Large scale fire tests with different types of fixed fire fighting system in the Runehamar tunnel

Haukur Ingason
Ying Zhen Li
Magnus Bobert
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Abstract

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The report presents the main results of the six large-scale tests with different types of fixed firefighting system (FFFS) that were carried out in the Runehamar tunnel in June 2016. It describes the background to the tests and the performance of the different systems, and draws conclusions regarding the efficiency of the systems. The fire load consisted of 420 standardised wooden pallets and a target of 21 wooden pallets. Five of the tests were carried out with a 30 m long deluge zone delivering varying water densities using three different types of side-wall nozzle and an interval distance of 5 m. One test with 93°C glass-bulb nozzles (sprinkler head) in the same zone was also conducted. In the five deluge tests, the detection system was simulated using thermocouples in the tunnel ceiling. The alarm was registered when the ceiling gas temperature reached 141°C, and the system was activated manually after a delay of 4 minutes. The protection goal of the system was to prevent fire spread to a target positioned 5 m from the rear of the main fuel area, and to ensure that the fire did not exceed 30 MW in size. The system setups tested were found to meet these goals.

Keywords: Wood pallets, Fixed Firefighting System (FFFS), heat release rate, water density, time delay.

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Preface

The Swedish Transport Administration (STA) initiated this project, and was responsible for establishing the protection goals of the systems tested. Its purpose was to test the performance of new types of side-wall nozzles (horizontal spray) for different tunnel projects in Sweden. The tests can be regarded as a continuation of the large-scale testing carried out in the Runehamar tunnel in 2013.

We would like to thank tunnel safety officer Ulf Lundström of the STA, and Conny Becker of Brandskyddslaget AB. We would also like to thank all of the technicians at SP Fire Research and SP Fire Research A/S in Trondheim for their great work. Thanks also to Per Fiva of the Norwegian Public Road Administration in Åndalsnes, who was the contact person at the Runehamar tunnel. The nozzles tested were provided by TYCO Fire Protection Products, who is gratefully acknowledged.
Summary

Six large-scale tests with Fixed Firefighting System (FFFS) were carried out in the Runehamar tunnel in June 2016. The fire load consisted of 420 standardised wooden pallets and a target of 21 wooden pallets. The test setup was the same as for the tests carried out in Runehamar in 2013. Five of the tests were carried out with a 30 m long deluge zone delivering varying water densities using three different types of side-wall nozzle and an interval distance of 5 m. One test with 93°C glass-bulb nozzles (sprinkler head) in the same zone was also conducted (automatic sprinkler system). In the five deluge tests, the detection system was simulated using thermocouples in the tunnel ceiling. The alarm was registered when the ceiling gas temperature reached 141°C, and the system was activated manually after a delay of 4 minutes. The protection goal of the system was to prevent fire spread to a target positioned 5 m from the rear of the main fuel area, and to ensure that the fire did not exceed 30 MW in size. The system setups tested were found to meet these goals.

The heat release rate for the deluge systems upon activation ranged between approximately 8 and 12 MW. In five of the tests, the heat release rate was controlled within 15 minutes of activation. The fire was then suppressed over a period of 10-30 minutes by the TN-25 nozzles, indicating that the system prevented further fire spread within the main fuel area. This nozzle was the best of those tested in terms of performance. During the testing of the TN-17 nozzle, for example, the fire redeveloped after roughly 45 minutes, although the heat release rate never exceeded the maximum value prior to that period.

Testing with a sprinkler head (glass bulb) showed the potential of this type of system with regard to tunnels with a lower ventilation rate (~2 m/s or less), or where the ventilation strategy involves reducing the velocity after a fire alarm. Further testing is needed in order to explore the limitations of these systems, however, particularly as using a sprinkler head that emits larger droplets and an automatic activation device (bulb or a link) seems to be a feasible method.

The FFFS was able to maintain a heat release rate of lower than 30 MW in all five cases using a deluge. Following the activation of the system, the maximum temperature at the ceiling never exceeded 800°C.

A pile of pallets, representing a target, was located 5 m from the end of the main fuel stack. It was used to assess the risk of fire spread to adjacent vehicles. In all of the tests in which the FFFS was operational, the target was unaffected by the main fire.

The primary benefit of the FFFS is that it can be used to increase safety in tunnels, as such systems are able to fight fires that are relatively large and thereby potentially prevent major disasters. In a scenario in which congestion is an issue, and more specifically when a queue forms, the system increases safety by minimising the risk of propagation of a fire between the vehicles.
1 Introduction

In 2013, SP Fire Research performed six large-scale tests in the Runehamar tunnel on behalf of the Swedish Transport Administration (STA) [1]. These large-scale tests are referred to hereafter as ‘the 2013 tests’. The purpose was to test a new concept, using large-droplet, side-wall nozzles for the Stockholm bypass tunnel. The test series used a water density of 10 mm/min, with 1.1 bar nozzle pressure. This new nozzle type was originally given the working title ‘T-REX’, but is now manufactured under the name ‘TN-25’¹ (Tunnel Nozzle with orifice K-25²) by Tyco (Tyco Fire Protection Products). The T-Rex nozzle concept was originally developed by Brandskyddslaget AB³, but was subsequently altered and produced by Tyco.

Prior to the 2013 tests, the STA decided to test a new safety concept using sprinkler technology, with large-droplet, side-wall nozzles mounted at the centre line of the tunnel ceiling. It was felt to be very important that adequate fire protection will be in place, as the Stockholm bypass will be a critical part of the transportation infrastructure of the region. The forecasted traffic density indicated that there was a risk of congestion in the tunnels, and it was therefore decided to use a fixed firefighting system. Tests using the TN-25 nozzle and 10 mm/min water density showed that the system performed very well, and in accordance with the requirements of the STA. The results of the 2013 tests are presented in References [1-3]. The design of the 2013 tests was based on a model-scale study carried out by SP Fire Research prior to the large-scale tests [4].

New tunnel projects have come into focus in Sweden since 2013, and the installation of fixed firefighting systems (FFFS) is being considered for many. One is an existing tunnel (the Göta Tunnel) in which an predicted change in the traffic situation may consider a solution using a FFFS, but with a lower water density than is necessary in the Stockholm bypass tunnel. This has resulted in renewed discussion regarding the performance of large-droplet, side-wall systems with lower water densities and nozzle pressures, focused primarily on limited access to water supply and complications in reconstructing drainage systems.

The timeline for the Stockholm bypass project was well suited to the 2013 tests. The discussed TN-25 solution made it possible to design the system with regard to its requirements, in terms of both the water supply capacity and drainage system. There were, however, questions raised regarding systems located in exit ramps using a lower nozzle pressure. These ramps were narrower than the main tunnel tubes, and so require reduced throwing lengths and thus less nozzle pressure. The testing of the TN-25 with a lower nozzle pressure was therefore added to the 2016 test programme. The operational nozzle pressure used during the 2013 tests was 1.1 bar, with a throwing length of 7.5 m; in the tests presented here, the nozzle pressure used was much lower, at 0.55 and 0.69 bar, respectively. The throwing length was about 6 m for this pressure range.

In 2012, just as the discussion of side-wall nozzles had begun, a new tunnel was in the final stages of being designed (the Northern Link tunnel in Stockholm). Here, nozzles that were already on the market were chosen in order for the design of the water spray system to be finalised in time. The nozzle chosen was the Extended Coverage Ordinary Hazard (ECOH) SW-24⁴ with a K factor of 160 l/min/bar¹/² (K-11.2). The theoretical droplet diameter for this nozzle is roughly 60% of that of the TN-25 nozzles at 1.1 bar, with a

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² This is in US units (gpm/psi¹/²), corresponding to 360 l/min/bar¹/² in SI units.
³ Conny Becker at Brandskyddslaget AB was the person who originally proposed it.
The 2013 tests with the TN-25 nozzle demonstrated that large-droplet, side-wall nozzles are effective in controlling fire size and fire spread for the tested scenario, which used wooden pallets [1]. TYCO proposed to the STA the development of a similar type of large-droplet, side-wall nozzle, but with a lower K factor that would yield similar throwing lengths. This would mean a lower water flow rate and slightly higher nozzle pressure, and thus lower water density in mm/min. A prototype, designated ‘TN-17’, with a K factor of 240 l/min/bar^{1/2} (K-17), was therefore provided for the 2016 tests.

