similar to heat detectors, the response of the smoke detectors has a delay, which can be estimated using some validated models, for example, the model proposed by Cleary et al. [40]. In practice, the dust sensors for air quality control can be used as complementary smoke detectors in case of a fire.

Flame detectors sense electromagnetic radiation and are designed to discriminate flame radiation from the other sources. The radiation wavelengths can be in the ultraviolet, visible, or infrared portions of the spectrum. Protection against false alarms due to sunlight, the lighting system in the tunnel, and the light from the vehicles is necessary.

Visual Image flame and/or smoke detectors digitize the video images from cameras and use computer software to identify flames or smoke. The algorithms used can become very complicated in order to distinguish the flame and/or smoke from the other items such as light and dust.

CCTV monitors have been used in many tunnels mainly for traffic control but can also be used for monitoring fire accidents and for triggering an alarm manually.

Spot heat detection measures the heat inside the tunnel at a certain interval, for example, placement of thermocouples every 30 m. The response of spot heat detectors has been systematically investigated. Heskestad [41] proposed the use of the Response Time Index (RTI) to rank different types of automatic sprinklers and detectors.

The CO_2 and CO sensors have been used in many tunnels for controlling air quality inside the tunnel under normal ventilation. Although they are not designed for fire detection, they can be used as a complementary system for fire detection in tunnels.

Besides these detection systems, the fire could also be detected immediately by a driver or passenger, who could sound the alarm afterward by either pushing the fire alarm button inside the tunnel or communicating with tunnel managers or fire brigade in other ways. More information on fire detection can be found in the literature, for example, Schifiliti et al. [42], Maciocia and Rogner, and Zalosh and Chantranuwat [43].

In summary, different detection systems are used in tunnels, mainly depending on the designed safety level for the specific tunnel. For a detection system in combination with a fire suppression system, it must be able to exactly determine the location of fire site. From this view point, LTHD is required. Further, the use of dust detectors and CO/CO_2 measurement equipment designed for normal ventilation as complement to fire detectors is a good combination, but the distance between installations should be shortened for better performance.

16.5.2 Summary of Fire Detection Tests in Tunnels

A summary of fire detection tests in tunnels is presented in Table 16.2. Most of the tests were carried out in Europe focusing on LTHD systems. Quite limited information is available in the literature.

Only the three well documented test series, that is, the 2nd Benelux tunnel fire detection tests in 2000/2001, the Runehamar tunnel fire detection tests in 2007 and the Viger tunnel fire detection tests in 2007 are discussed in detail in the following.

16.5.2.1 Second Benelux tunnel fire detection tests—2000/2001

During 2000–2001, 13 fire detection tests were carried out in the 2nd Benelux tunnel [45] consisting of eight small fires and five larger fires (three pool fires, one van fire, and one simulated truck load fire. Three different LTHD systems were placed both close to the wall and around 3.5 m from one wall (based on estimation). One detection system consisted of a glass fiber detector cable and the other two were electronic sensors on regular distances of several meters. Three different fire source locations were tested. The ventilation velocity varied from 0–5 m/s. The sizes of the pools used in the tests varied from 0.5 to around 2 m^2.

The maximum temperature measured by the systems for each test were in the range of 20–30 °C, however, the detection location differed more than 20 m in some tests with high velocities. The difference between the detection location and the fire location is mainly due to the effect of ventilation, and partly due to the placement between the fire location and the detectors and the measurement error of the LTHDs.

16.5.2.2 Runehamar Tunnel Fire Detection Tests—2007

A total of eight tests were carried out to investigate the performance of different LTHD and smoke detection in the Runehamar tunnel in 2007 [46]. In seven of the tests, the fire sources were a square heptane pool with a side length of 0.4–1 m and

Table 16.2 Summary of fire detection tests in tunnels [43–47]

Year	Tunnel	Country	Type of detection	Fire source	HRR (MW)	Ventilation velocity, u_o (m/s)
1992	Mositunnel	Switzerland	Line type heat detector, spot heat detector, and smoke detectors	Pool fire 0.5–4 m^2		Mostly 1
1999	Schonberg and Gubrist tunnel	Switzerland	Line type heat detector (fiber optic)	Gasoline		
1999	Colli Berici unused tunnel	Italy	Line type heat detector			
1999	CSIRO	Australia	Line type heat detector	Hot smoke	1.36	
2000	Hagerbach model tunnel	Switzerland		Gasoline 0.25–0.75 m^2	0.42–1	0.75–2.8
2000	Felbertauern Tunnel	Switzerland		Diesel 2 m^2, 3 m^2 and ethano 1 m^2		3.5–11.0
2000	Boemlafjord Tunnel	Finland				3
2001	Shimizu Tunnel	Japan		Gasoline, car, 1–9 m^2		2–3
2001	Second Benelux Tunnel	Netherlands	Line type heat detector	Gasonline, van, simulated truck	1–25	0–5
2007	Runehamar Tunnel	Norway	Line type heat, smoke detector	Heptance, car	0.2–3	1.1–1.8
2007	Viger tunnel	Canada	Line type heat, flame detector and Visual image fire detection	Gasoline pool, 0.09–0.36 m^2	0.125–0.65	0–2.5

