Model scale tunnel fire tests with water-based fire suppression systems

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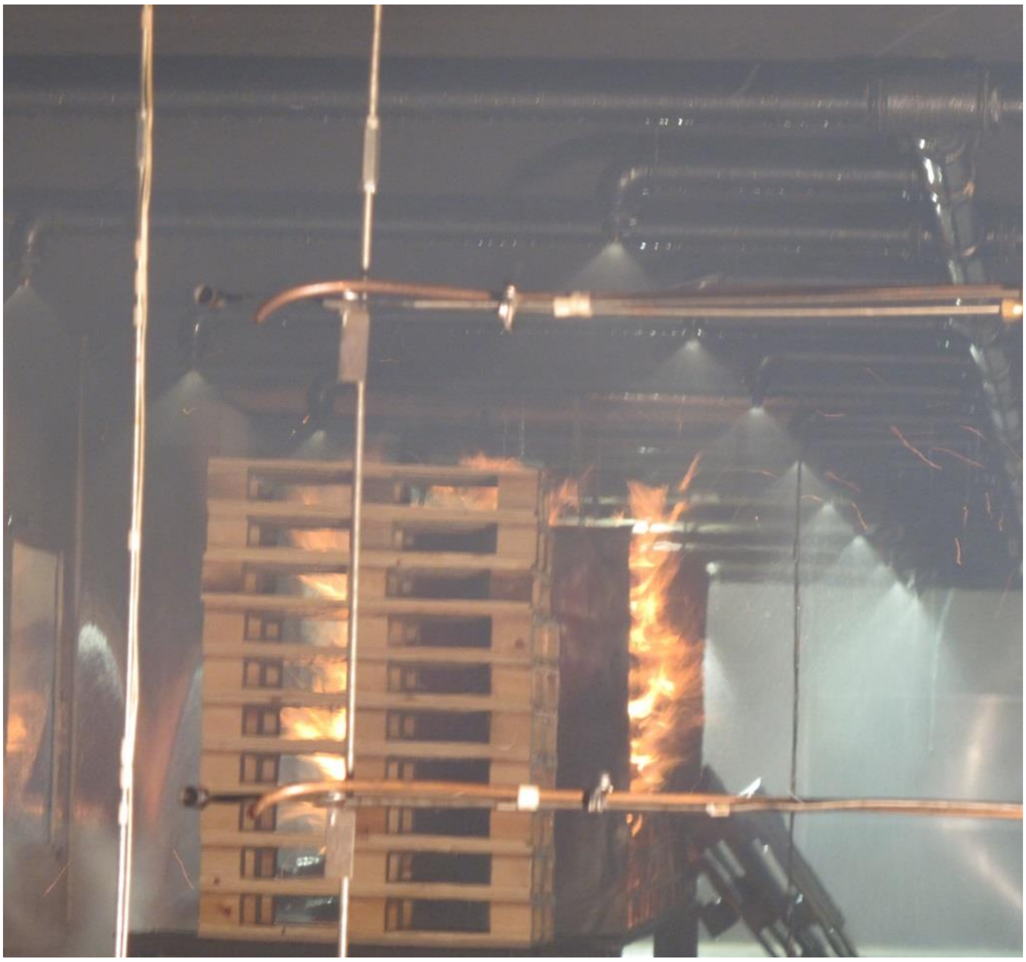

Fire Research

SP Report 2014:02

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Abstract

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A total of 18 tests were carried out in the 1:4 model scale tunnels with water-based fire suppression systems together with one free-burn test. The key parameters including fuel load covers, activation time, water flow rate, nozzle type, ventilation velocity, sprinkler section length and tunnel width were tested. Technical information and analyses of test data are presented in this report with a focus on the influence of these different parameters on the design fire in a tunnel with a water-based fire suppression system. Further, guidance for the design fires in tunnels with water-based fire suppression systems is proposed.

Key words: model scale tests, tunnel fire, fire suppression, ventilation, activation

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Contents

Preface

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Anders Palm, SSBF
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Summary

To fill in the knowledge gap in performance of water-based fire suppression systems in tunnels with a focus on the design fire, a total of 18 tests were carried out in the 1:4 model scale tunnels with water-based fire suppression systems together with one free-burn test. The key parameters including fuel load covers (ceiling cover and end blocks), activation time, water flow rate, nozzle type, ventilation velocity, sprinkler section length and tunnel width were tested. Three types of nozzles were used in the tests, including two normal nozzles K5 (K-factor 5) and K9 and one special nozzle T-Rex.