There is a strongly held opinion among tunnel engineers and sprinkler experts that thermal devices such as glass bulbs (automatic sprinkler heads) are not useful in tunnels with a longitudinal ventilation flow, and so deluge zones combined with detection systems have traditionally been used. The rationale is that convective flow from the fire can activate the wrong sprinkler heads downstream, jeopardising the entire system as too many sprinkler heads are activated (leading to a collapse of the FFFS). However, the STA is considering the installation of sprinkler heads for a specific tunnel project with a low longitudinal velocity. One reason for this is that SP Fire Research conducted an extensive small-scale research programme in order to explore the applicability of automatic sprinkler heads in longitudinal flow in tunnels [5, 6], which showed that sprinkler heads would work well in this application with a low longitudinal velocity, as well as in tunnels which ordinarily have a high ventilation rate that is reduced on activation, and those with transversal or natural ventilation. Li and Ingason [5, 6] clearly demarcate the limits for failure of a system based on longitudinal velocity, water flow rate, and activation temperature. ‘Low velocity’ is not defined by the authors but, based on the failure graphs presented, it is in the order of less than 2-3 m/s; ‘high’ velocities are those greater than 5-6 m/s. In order to further explore the model-scale results of the low-velocity scenario, it was decided to add a test that used sprinkler heads (equipped with glass bulb). The SW-24 sprinkler head, which is manufactured with 93°C fast-response bulbs, was selected, as the TN nozzles are not available with an automatic thermal device.

The general layout of the side-wall nozzle system discussed here is as follows; a pipe is positioned in the middle of the tunnel ceiling, with a pair of nozzles every 5 m, which horizontally spray water in two directions. This means that the nozzles are positioned back-to-back on the central ceiling pipe. The throwing lengths are in the order of 6-8 m, depending on the type of nozzle and pressure at the nozzle. The uniqueness of the system lies in its simplicity, and the fact that large droplets are thrown in the direction of both tunnel walls. This is not a common solution for tunnels, but a similar side-wall concept has been used in Australia and the US, albeit with smaller droplets [1]. The main goal of the system is to limit fire size and prevent fire spread during the period of evacuation in a congested traffic scenario inside the tunnel system.

The purpose of the 2016 tests was as follows:

1) To have a set of results to compare against those of the 2013 tests, which used the TN-25 nozzle, but using a lower nozzle pressure.
2) To test a new prototype nozzle, TN-17, in order to explore the possibility of using a lower flow rate but maintaining the same throwing length.
3) To test the Northern Link tunnel deluge system using the SW-24 nozzle.
4) To test a sprinkler head of type SW-24 (automatic).

Insofar as possible, the tests were to be performed under the same conditions as those of the 2013 tests. The same test setup and velocities were used in the Runehamar tunnel, which is situated roughly 5 km from Åndalsnes, Norway. It is a two-way asphalted road.
tunnel that was taken out of service in the late 1980s, and is approximately 1,600 m long, 6 m high, and 9 m wide, with a cross-section of approximately 47 m². The tunnel has an average uphill slope of 0.5% up to roughly 500 m from the east portal (where the fans are located), followed by a 200 m-long plateau and then a 900 m-long downhill section with an average slope of 1% towards the west portal. The fire was located 600 m from the east portal, i.e. on the plateau section of the tunnel. The tunnel is protected with shotcrete at the test location.

Detailed information about the test setup and programme is given in the following chapter. The test results are presented in the main text of the report, as well as in Appendices A and B. A theoretical description of the parameters obtained is presented in Appendix C.
2 Description of experimental setup

2.1 Description of water spray system

The same water spray system setup was used as in the 2013 tests [1]. The pipe was placed at the ceiling on one side of the tunnel, with nozzles discharging water towards the opposite wall and the fuel (see Figure 1). The water density in the deluge zone of the water spray system was the same as if the pipe had been located at the centre of a full-sized tunnel, where the system would be placed centrally and use a T-coupling to throw water symmetrically in both directions. The deluge zone was 30 m long, and the total water flow rate varied depending on the nozzle type used. In a full-sized tunnel, the deluge zone would be at least 50 m in length. A 600 m-long ground pipe (on the surface of the road) with a diameter of 140 mm (inside diameter of 127 mm) delivered the water from the water tank, located outside the tunnel portal. The ground pipe was connected to the ceiling pipe as shown in Figure 1. The water tank had a volume of 230 m³, and was refilled between tests with groundwater from the nearby mountain. The total tank water was sufficient to maintain a 120 minute continuous delivery of water for each test, using a 55 kW electrical pump with a maximum flow capacity of 2300 lpm at 7 bar.

![Figure 1: The test setup and water spray system after activation.](image)

The nozzles used are shown in Figure 2. They were fitted to the 140 mm diameter pipe with a T-coupling, as shown in Figure 3. The nozzles were located close to the tunnel wall, 4.65 m above the road surface. The height up to the ceiling was approximately 0.7 m. The distance between the nozzles and the side-wall was approximately 0.4 m. The pipe system and the nozzle locations are shown in Figure 1 and Figure 6. The nozzles were mounted every 5 m over a distance of 25 m. The total length of the ceiling pipe was 30 m (deluge zone).
The three nozzle types used in the tests. The K-factor varied for each: For TN-25 it was 360 l/min/bar$^{1/2}$; for TN-17 it was 240 l/min/bar$^{1/2}$; for SW-24 it was 160 l/min/bar$^{1/2}$.

The nozzles were fitted with a T-coupling to a pipe with a diameter of 140 mm, located at the ceiling and close to the tunnel wall. The nozzles were mounted every 5 m, and sprayed water horizontally in one direction [1].
The TN-25 is a horizontal spray nozzle with a K-factor of 362.9 l/min/bar\(^{1/2}\) (25.2 gpm/psi\(^{1/2}\)), and is a specialised open-deluge nozzle for use in tunnel fire protection systems. Its minimum and maximum working pressures are 0.7 and 2.1 bar, respectively, according to the data sheet. The TN-17 is a prototype, and not currently available on the market. Its K-factor is 240 l/min/bar\(^{1/2}\) (17 gpm/psi\(^{1/2}\)). The third nozzle was a SW-24, with a K-factor of 161.3 l/min/bar\(^{1/2}\) (11.2 gpm/psi\(^{1/2}\)) and maximum working pressure of 12.1 bar. The SW-24 is an ECOH (Extended Coverage Ordinary Hazard) horizontal sidewall nozzle that uses a standard-response glass bulb, originally designed for use in ordinary hazard occupancies. The SW-24 sprinkler head used had a 3 mm-thick 93°C (green) glass bulb. In one deluge test with the SW-24 nozzles, the glass bulbs were removed prior to testing.

### 2.2 Fire source

The fire source consisted of 420 wooden pallets placed in the centre of the tunnel, 600 m from the west portal. This type of test fuel mock-up is often used to simulate the payload of a Heavy Goods Vehicle (HGV) trailer. A target, consisting of a pile of 21 wooden pallets, was positioned 5 m from the rear of the fuel mock-up in order to evaluate the risk of fire spread.

The wooden pallets were placed on lightweight concrete slabs (Siporex), with 12 mm-thick plywood boards mounted on top of the slabs. Ten rows, each consisting of 2 piles of 21 pallets, were placed on the slabs, as was the target, which constituted one additional row. In Figure 4, the main fuel load is shown in detail from the side. In order to maintain the correct distance between the sprinkler nozzles and the top of the fuel load, the concrete platform was 0.2 m high. Based on experiences gleaned during the 2013 tests, this was not expected to influence the final results. Each pallet measured 0.8 x 1.2 m, i.e. the width of the fuel load was 2.4 m, weighed roughly 24 kg, and was approximately 0.143 m high. The total length of the fuel load was just over 8 m, and its total height was 3.03 m. The exposed fuel surface of one pallet was 3.3 m\(^2\), and the heat release rate per square metre of exposed fuel surface was estimated at 0.06 MW [7]. Thus, one row of wooden pallets was expected to produce 8 MW, and two rows 16 MW. As the process was dynamic and the two rows did not burn in exactly the same manner and time, it was expected that the combined energy output of the two burning piles would be slightly lower than 16 MW, however.

In total, the fuel load weighed just over 10 tonnes (441 x 24 kg). This meant that the potential energy content was approximately 180 GJ. The target consisted of 21 pallets, giving an additional energy of approximately 9 GJ, bringing the total to 189 GJ. The moisture content in the wooden pallets varied between 15 and 20%. In the 2013 tests, one test was carried out without water. The fire developed fully, and the target was consumed. Some fuel was left over, but most of the pallets were entirely consumed. The measured total energy consumed was 181 GJ, which is quite close to the theoretical value estimated [1].

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Figure 4  A side view of the fuel load, which consisted of 420 standard EUR wooden pallets. A steel frame was mounted to support the steel sheets that covered the wooden pallets at the ends and the top [1].