in one test the fire source was a real car. For the LTHD, a fixed alarm limit was set to 3 °C in 4 min, while for smoke detectors, the soot or dust density was generally greater than 3000 µg/m^3. The smoke detectors were placed 62.5 and 125 m downstream of the fire source. The results showed that for heptane pool fires the heat detection worked very well but not for the car fire test, and the smoke and dust detectors worked well in the car fire test but not as good as the heat detection for pool fires. It was concluded that the airflow increases the time to detect for heat detection systems and decreases the detection time for smoke detection. However, this conclusion could be questionable. Note that the pool fires resulted in a rapid increase in temperature at the early stage, and thus could not be representative of typical vehicle fires. In such cases, using the temperature increase rate as the criteria for fire detection is not comparable to smoke detection. Further, the better performance of smoke detection in case of a car fire is mostly attributed to the slowly growing fire which cannot trigger the heat detectors. The smoke detectors tested were more sensitive compared to the heat detectors, however, the disadvantages of smoke detectors are the long delay of measurement due to smoke transportation, tube suction and measurement in the collector, and the disability in determining the exact fire location for the fire suppression system or evacuation or fire fighting. In case of a fast growing fire, heat detection can be expected to perform better.

16.5.2.3 Viger Tunnel Fire Detection Tests—2007

In 2007, nine tests were carried out in Tube A of Carré-Viger Tunnel located in downtown Montreal, Canada [47]. The section of the tunnel used in the tests was 400 m long, 5 m high, and 16.8 m wide (four traffic lanes). Six fire detection systems were evaluated in the test series, including two linear heat detection systems, one optical flame detector, and three video image detection (VID) systems. Two LTHDs were installed on the ceiling of the tunnel.

Gasoline was used as fuel in all the tests. The fire scenarios used in the tests included a small gasoline pool fire (0.09 m^2), a gasoline pool fire (0.36 m^2) located underneath a simulated vehicle, and a gasoline pool fire (0.36 m^2) located behind a large simulated vehicle. The HRRs varied from 125–650 kW as measured using a calorimeter. Four tests were conducted with a small gasoline pool fire (0.09 m^2) at different locations in the tunnel. The peak HRR produced by the fire was approximately 125 kW. The tests were designed to study the effect of changing fire location on the response of the detection systems to a small open pool fire. There was minimal airflow in the tunnel during these tests. In this scenario, the fire developed very quickly and substantial smoke was produced. Three tests were conducted with a pool fire located underneath a simulated vehicle. The tests were used to study the impact of airflow on the response of detection systems to a small fire (0.6 m × 0.6 fuel pan) located underneath a vehicle. The average airflow velocities varied from 0–2.5 m/s.

16.5.3 A Short Discussion

A detection system used in combination with a fire suppression system needs to be able to exactly determine the location of fire site. From this viewpoint, LTHD is required. Further, smoke detectors could be good supplementary detectors in tunnels, and use of normal dust detectors as smoke detectors in case of a fire could be a good option. Further, CCTV used for traffic control can also be used to confirm the exact location of the fire accident. Other detection technology can be used as aids. In short, a combination of different detection systems which include at least LTHD, smoke/dust detectors and/or CCTV monitoring forms a reliable fire detection system.

16.6 Summary

The basic concepts of fire suppressions systems are described. There are mainly two water-based fire suppression systems used in tunnels, that is, water spray systems and water mist systems. The main difference is the pressure and water droplet size.

The mechanisms of extinguishment of fires using water-based fire suppression systems are introduced, which can be classified into two types: condensed phase suppression and gas phase suppression. In the condensed phase, surface cooling is the main mechanism. In the gas phase, it can be categorized into gas cooling, heat capacity and dilution effects, and kinetic effects. In a ventilated tunnel fire, the vaporized water vapor will be blown away from the fuel surfaces, and thus the dilution effect is reduced significantly. Small droplets could also be blown away. The main extinguishment mechanism is fuel surface cooling in tunnel fires. This suggests that the water spray systems with larger water flow rates will have better performance in suppression of tunnel fires with longitudinal ventilation.

The critical conditions at extinction are discussed. Further, suppression of realistic fires are discussed where both the water flow rate and the total water flow used for fire suppression are discussed.

A summary of fire suppression tests carried out in tunnels, and their main findings, is presented. The use of fire suppression systems in a tunnel is always a cost-effectiveness issue. The capability of fire suppression systems must be improved to effectively suppress fires rather than merely control them.

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