The results show that the activation time plays an important role in fire suppression efficiency. For a late activation, the fire could approximate a fully developed fire and result in catastrophic consequences. In these cases, the fires are much more difficult to suppress and further the benefit from a fire suppression system becomes limited. In order to reduce the heat release rate and suppress the fire efficiently, the fire suppression system should be activated as early as possible.

The water flow rate influences the performance of a fire suppression system in a tunnel fire without ceiling coverage significantly and the water flow rate of 5 mm/min (10 mm/min in full scale) is efficient to extinguish the fire, but 2.5 mm/min (5 mm/min in full scale) is not great enough which resulted in a maximum heat release rate of 46 % of that in a free-burn test. However, the influence of water flow rate on the performance of a fire suppression system with ceiling coverage is insignificant.

The fire suppression systems using normal nozzles cannot effectively suppress the fire with ceiling coverage, however, the nozzles K9 discharging larger droplets performs slightly better. In these tests with the two normal nozzles (K5 and K9), the maximum heat release rate were reduced to around 23 % to 32 % of that in a free-burn test for water flow rate of 5 mm/min to 7.5 mm/min (50 % change), corresponding to 10 mm/min to 15 mm/min in full scale, respectively. This indicates that within the range of water flow rate tested, an increase of 50 % in water flow rate only results in a decrease in the maximum heat release rate of approximately 9 % of that in a free-burn test. As a comparison, the fire suppression systems using T-Rex nozzles with a water flow rate of 5 mm/min (10 mm/min in full scale) effectively suppressed the fires, except in the tests in the narrow tunnel with an activation time delay of 2 min. It can be concluded that in the tested scenarios, the T-Rex system with larger droplets performs better than the other two systems with normal nozzles.

The ceiling coverage plays an important role in fire suppression. The fire with a ceiling coverage is much more difficult to suppress and corresponds to the worse scenario compared to the case without ceiling coverage. In the tests with ceiling coverage, the fires were difficult to suppress using normal nozzles. Only the T-Rex nozzles performed well in corresponding situations. Further, the ceiling coverage materials generally may not affect the performance of the fire suppression system since in the tests even a thin combustible cover (3 mm plywood board) was protected well by the fire suppression system after activation. Note that the

activation time was simulated well in the tests by use of the commonly-used heat detection algorithm (or even conservative in some tests), therefore the scenario simulated should be quite realistic. In other words, the combustible covers normally used may probably not burn out before the activation of a fire suppression system and will probably be protected well by the fire suppression system, with the exception that the ceiling cover is very thin and highly combustible such as thin tarpaulin.

Without the end blocks (in front and at the end of the fuels), the fuels were directly exposed to wind, and the high ventilation significantly increased the fire growth rate and thus increased the difficulty in fire suppression. For fuels with end blocks, the fire develops much more slowly and could be more easily suppressed. According to this, a suggestion can be made to the vehicle industry that the heavy good vehicle trailers should all have steel end blocks.

Tunnel ventilation affects the performance of a fire suppression system by influencing the fire development. Further, under low ventilation conditions, heat or smoke fire detection systems can be triggered much earlier and thereby the fire suppression system can be activated earlier. Therefore, the fire under low ventilation was more easily suppressed due to both the low heat release rate at the activation time, and the slow fire growth.

The decrease of sprinkler section length from 12.5 m to 7.5 m (50 m to 30 m in full scale) did not affect the performance of the fire suppression system with large droplets nozzles (T-Rex), and the key sprinkler section corresponds to the section covering the fire source. In contrast, the tunnel cross-section shows some influence on the performance of the fire suppression system. For early activation, the tunnel width shows no influence. However, for the activation delay of 2 min, the fire in the narrow tunnel was not efficiently suppressed. The main reason could be that close to the fire source, the fuels together with end blocks increased the local gas velocity by obstruction, which stimulates the fire growth and make the fire more difficult to suppress.