Both the front and back of the fire source was covered with steel plates, as was the area above the pallets. This arrangement made it difficult for water to directly penetrate the pallets, increasing the rigorousness of the test by reducing the ability of the system to fight the fire from above. A tarpaulin was mounted on the sides not covered by steel sheets during one of the 2013 tests, but this was not used in this study, both for practical reasons and because the test-setup had already been tested.

Figure 5 depicts the system schematically and in a photograph, with the wooden pallets in place. The pallets were ignited just behind the front plate, at the level of the lowest pallet. The ignition source consisted of two rectangular heptane pools of 0.2 × 0.8 m, which were placed in front of the wooden pallet piles at floor level. Each pan was filled with 2.5 l of heptane. Together, they produced a total heat release rate of approximately 0.5 MW.

Figure 5  Steel plates on the front and back of the pallets, and above them.

### 2.3 The mock-up setup

The setup of the mock-up in relation to the nozzles followed that used for the 2013 tests [1]. The vertical distance between the nozzles and the tops of the wooden pallets was 0.8 m. The horizontal distance from the opposite wall to the wooden pallets was 2.5 m (see Figure 6), and the horizontal distance between the nozzles and the vertical side of the wooden pallets was 2 m. The distance between each nozzle and the nearest wall was approximately 0.4 m, with a further space of 1.7 m from the wall to the ground pipe. The tunnel height was 6 m, and the total width of the road surface was 8.6 m.
2.4 Instrumentation

Gas temperature, gas concentration, visibility, radiation, water flow rate, and water pressure were measured every second. The heat release rate in MW was determined by measuring the gas and air flows approximately 1000 m from the fire, where a measurement station was located at the point marked as ‘Pile A’, at x= c. 1000 m, in Figure 7. In total, 22 thermocouples, 6 bi-directional pressure probes, 3 gas analysers (O$_2$, CO$_2$, and CO), 5 plate thermometers (PT), 2 photocells, 1 water pressure monitor, and 1 water flow gauge were used in these tests. The location of each instrument is shown in Figure 7.

All of the ceiling thermocouples (Type K, 0.5 mm) were placed 0.4 m below the ceiling, except at Pile A. PTs were mounted at the ceiling at x=-18, 0, 9, and 150 m in order to estimate the incident heat flux towards this position. There was also a PT 1.5 m above the road surface, at x=-18 m. All of the PTs were placed so that their plates always faced the fire source.

One of the two photocell visibility instruments was placed at the measurement station (x= c. 1000 m), with the other at x= 150 m. Smoke density was presented as a reduction (%) of air transparency over a given length (1.1 m), and was measured 1.5 m above the road surface. Air transparency was used to calculate visibility in m.

The thermocouples (Type K, 0.5 mm) were located close (50 mm away) to the nozzle positions N2, N4, and N6. The nozzles were positioned at the ceiling (see Figure 6), 3.2 m from the centre line of the fuel load, and at a distance corresponding to x= -12.5 (N1), -7.5 (N2), -2.5 (N3), 2.5 (N4), 7.5 (N5), and 12.5 m (N6). The bi-directional probe and the thermocouple upstream at x= -50 m were placed at the centre line of the tunnel cross-section (see Figure 7).
Figure 7  The layout of the instruments used in the test series.

The transportation time was factored into the calculation of the heat release rate, which was based on an oxygen calorimetry (O₂, CO₂, and CO), and the same technique as used in References [1-3] was employed. More information about the calculation of the heat release rate, visibility, and heat flux based on the measurements used is given in Appendix C.
3 Test procedure

For the tests that used the deluge system, a similar test procedure was used as in the 2013 tests [1], and the 2016 test programme is shown in Table 1. Five tests were performed with a deluge system (Tests 1-5), and one with sprinkler heads that used glass bulbs (Test 6).

To mimic a real detection scenario for the deluge system, the detection temperature was set at 141°C, and the first ceiling thermocouple to register this temperature was used as starting time (alarm) for the delay period. In all five tests the thermocouple at x = 4.5 m (7.3 m from the centre of the first row of piles, where the fire was ignited) reached the ‘detection’ temperature first. A four-minute ‘delay’ between detection (alarm) and activation was implemented for Tests 1-5 in order to simulate the manual operation time that a traffic control centre takes to initialise activation. In the 2013 tests this delay was varied – 2, 4, and 8 minutes – while the STA decided to maintain a constant four-minute delay for the tests presented in this report. Based on experiences during the 2013 test series, this corresponds to a heat release rate of roughly 10-15 MW at the point in time at which the water spray system is activated.

The longitudinal velocity during all of the deluge tests was set at 3 m/s, corresponding to a critical velocity for this type of tunnel and no backlayering of smoke. The velocity in Test 6, which used sprinkler heads, was set at 2 m/s, as it is known that, in the real tunnel in which these sprinkler heads are to be installed, the longitudinal velocity is lower than 2 m/s. An additional reason for this relates to safety, in that the decision was made in order to prevent long backlayering. The fire protection mounted at the tunnel ceiling was limited on the upstream side of the fire. It was found in previous model-scale studies that the automatic system should be able to work with this longitudinal velocity [6]. The decision to use a detection temperature of 141°C was based on the results obtained during the model scale tests [4], and further confirmed by the 2013 test results. Table 1 and Table 2 present the test sequence, test dates, and physical parameters that were varied.

Table 1 Test programme of the 2016 large-scale tests in the Runehamar tunnel.

<table>
<thead>
<tr>
<th>Test number</th>
<th>Test date</th>
<th>Nozzle type</th>
<th>K-factor</th>
<th>Flow rate per nozzle</th>
<th>Total flow rate</th>
<th>Nozzle Pressure</th>
<th>Wind speed</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>June 2016</td>
<td></td>
<td>l/(min·bar$^{1/2}$)</td>
<td>l/min</td>
<td>l/min</td>
<td>bar</td>
<td>m/s</td>
</tr>
<tr>
<td>1</td>
<td>13</td>
<td>TN-25</td>
<td>360</td>
<td>300</td>
<td>1800</td>
<td>0.69</td>
<td>3</td>
</tr>
<tr>
<td>2</td>
<td>14</td>
<td>TN-17</td>
<td>240</td>
<td>268</td>
<td>1608</td>
<td>1.25</td>
<td>3</td>
</tr>
<tr>
<td>3</td>
<td>15</td>
<td>TN-17</td>
<td>240</td>
<td>233</td>
<td>1400</td>
<td>0.95</td>
<td>3</td>
</tr>
<tr>
<td>4</td>
<td>16</td>
<td>TN-25</td>
<td>360</td>
<td>268</td>
<td>1608</td>
<td>0.55</td>
<td>3</td>
</tr>
<tr>
<td>5</td>
<td>17</td>
<td>SW-24</td>
<td>160</td>
<td>233</td>
<td>1400</td>
<td>2.13</td>
<td>3</td>
</tr>
<tr>
<td>6</td>
<td>20</td>
<td>SW-24 bulb</td>
<td>160</td>
<td>298</td>
<td>See Figure 24</td>
<td>See Figure 24</td>
<td>2</td>
</tr>
</tbody>
</table>
Table 2   Activation times recorded during the tests.

<table>
<thead>
<tr>
<th>Test number</th>
<th>Time of detection at 141°C (min:s)</th>
<th>Time of water at nozzles (min:s)</th>
<th>Time of fully developed flow in nozzles (min:s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3:55</td>
<td>7:53</td>
<td>8:16</td>
</tr>
<tr>
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<td>3:42</td>
<td>7:52</td>
<td>8:15</td>
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<tr>
<td>3</td>
<td>3:27</td>
<td>7:44</td>
<td>8:12</td>
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<td>4</td>
<td>4:17</td>
<td>8:22</td>
<td>8:47</td>
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<tr>
<td>5</td>
<td>4:06</td>
<td>8:10</td>
<td>8:33</td>
</tr>
<tr>
<td>6</td>
<td>-</td>
<td>N4; 5:22</td>
<td>N5; 5:45&lt;sup&gt;6&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td></td>
<td>N3; 6:47</td>
<td>N6; 30:56</td>
</tr>
</tbody>
</table>

As Table 2 shows, the activation times varied slightly for the deluge tests (1-5), with an average of 8:03 and a maximum difference of 29 seconds. The heat release rate at activation varied between 8 and 12 MW (see Section 4.1). In most cases, two rows of piles were involved in the fire at the point in time at which the system activated.

Tests with each nozzle type and flow rate set were carried out before each fire test. The spray pattern for the nozzles used is shown in Figure 8 and Figure 9.

![Figure 8](image1.png) Left: The spray pattern of the TN-25 nozzle at 1800 l/min (0.69 bar). Right: The TN-17 nozzle at 1608 l/min (1.25 bar).

![Figure 9](image2.png) Left: The TN-25 at 1608 l/min (0.55 bar). Right: The SW-24 nozzle at 1400 l/min (2.1 bar).

<sup>6</sup> Estimated based on flow rate and pressure measurements.
The throwing length, trajectory, and spray pattern varied, as can be seen in Figure 8 and Figure 9. Droplet size was dependent on nozzle pressure and K-factor. The largest droplets were emitted by the TN-25, and the smallest by the SW-24. The pressure of the TN-25 in Test 4 was only 0.55 bar, which is lower than the minimum working pressure recommended by the manufacturer, giving an observed throwing length of approximately 6 m. The throwing length for the SW-24 with a 2.1 bar nozzle pressure was roughly 7.5 m. The difference in throwing length between the two can be observed by comparing Figure 8 and Figure 9. The TN-17 had a lower K-factor and a higher pressure than the TN-25; thus, as can be expected, the TN-17’s droplet size and throwing length (approximately 6.7 m) fell between those of the TN-25 and SW-24. The throwing lengths are dependent on the pressure and direction of the nozzles. The throwing lengths given here should therefore only be regarded as tentative.
4 Results

In the following, a summary of the test results is given. Appendix A contains photographs taken during the six tests at different times following ignition, providing an overview of the development of each fire in relation to the nozzle type used. Appendix B presents the measured data of each test as a function of time.

4.1 Heat release rate

Figure 10 presents the calculated heat release rates, based on mass flow rates of O₂, CO₂, and CO, of all of the tests. The method of calculating heat release rate is presented in Appendix C. In the tests which used TN nozzles (larger droplets) the maximum heat release rate did not exceed 15 MW throughout the testing period. The lowest operational nozzle pressure with a large K-factor gave the best results (Test 4; TN-25, 0.55 bar). During the SW-24 tests the maximum heat release rate did not exceed 30 MW, except for one peak value of 31 MW after 48 minutes (Test 6; sprinkler head).

Several observations and experiences from the 2013 tests are of relevance here, primarily in relation to fire development. In the tests described here, fire growth prior to activation was generally consistent, with time variations restricted to less than half a minute and heat release rate variations confined to several MW. One reason for this was the type of fuel used (piled wooden pallets); another was the fact that the fire was initially shielded from the wind by a steel plate, positioned in front of the fuel. This windbreak slowed the growth of the fire, and has a counterpart in most vehicles, where there is often some kind of windbreak in front of the fuel. One of the tests of the 2013 series was performed without this windbreak. The fire growth was much faster and the fire spread to more pallets before the system was activated. The heat release rate at activation (7:17 after ignition) was 28 MW, instead of the 8-12 MW obtained here. In a similar 2013 test (Test 2-2013), a four-minute delay and windbreak deployment at a ventilation rate velocity of 3 m/s resulted in an activation time of 8:20 and a heat release rate of 15 MW. These are quite similar figures, indicating that this test procedure leads to consistent fire development.

Another test in the 2013 test series featured a tarpaulin placed on the sides not covered by steel sheets. Here, a long delay in activation, primarily due to the fact that the ceiling temperature of 141°C was obtained very late, as the tarpaulin greatly influenced the initial fire growth rate, was caused by a process of inertisation. The fire began to develop more rapidly when the tarpaulin was burned away on the sides closest to the ignition point, and activation occurred after 18:25. The heat release rate did not exceed 16 MW. This was one of the reasons a tarpaulin was not used in this study, along with the practical inconvenience of working with it due to its weight.

One of the 2013 tests involved a planned long pre-burn time, i.e. a delay of 12 minutes following detection. This scenario, however, stressed the pipes in the ceiling and, when the system was activated at 15:48, a coupling broke and so the majority of the water never reached the fire. The maximum heat release rate obtained was 79 MW [1]. In retrospect, however, this test was very valuable, as it showed how large a fire can become if the system is not activated, and also allowed the total energy content in GJ to be calculated.

Figure 11 shows the fire conditions at 9 minutes after ignition and shortly after activation for all of the tests. The heat release rate was in the range of 8-12 MW for all of the tests. This can be compared to the measured heat release rates presented in Figure 10. A similar series of photographs is provided in Figure 12, each of which was taken 30 minutes into the test. The heat release rate at this point was roughly 10 MW for Tests 1-4 and 23-26.
MW for Tests 5 and 6. These photographs give a good overview of the fire size when the system is operating properly. More photographs from different points in time are presented in Appendix A.

![Heat release rate in MW](image)

**Figure 10** The measured heat release rates for Tests 1-6.

![Fire development 9 minutes into the tests](image)

**Figure 11** Fire development 9 minutes into the tests. All of the systems had been activated at this point, and the heat release rates were in the range of 8-12 MW.
Figure 12  Fire development 30 minutes into the tests. The heat release rate was in the range of 10 MW for Tests 1-4 and 23-26 MW for Tests 5 and 6.

4.1.1  Deluge system

One of the important criteria set by the STA was that, following the activation of the deluge system, the total heat release rate should not exceed 30 MW. As can be seen in Figure 13, this was met by all of the deluge systems (Tests 1-5).

Figure 13  The measured heat release rates for Tests 1-5.

In the 2013 tests, a TN-25 deluge system with a total flow of 2250 l/min and 1.1 bar nozzle pressure was used (Test 2 - 2013). It is of interest to compare the corresponding test, which used a four-minute delay, to the two TN-25 tests performed for this study (Figure 14). The 2013 test showed similar initial fire behaviour, although the secondary peak was higher and took longer to be controlled due to the fact that, in lowering the
pressure at the nozzle, the droplets became larger and so the throwing trajectory or pattern towards the side of the fuel load changed. More water was delivered to the side of the fuel load that was close to the nozzles, effectively preventing further spreading inside the fuel area. The same trend can be observed here in that, after an initial constant period of around 15 minutes, the heat release rate continuously decreased, down to a total suppression.

![Graph of heat release rate in MW over Time (min)](image)

*Figure 14* The measured heat release rates for Tests 1 and 4 (TN-25) and Test 2 from 2013, which used a TN-25 nozzle with 2250 l/min and a four-minute delay.

The TN-17 nozzle (Tests 2 and 3) produced smaller droplets than the TN-25 (Tests 1 and 4), as is shown in Figure 15, which demonstrates that the TN-25 yielded better results with regard to the risk of fire spread within the fuel area. The TN-17 was less able to control the fire spread throughout the test period. After an initial constant period of around 15 minutes the heat release rate continuously decreased, but after approximately 45 minutes the fire began to increase in size again, and continued to do so until the end of the test (see Figure 15).

One possible reason for this may have been the influence of the wind as the fire travelled through the fuel load, which became more pronounced as the fuel burned further downstream from the windbreak. This, together with how the water was delivered to the sides of the fuel load, was crucial. Generally, the pallets that directly faced the water spray (water side) survived longer than those on the other side (low water side), as the water directly hit the pallets on the water side but not those on the low water side. As the first row of pallets started to fall over or burn out entirely, the wind increasingly affected the fire growth rate, to the point where the system was no longer able to stop the fire spread effectively. This was the case for both the TN-17 and SW-24 nozzles. If the system is to stop the fire spread, this should be done before the fire has spread beyond 2-3 pallet rows.

In summary, how effectively the water was delivered to the piles on the low water side and to what extent the fire was suppressed before spreading to the second and third rows directly influenced whether the system was able to prevent further spreading. In order to further illustrate this, two photographs are shown in Figure 16, which shows the conditions on the water side 40 minutes after ignition, and Figure 17, which shows the conditions 50 minutes after ignition. In Figure 16 (Test 4) the fire is clearly near-
suppressed, whereas in Figure 17 (Test 3) the fire has begun to re-develop. This behaviour can also be seen in the heat release rate curves in Figure 15.

![Heat release rate in MW](image)

*Figure 15* The measured heat release rates for Tests 2 and 3 (TN-17) and Tests 1 and 4 (TN-25).

![Test 4](image) ![Test 3](image)

*Figure 16* The conditions behind the steel plate after 40 minutes.

![Test 4](image) ![Test 3](image)

*Figure 17* The conditions behind the steel plate after 50 minutes.

The tests show that the SW-24 deluge nozzles are not as effective as the TN nozzles. There is also a difference between the TN-25 and the TN-17 nozzles, as is discussed above, in that the TN-25 nozzles were able to stop the fire spread within the fuel load such that it spread to two or three pallet rows at most. This can be seen in Figure 18, where seven rows are intact and two and a half are burned or have fallen over.
The TN-17 nozzles worked equally well initially, and controlled the fire for over 15 minutes following activation. However, after roughly 45 minutes they were unable to continue to suppress the fire spread, and the heat release rate increased again, albeit not to the level measured during the initial period. After the test, at least 4 piles were intact on the water side, but all were burned out on the low water side, likely due to this secondary phase. This can be seen in Figure 19, where at least three piles are still intact and the rest is partially burned.

The main reason for this difference in the nozzles relates to droplet size and how the water was delivered. Droplet size and trajectory both play a major role in the performance of this type of side-wall water spray system. In Figure 20, the remains of the fuel after
Test 5 (SW-24, deluge) is shown. Much of the fuel load was consumed by the fire, as can be seen by the heat release rate curves.

Figure 20 The conditions after Test 5 (SW-24).

The most effective way of comparing the efficiency of different nozzles is to integrate the total energy released during the test. The results are shown in further detail in Section 4.3.

4.1.2 Automatic sprinkler

The test that used sprinkler heads (with glass bulbs) was different from those which used the deluge system (six open nozzles). Instead of starting the pump and directing it towards open nozzles (the ground pipe was full of water and the ceiling pipe was empty), the ceiling pipes were filled with water and pressurised at 5 bar. When a glass bulb was activated, water sprayed from that nozzle and the pump was activated. This created a short pressure drop, but this was recovered as soon as the pump built up the pressure to maximum again.

The longitudinal velocity was reduced from 3 to 2 m/s in order to maintain a certain level of backlayering, as the sprinkler system is sensitive to longitudinal velocity. The longitudinal velocity was not reduced further so as to prevent long backlayering lengths. The total backlayering after around 30 minutes was approximately 40 m, as confirmed by the thermocouples in the ceiling (see Section 4.2).

In Figure 21, a direct comparison between the deluge system and the SW-24 sprinkler heads is shown. It highlights the fact that the deluge system was better able to maintain control initially, as it delivered water to the entire fuel load, unlike the automatic sprinkler system. This is also reflected in the heat release rate curve, as the nozzles further downstream were opened first. Both of the systems began to control the heat release rate at about the same time; approximately 20 minutes into the test.
The measured heat release rates for Test 5 (SW-24, deluge) and Test 6 (SW-24, sprinkler head).

The activation sequence of the sprinkler heads was of particular interest. All six sprinkler heads were equipped with bulbs (designated ‘N1’ to ‘N6’), with additional bulbs mounted at various points downstream of the fire in order to indicate if, and where, the temperature rose above 93°C (the temperature at which the bulbs break). The locations of these bulbs were 𝑥= 17.5, 27.5, and 47.5 m, respectively. It should be noted that no water was connected to these bulbs, and so they did not contribute by cooling the air after 𝑥= 17.5 m if they were activated.

The degree of control over the fire was very similar to that of the deluge system, as can be seen in Figure 21. This is also confirmed by how much fuel remained after the test, as shown in Figure 22.

The nozzle pressure and flow measurements give a very good indication of what occurred when the first sprinkler head opened. It is clear from Figure 23 that sprinkler head N4
activated first, and this was registered by a pressure gauge (see Figure 24). The pressure dropped from 5 bar (when the valve was closed) to 0.5 bar (when N4 opened). The water flow was very low at the beginning, as can be seen in the left photograph of Figure 23. This occurs at 5:22, when the bulb broke and the water pressure dropped, prior to the pump building up the pressure again. At 5:45 a clear change is observable in the character of the flow pattern, and the total flow increased to 750 l/min. Figure 24 shows both pressure and flow rate over the first 10 minutes. Exactly when the second sprinkler head opened is not possible to say, but it certainly took place between 5:22 and 5:45. The flow rate at this point was 750 l/min, and the water pressure was 5.5 bar, corresponding exactly to two open sprinkler heads (see Appendix C.4). At 6:47, N3 activated, and at 30:56 N6 (the last sprinkler head) activated. After the test it was found that all three of the additional glass bulbs mounted downstream the sprinkler heads had been broken as well.

![Figure 23](image1.jpg)

*Figure 23*  **Left:** The initial spray pattern of N4, immediately after the bulb broke. **Right:** The moment when N4 attained full pressure (5.5 bar).

![Figure 24](image2.jpg)

*Figure 24*  **Water pressure during Test 6.**  **Right:** Water flow rate during Test 6.

### 4.2 Gas temperature

In the following, a presentation of the measured gas temperatures at the centre line of the tunnel ceiling at distances x = -4.5, -1.5, 0, 1.5, 4.5, 9.0, 15, 25, and 150 m are given for all six of the tests. Figures 25-35 give the ceiling gas temperatures, measured 0.4 m below the ceiling, for each x position, which are shown in more detail in Figure 7. The first position, x = -4.5 m, was just in front of the initial fire source. It is clear from the measurements that a certain amount of convective heat was transported upstream, along the ceiling flow. The gas temperature prior to activation was almost 400°C in all of the tests. When the system was activated during Tests 1-5, it cooled these gases effectively. In Test 6 the temperature was initially lowered, but increased again as the backlayering continued to increase in effect. The backlayering length was estimated to be approximately 55 m at its peak. At position x = -1.5 m, roughly 2.3 m from the centre
of the fire, the temperature was between 500 and 600°C. This was the case for the first 30 minutes, but the fire slowly spread further downstream (in the positive x direction), and after 30 minutes the backlayering disappeared, even though it was clear that the fire was ongoing. The fire inside the fuel load behaved in the manner of a travelling fire, which explains why it was not present at the level of the ceiling after the 30 minute mark.

![Ceiling temperature at x= -4.5 m](image)

**Figure 25**  The measured gas temperatures at the level of the ceiling at x= -4.5 m for Tests 1-6 (the centre of the initial fire is x= -3.8 m). This is the temperature just upstream of the initial fire start point.

![Ceiling temperature at x= -1.5 m](image)

**Figure 26**  The measured gas temperatures at the level of the ceiling at x= -1.5 m for Tests 1-6 (the centre of the initial fire is x= -3.8 m).
The highest temperatures were recorded at \( x = 0 \) m, which was 3.8 m from the initial fire source. As the fire grew its position changed, and the temperature was reduced after a given time due to longitudinal flow. In some cases the ceiling temperature increased as the fire travelled through the fuel area, see for example Figures 29 - 31. Note that the maximum ceiling gas temperature did not exceed 800°C in any of the positions presented in Figures 25-35. The highest temperatures were measured at \( x = 0 \) and \( x = 1.5 \) m, in descending order of magnitude.

**Figure 27**  The measured gas temperatures at the level of the ceiling at \( x = 0 \) m for Tests 1-6.

**Figure 28**  The measured gas temperatures at the level of the ceiling at \( x = 1.5 \) m for Tests 1-6.
Figure 29  The measured gas temperatures at the level of the ceiling at $x=4.5$ m for Tests 1-6.

Figure 30  The measured gas temperatures at the level of the ceiling at $x=9$ m for Tests 1-6.
Figure 31  The measured gas temperatures at the level of the ceiling at x= 15 m for Tests 1-6.

Figure 32  The measured gas temperatures at the level of the ceiling at x= 25 m for Tests 1-6.
Figure 33 The measured gas temperatures at the level of the ceiling at x = 150 m for Tests 1-6.

On the upstream side, measurements were also made at x = -10, -18, -30, and -50 m so as to estimate the backlayering length for Test 6. The highest temperatures were measured roughly 26 minutes into the test at these points, when the heat release rate was approximately 25 MW. The following maximum temperatures were obtained: x = -10 m, 180°C; x = -18 m, 210°C; x = -30 m, around 100°C; x = -50 m, no significant increase in temperature. 40 m is likely a good estimate for the average backlayering length. Calculations performed using equations presented in Appendix C.7, which are only valid for free-burning fires, give a maximum backlayering distance equivalent to the location x = -55 m at a longitudinal velocity of 2 m/s. Due to the convective cooling of the fire plume of a 25 MW fire, one would expect the backlayering length to be somewhat lower, and so the calculated and measured values for backlayering length correlate relatively well.

The maximum gas temperature measured during the free-burning test conducted in 2013 was 1366°C [1]. This clearly demonstrates the impact that these water spray systems have in terms of protecting the tunnel construction.

4.3 Total energy content

Table 3 presents a summary of the test results. The parameters given are the heat release rate at activation, $Q_{act}$, the highest ceiling temperature at activation, $T_{act}$, the maximum heat release rate after the system has been activated, $Q_{max, after act}$, and the incident maximum heat flux to the ceiling at $x = 0$ m, $q''_{max}$. This value is presented as the value at activation/maximum value after activation. Total energy, $E_{tot}$, is also given in GJ, and is an integrated value from the heat release rate curves for the entire test period. The total energy content of the fire load can be estimated by multiplying its mass with the theoretical heat of combustion for wood. There were 441 wooden pallets including those of the target, with each weighing around 24 kg. The theoretical heat of combustion for wood can be obtained from Tewarson [8]; 17.9 MJ/kg. This means that the total potential heat energy for this fuel load was 189 GJ.
In the last column, a value is given for the equivalent number of pallets that have been consumed. This value was obtained by taking $E_{tot}$ for each test and dividing it by the heat of combustion and weight of all of the pallets. This figure does not necessarily correlate exactly with ocular inspections performed following the tests, but gives a good indication of how many pallets were consumed.

Table 3  Summary of the key heat energy parameters of the tests.

<table>
<thead>
<tr>
<th>Test no.</th>
<th>$t_{act}$ (m:s)</th>
<th>$Q_{act}$ (MW)</th>
<th>$T_{act}$ (°C)</th>
<th>$Q_{max, after act}$ (MW)</th>
<th>$\dot{q}_{max, after act}$ (kW/m²)</th>
<th>$E_{tot}$ (GJ)</th>
<th>Equivalent number of pallets consumed</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>7:53</td>
<td>12.0</td>
<td>423</td>
<td>14.9</td>
<td>19/11</td>
<td>33</td>
<td>76</td>
</tr>
<tr>
<td>2</td>
<td>7:52</td>
<td>8.0</td>
<td>393</td>
<td>13.9</td>
<td>10/19</td>
<td>49</td>
<td>113</td>
</tr>
<tr>
<td>3</td>
<td>7:44</td>
<td>9.5</td>
<td>524</td>
<td>16.5</td>
<td>18/12</td>
<td>45</td>
<td>104</td>
</tr>
<tr>
<td>4</td>
<td>8:22</td>
<td>12.2</td>
<td>409</td>
<td>14.0</td>
<td>12/15</td>
<td>23</td>
<td>53</td>
</tr>
<tr>
<td>5</td>
<td>8:10</td>
<td>11.4</td>
<td>531</td>
<td>29.7</td>
<td>21/36</td>
<td>78</td>
<td>181</td>
</tr>
<tr>
<td>6</td>
<td>N4; 5:22</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>N5; 5:45</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>N3; 6:47</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>N6; 30:56</td>
<td>5.1</td>
<td>525</td>
<td>31.1</td>
<td>12/14</td>
<td>75</td>
<td>174</td>
</tr>
</tbody>
</table>

The heat release rate at activation ranged from 5 to 12 MW for all tests. The deluge tests varied between 8 and 12.2 MW. The ceiling temperature was in the range of 393-531°C. The maximum heat release rate after activation for the deluge tests ranged from 13.9 to 29.7 MW. For Test 6, the maximum heat release rate after activation was 31.1 MW. The maximum incident heat release rate as directed towards the ceiling after activation was found not to exceed 36 kW/m². This value is low as compared to the values measured in the tests in 2013 (approximately 400 kW/m²), when no water spray system was used.

4.4  Visibility

Visibility was measured at two positions downstream of the fire, and 1.5 m above the road surface. The positions were $x= 150$ and 1000 m, and the results are shown in Appendix B for each of the tests.

Figure 34-36 give examples of the visibility measurements, which show that visibility was worse further away as there was no stratification at that location. At $x= 150$ m there was a stratification, which is confirmed by temperature measurements at the same location. This can be seen in Appendix B, where these temperature readings are presented.

The best visibility at $x= 150$ m was obtained in Test 4, which used the low-pressure TN-25 nozzle. Further away, at $x= 1000$ m, the visibility was roughly the same for all tests, although Test 4 seemingly yielded the best visibility and Test 5 the worst, with nearly zero.
Figure 34: The measured visibility during Test 4 (TN-25).

Figure 35: The measured visibility during Test 3 (TN-17).

Figure 36: The measured visibility during Test 5 (SW-24).
4.5 Gas analysis

The carbon monoxide volume concentrations at the mid-tunnel height and 1000 m downstream of the fire are given in Figure 37, which clearly show that the CO concentrations of Tests 1 and 4 (TN-25) correlate well. The results of the tests that used TN-17 lie at a higher level, with those of SW-24 higher still. This is in accordance with the order of the heat release rates in the tests. Note that a lower ventilation velocity was used for Test 6, and thus higher CO concentrations were obtained than during Test 5.

![Carbon monoxide](image)

**Figure 37 Carbon monoxide volume concentration during Tests 1-6.**

In Table 4, a summary of the maximum and minimum values for gas measurements at the mid-tunnel height and 1000 m downstream of the fire are given. A trend similar to that of CO can be observed for CO₂.

Furthermore, comparison of the test data with that of the 2013 free-burning test indicates that, when the water was applied, the production of incomplete combustion products, such as CO, increased. Further research is needed to investigate the implications of this, however.

**Table 4 Maximum or minimum values for gas measurements at mid tunnel height and 1000 m downstream of the fire.**

<table>
<thead>
<tr>
<th>Test number</th>
<th>O₂ (x=1000) m (%)</th>
<th>CO₂ (x=1000) m (%)</th>
<th>CO (x=1000) m (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>20.3</td>
<td>0.49</td>
<td>0.07</td>
</tr>
<tr>
<td>2</td>
<td>20.2</td>
<td>0.59</td>
<td>0.10</td>
</tr>
<tr>
<td>3</td>
<td>20.1</td>
<td>0.77</td>
<td>0.12</td>
</tr>
<tr>
<td>4</td>
<td>20.4</td>
<td>0.48</td>
<td>0.07</td>
</tr>
<tr>
<td>5</td>
<td>19.4</td>
<td>1.34</td>
<td>0.14</td>
</tr>
<tr>
<td>6</td>
<td>19.3</td>
<td>1.43</td>
<td>0.24</td>
</tr>
</tbody>
</table>
5 Conclusions

Larger droplets better penetrated the fuel load and facilitated the cooling of surfaces directly, preventing further flame spread within the fuel load. The wooden pallets that were closer to the water spray system were more effectively extinguished, although this is also dependent on the trajectory of the droplets, which in turn is directly related to nozzle geometry, pressure, and K-factor. A higher nozzle pressure for the same K-factor raises the trajectory of the droplets and increases the throwing length. Taken together, these parameters determine the efficiency with which flame spread was controlled within the fuel load.

The TN-25 nozzle, using a lower pressure and water flow rate, did not perform worse than in the 2013 tests. On the contrary, the results have improved, particularly for the lowest pressure setting. It should, however, be noted that this operating pressure is less than the minimum requirement given by the manufacturer. The prototype TN-17 performed similarly to the TN-25 during the first 30 minutes of the test but, around 45 minutes in, the fire redeveloped. The maximum heat release rate after the redevelopment was not higher than that of the first phase. The SW-24 nozzle performed most poorly, although it protected the construction well and kept the maximum heat release rate below that set by the STA as a goal.

The heat release rate upon activation ranged from approximately 5 to 12 MW. During the TN nozzle tests the heat release rate remained under control for a period of 15 minutes following activation, after which the fire size decreased over a period of 10-30 minutes. The TN-25 system prevented further flame spread within the fuel load, while the fire during the TN-17 test redeveloped after 45 minutes.

Testing with a sprinkler head showed the potential of this type of system with regard to tunnels with a lower ventilation rate, or where the ventilation strategy involves reducing the velocity after a fire alarm. Further testing is needed in order to explore the limitations of these systems, however, particularly as using a sprinkler that emits larger droplets and an automatic device seems to be a feasible method.

The FFFS was able to maintain a heat release rate of lower than 30 MW in all five tests using a deluge. Following the activation of the system, the maximum temperature at the ceiling never exceeded 800°C.

A pile of pallets, representing a target, was located 5 m from the end of the main fuel stack. It was used to assess the risk of fire spread to adjacent vehicles. In all of the tests in which the FFFS was operational, the target was unaffected by the main fire.

The primary benefit of the FFFS is that it can be used to increase safety in tunnels, as such systems are able to fight fires that are relatively large and thereby potentially prevent major disasters. In a scenario in which congestion is an issue, and more specifically when a queue forms, the system increases safety by minimising the risk of propagation of a fire as it could occur.
6 References


Appendix A – Photographs taken during testing

Figure A1  Photographs of the six tests, taken prior to ignition. The layout of the photographs with respect to the tests in the other Figures of this appendix is the same as here.

Figure A2  Photographs of the six tests, 1 minute after ignition.
Figure A3  Photographs of the six tests, 3 minutes after ignition.

Figure A4  Photographs of the six tests, 6 minutes after ignition.
Figure A5  Photographs of the six tests, 7 minutes after ignition.

Figure A6  Photographs of the six tests, 9 minutes after ignition.
Figure A7  Photographs of the six tests, 11 minutes after ignition.

Figure A8  Photographs of the six tests, 14 minutes after ignition.
Figure A9  Photographs of the six tests, 17 minutes after ignition.

Figure A10  Photographs of the six tests, 20 minutes after ignition.
Figure A11  Photographs of the six tests, 25 minutes after ignition.

Figure A12  Photographs of the six tests, 30 minutes after ignition.
Figure A13  Photographs of the six tests, 60 minutes after ignition.
Appendix B – Results for Tests 1-6

B.1 Test 1

Figure B1-1 The measured heat release rate: Test 1.

Figure B1-2 The measured gas temperature at ceiling level, and upstream of the fire at distances x and 40 cm below the ceiling: Test 1.

Figure B1-3 The measured gas temperature at ceiling level, and downstream of the fire at distances x and 40 cm below the ceiling: Test 1.
Figure B1-4  The measured gas temperature downstream of the fire at distance $x = 1000$ m, and at different heights above the road surface: Test 1.

Figure B1-5  The measured gas velocity downstream of the fire at distance $x = 1000$ m, and at different heights above the road surface: Test 1.

Figure B1-6  The measured smoke visibility at $x = 1000$ m and 150 m downstream of the fire, and 1.5 m above the road surface: Test 1.
Figure B1-7 The measured gas temperature at x=150 m downstream of the fire, and at two heights above the road surface: Test 1.

Figure B1-8 The measured heat flux to the ceiling at different distances along the ceiling: Test 1.

Figure B1-9 The measured gas temperature at different nozzle locations: Test 1.
B.2 Test 2

Figure B2-1 The measured heat release rate: Test 2.

Figure B2-2 The measured gas temperature at ceiling level, and upstream of the fire at distances x and 40 cm below the ceiling: Test 2.

Figure B2-3 The measured gas temperature at ceiling level, and downstream of the fire at distances x and 40 cm below the ceiling: Test 2.
Figure B2-4 The measured gas temperature downstream of the fire at distance $x = 1000$ m, and at different heights above the road surface: Test 2.

Figure B2-5 The measured gas velocity downstream of the fire at distance $x = 1000$ m, and at different heights above the road surface: Test 2.

Figure B2-6 The measured smoke visibility at $x = 1000$ m and $150$ m downstream of the fire, and $1.5$ m above the road surface: Test 2.
Figure B2-7 The measured gas temperature at $x = 150$ m downstream of the fire, and at two heights above the road surface: Test 2.

Figure B2-8 The measured heat flux to the ceiling at different distances along the ceiling: Test 2.

Figure B2-9 The measured gas temperature at different nozzle locations: Test 2.
B.3 Test 3

**Figure B3-1** The measured heat release rate: Test 3.

**Figure B3-2** The measured gas temperature at ceiling level, and upstream of the fire at distances x and 40 cm below the ceiling: Test 3.

**Figure B3-3** The measured gas temperature at ceiling level, and downstream of the fire at distances x and 40 cm below the ceiling: Test 3.
Figure B3-4 The measured gas temperature downstream of the fire at distance $x = 1000$ m, and at different heights above the road surface: Test 3.

Figure B3-5 The measured gas velocity downstream of the fire at distance $x = 1000$ m, and at different heights above the road surface: Test 3.

Figure B3-6 The measured smoke visibility at $x = 1000$ m and 150 m downstream of the fire, and 1.5 m above the road surface: Test 3.
**Figure B3-7** The measured gas temperature at x= 150 m downstream of the fire, and at two heights above the road surface: Test 3.

**Figure B3-8** The measured heat flux to the ceiling at different distances along the ceiling: Test 3.

**Figure B3-9** The measured gas temperature at different nozzle locations: Test 3.
B.4 Test 4

Figure B4-1 The measured heat release rate: Test 4.

Figure B4-2 The measured gas temperature at ceiling and upstream the fire at different distances x and 40 cm below ceiling: Test 4.

Figure B4-3 The measured gas temperature at ceiling level, and downstream of the fire at distances x and 40 cm below the ceiling: Test 4.
Figure B4-4 The measured gas temperature downstream of the fire at distance $x = 1000 \text{ m}$, and at different heights above the road surface: Test 4.

Figure B4-5 The measured gas velocity downstream of the fire at distance $x = 1000 \text{ m}$, and at different heights above the road surface: Test 4.

Figure B4-6 The measured smoke visibility at $x = 1000 \text{ m}$ and $150 \text{ m}$ downstream of the fire, and $1.5 \text{ m}$ above the road surface: Test 4.
Figure B4-7 The measured gas temperature at x = 150 m downstream of the fire, and at two heights above the road surface: Test 4.

Figure B4-8 The measured heat flux to the ceiling at different distances along the ceiling: Test 4.

Figure B4-9 The measured gas temperature at different nozzle locations: Test 4.
B.5  Test 5

Figure B5-1  The measured heat release rate: Test 5.

Figure B5-2  The measured gas temperature at ceiling and upstream the fire at different distances x and 40 cm below ceiling: Test 5.

Figure B5-3  The measured gas temperature at ceiling level, and downstream of the fire at distances x and 40 cm below the ceiling: Test 5.
Figure B5-4 The measured gas temperature downstream of the fire at distance $x=1000$ m, and at different heights above the road surface: Test 5.

Figure B5-5 The measured gas velocity downstream of the fire at distance $x=1000$ m, and at different heights above the road surface: Test 5.

Figure B5-6 The measured smoke visibility at $x=1000$ m and $150$ m downstream of the fire, and $1.5$ m above the road surface: Test 5.
Figure B5-7  The measured gas temperature at $x = 150$ m downstream of the fire, and at two heights above the road surface: Test 5.

Figure B5-8  The measured heat flux to the ceiling at different distances along the ceiling: Test 5.

Figure B5-9  The measured gas temperature at different nozzle locations: Test 5.
B.6 Test 6

Figure B6-1 The measured heat release rate: Test 6.

Figure B6-2 The measured gas temperature at ceiling and upstream the fire at different distances \( x \) and 40 cm below ceiling: Test 6.

Figure B6-3 The measured gas temperature at ceiling level, and downstream of the fire at distances \( x \) and 40 cm below the ceiling: Test 6.
Figure B6-4 The measured gas temperature downstream of the fire at distance x = 1000 m, and at different heights above the road surface: Test 6.

Figure B6-5 The measured gas velocity downstream of the fire at distance x = 1000 m, and at different heights above the road surface: Test 6.

Figure B6-6 The measured smoke visibility at x = 1000 m and 150 m downstream of the fire, and 1.5 m above the road surface: Test 6.
Figure B6-7  The measured gas temperature at $x=150$ m downstream of the fire, and at two heights above the road surface: Test 6.

Figure B6-8  The measured heat flux to the ceiling at different distances along the ceiling: Test 6.

Figure B6-9  The measured gas temperature at different nozzle locations: Test 6.
Appendix C – Theoretical aspects

In the following, a summary of the equations used to calculate different parameters is presented.

C.1 Heat release rate

Heat release rates can be estimated using the oxygen consumption method [9]:

\[
Q = \sum_i \left[ \Delta H_{O_2} \phi_i - (\Delta H_{O_2,CO} - \Delta H_{O_2}) \right] \frac{1-\phi_i}{2} \left( \frac{X_{CO,j}}{X_{O_2,j}} \right) \frac{\dot{m}_i}{1+\phi_i(\alpha-1)} \frac{M_{O_2}}{M_a} (1-X_{H_2O,j}^0) X_{O_2,j}^0
\]  

(1)

where the oxygen depletion factor, \( \phi \), is expressed as:

\[
\phi = \frac{X_{O_2}^0 (1-X_{CO,CO}^0) - X_{O_2} (1-X_{CO}^0)}{(1-X_{O_2,CO}^0) - X_{CO}^0) X_{O_2}^0}
\]

In the above equations, \( Q \) is the heat release rate (kW), \( \Delta H_{O_2} \) is heat released per unit mass of \( O_2 \) consumed for complete combustion (no CO in product, 13.1 MJ/kg), \( \Delta H_{O_2,CO} \) is heat released per unit mass of \( O_2 \) consumed for combustion of CO to CO\(_2\) (17.6 MJ/kg), \( \dot{m}_i \) is the mass flow rate of the \( i \)th layer, \( M \) is molecular weight (kJ/kmol), \( \alpha \) is a constant (approx. 1.105), \( X_{O_2}^0 \) is the volume fraction of oxygen in the incoming air (ambient) or 0.2095, \( X_{CO}^0 \) is the volume fraction of carbon dioxide in the incoming air (ambient) or \( X_{CO}^0 \approx 0.00033 \), and \( X_{O_2} \) and \( X_{CO} \) are the volume fractions of oxygen and carbon dioxide, respectively, as measured by a gas analyser (dry) at the measuring station downstream of the fire. The superscripted 0 indicates the incoming fresh-air flow. The volume fraction of water vapour in the incoming fresh-air flow at ambient temperature, \( X_{H_2O}^0 \), was negligible. As the amount of evaporated water in the tunnel at the measurement station was considered to be much less than the total amount of the tunnel flow, and the gas temperatures at the sampling points were reasonably low, uncertainty due to water vapour in the heat release rate estimation was deemed to be negligible. Note that the tunnel was divided into several horizontal layers in order to estimate the heat release rates and other parameters. At each layer, the properties were assumed to be uniform.

Note that the heat release rate was estimated using data from the measurement station far downstream of the fire, and so the transportation time had to be considered. The actual time, \( \tau \), can be expressed as [10]:

\[
\tau = t - \frac{L}{u_o} \left[ 1 - \frac{1}{\xi} \ln \left( \frac{\psi + e^{\xi}}{\psi + 1} \right) \right]
\]  

(2)

where the two variables are defined as:

\[
\xi = \frac{h w_p L}{m_o c_p}, \quad \psi = \frac{2 Q}{3 m_o c_p T_o}
\]

where \( t \) is time (s), \( \tau \) is actual time corresponding to the fire source(s), \( h \) is lumped heat transfer coefficient (kW/(m\(^2\)-K)), \( u_o \) is longitudinal velocity (m/s), \( w_p \) is wet perimeter
(m), \(L\) is distance between fire and measurement station (m), \(c_p\) is heat capacity (kJ/(kg·K)), and \(T_o\) is ambient temperature (K).

### C.2 Visibility

Visibility, \(V_{is}\) (m), can be directly estimated using the extinction coefficient:

\[
V_{is} = \frac{a}{C_s}
\]  

(3)

The parameter \(a\) is a constant, and is related to the characteristics of the evacuation sign and the smoke. The value of \(a\) is in a range of 5-10 m for a light-emitting sign and 2-4 m for a reflecting sign. As light-emitting signs along the length of tunnels are required, a conservative value of 2 was chosen for the purposes of calculating visibility in this work. To clearly plot the results on graphs, a maximum value of 30 m was set for visibility.

The extinction coefficient, \(C_s\) (1/m), in Eq. (2) can be obtained by the following:

\[
C_s = \frac{1}{L} \ln\left(\frac{I_o}{I}\right)
\]  

(4)

where \(L\) is the light path length, \(I_o\) is the intensity of the incident light, and \(I\) is the intensity of light as viewed through the smoke.

### C.3 Heat flux

Plate thermometers were used to measure incident heat flux (kW/m\(^2\)), which can be calculated using the following equation [11, 12]:

\[
\dot{q}_{\text{PT}} = \varepsilon_{\text{PT}} \sigma T_{\text{PT}}^4 + (h_{\text{c,PT}} + K_{\text{cond}})(T_{\text{PT}} - T_{\infty}) + (\rho c_{\text{PT}} \delta)_{\text{PT}} \frac{\Delta T_{\text{PT}}}{\Delta t}
\]  

(5)

where the conduction correction factor \(K_{\text{cond}} = 8.43\) W/m\(^2\)-K, the surface emissivity of PT \(\varepsilon_{\text{PT}} = 0.8\), and the lumped heat capacity coefficient \((\rho c_{\text{PT}} \delta)_{\text{PT}} = 4202\) J/m\(^2\)-K [12]. The subscripted \(\infty\) indicates the surrounding gas. The terms in the numerator on the right-hand side are emissive radiation, convective heat loss, conductive heat loss, and accumulative heat gain, respectively.

### C.4 Nozzle flow

Water flow rate for each nozzle, \(\dot{q}_w\) (l/min), can be estimated as follows:

\[
\dot{q}_w = K \sqrt{\Delta P}
\]  

(6)

where \(K\) is the K-factor (l/(min-bar\(^{1/2}\))), and \(\Delta P\) is the operating pressure (bar). Total volume flow rate, \(\dot{q}_{w,\text{tot}}\) (l/min), can be simply calculated by multiplying the water flow rate for each nozzle by the total number of nozzles, as the operating pressures were approximately the same for all the nozzles.
Water flow density, \( \dot{q}_w \) (mm/min), can be obtained using:

\[
\dot{q}_w = \frac{\dot{q}_w}{A_c}
\]  

(7)

where \( A_c \) is the covered floor area for each nozzle (m\(^2\)).

### C.5 Droplet size

Dombrowski et al. [13] found that the median droplet diameter, \( d_m \), is related to a Weber number, i.e. the ratio of inertial forces to surface tension forces, and the correlation can be expressed as:

\[
\frac{d_m}{d_n} = C \text{We}^{-1/3}
\]  

(8)

where the Weber number, \( \text{We} \), is defined as:

\[
\text{We} = \frac{\rho u_n^2 d_n}{\sigma}
\]

In the above equation, \( d_n \) is the nozzle diameter (m), \( \sigma \) is the liquid surface tension (N/m), which can be considered as constant for a certain temperature (0.073 N/m at 20 °C), \( u_n \) is the initial discharge velocity of the droplets (m/s), and \( C \) is a coefficient. The coefficient \( C \) could differ from one nozzle to another. Based on the large-droplet sprinkler tests carried out by Yu [14], this coefficient is in the range of 2.3-4.5, although it may have differed for the nozzles used in this test series. A rough estimation indicates that the median droplet size in the tests was in the range of 1-2.5 mm.

### C.6 Gas velocity

Bi-directional probes [15] were used to measure the gas velocity, \( u_c \), which can be expressed as:

\[
u_c = \frac{1}{k} \sqrt{\frac{2T \Delta p}{\rho_o T_o}}
\]  

(9)

where \( T \) is the gas temperature, \( T_o \) is ambient temperature, \( k \) is a calibration coefficient, and \( \Delta p \) is the measured pressure difference.

The calibration constant \( k \) is a function of the Reynolds number, where the characteristic length is the diameter of the probe. The Reynolds number for these tests was found to be approximately 2000-5000, giving a calibration constant of 1.08 [18].

Since the velocity measured in the tests was not the average velocity of the fresh air, \( u_o \), a flow coefficient related to the measured velocity and the average velocity had to be determined. In the analysis of the measured data, the air mass flow rate was determined by dividing the flow into five equally distributed horizontal areas along the ceiling, where
every area corresponded to a bi-directional probe and thermocouple. The total air mass flow rate, \( \dot{m}_o \), was determined according to the following equation:

\[
\dot{m}_o = \zeta \sum_i \frac{\rho_o T_o}{T_i} A_i u_{i},
\]

(10)

The longitudinal air velocity, \( u_o \) (m/s), is estimated using:

\[
u_o = \frac{\dot{m}_o}{\rho_o A}
\]

(11)

where \( A \) is the cross-sectional area of the tunnel, \( A_i \) is the area of the \( i \)th tunnel cross-section, and \( \zeta \) is the flow coefficient. The subscripted \( o \) denotes fresh air (ambient temperature).

### C.7 Backlayering length

Dimensionless backlayering length in a tunnel fire can be estimated using the following equation [16]:

\[
L_b^* = \begin{cases} 
18.5 \ln(0.81 Q^{1/3} / u^*), & Q^* \leq 0.15 \\
18.5 \ln(0.43 / u^*), & Q^* > 0.15
\end{cases}
\]

(12)

In the above equation, dimensionless backlayering length, \( L_b^* \), is defined as:

\[
L_b^* = \frac{L_b}{H}
\]

(13)

Dimensionless heat release rate, \( Q^* \), is defined as:

\[
Q^* = \frac{\dot{Q}}{\rho_o c_p T_o g^{1/2} H^{5/2}}
\]

(14)

Dimensionless longitudinal velocity, \( u^* \), is defined as:

\[
u^* = \frac{u_o}{\sqrt{gH}}
\]

(15)

where \( g \) is acceleration due to gravity (m/s\(^2\)), \( H \) is tunnel height (m), and \( c_p \) is heat capacity (kJ/(kg·K)).
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