Fire spread to a target placed 1.25 m from the rear end of the main fire load (5 m in full scale) was prevented in all the tests with fire suppression. In the free-burn test 15, the target was ignited at 13.2 min (approx. 1.6 MW in model scale and 50 MW in full scale) and burn out after the test.

A key interest of the study is the design fire for a tunnel with a water-based fire suppression system. From the analysis of test data, it is concluded that for a normal deluge water spray system operated at a water flow rate of approximately 10 mm/min (or not lower than this value) in a realistic tunnel, 50 % of the maximum heat release rate in the free-burn test (test without fire suppression) could be considered as the design fire or the maximum heat release rate with fire suppression. If the burning vehicle has steel end blocks, 30 % of the total HRR without fire suppression could be considered as the design fire. These results correspond to full scale activation delay less than 4 min after a gas temperature of 141 ^{o}C was measured beneath the ceiling (heat detection), or the activation heat release rate was not over 16 MW in full scale. Comparison of these results to full scale test data will be carried out to further verify the findings.

1 Introduction

Today more and more are discussing the use of water-based fire suppression systems in tunnels. The development that has taken place over the past decade has not been reflected in regulations and standards. By introducing changes that may lead to so-called technical changes or benefit from the installation of a new security, cost effectiveness can be improved. The reason why this opportunity has not been exploited in the current regulatory framework is mostly due to the uncertainty concerning these issues. There have been many full-scale trials, but some common conclusions about the efficiency of water-based fire suppression systems with respect to the reduced fire size or reduced impact on the design of ventilation system and tunnel structure protection have not been done. There is now a need to make an overall evaluation of this area of research.

The design of the Stockholm Bypass, which is the largest tunnel project in Sweden has been discussed extensively. After introducing water-based fire suppression systems in the tunnel, some benefit can be obtained in the design and development of other safety features. A water-based fire suppression system affects the rate of fire development and therefore the environment in the tunnel. This in turn affects the design of the ventilation system and also the temperature on the structure. The only question is how much and in what way? There are many parameters that can affect the outcome, such as water density in mm/min, droplet size, the activation time, longitudinal ventilation velocity and burning vehicle design and size. Today the design fire for the ventilation system is an around 100 MW fire, but if the water-based fire suppression system is installed it could be reduced to 50 MW, dependent on the system used and the fire scenario. This lower heat release rate in turn affects the design of the ventilation system, making it perhaps possible to work with a smaller fan capacity. This in turn affects the total investment cost. Another consequence is that the gas temperature in the ceiling near the fire will be reduced from 1350 ^{o}C to lower than 1000 ^{o}C, which requires less protection for the tunnel structure. In order to get the benefit from lower design fires for tunnels with water-based fire suppressions, the reliability of the systems has to be clearly addressed. It is a complex issue that probably cannot be simply answered in this project, but it will be included as a parameter and discussed later.

There is also an intense discussion within NFPA502 [1] concerning which design fire to choose for a road tunnel installed with water-based fire suppression system. NFPA502 committee works out a standard on fire safety in road tunnels. PIARC, i.e. World Road Association, has also discussed the issue. There are two discussion groups, i.e. those who are for the introduction of a reduced design fire, and those who do not believe that one can choose a new design fire because of the ignorance that prevails on the issue. An important reason for the discussion of existence is the lack of holistic approach to objectively discuss the issue on the basis of known facts. Most attempts which have been made today are water-based fire suppression systems (water mist systems) with relatively low water flow rate and small droplets. It is known that small droplets cools the gas temperature very efficiently compared to large droplets. The reduction in the heat release rate can vary significantly, but in these cases even if the fire size is not efficiently affected, the surrounding fire gases are cooled effectively. The large droplets coming from the low pressure system, however, survive the hot plume of a fire and can cool the fuel surface more efficiently and thus reduce fire size more efficiently. The benefits may disappear if the vehicle is to be protected, e.g. covered with sheet metal or any other material that prevent the drops to reach the fuel surfaces. However, the risk of fire spread to outside of the vehicle is greatly reduced. The manufacturers of water mist systems have access to many experimental data but the data are generally not available to others. Regardless, there are many authorities, consultants and tunnel owners who place great value in resolving the issue of the influence of water on the design fire. By compiling the knowledge available today and make a judgment based on that, there is ample opportunity to resolve the problem.

The final goal of the project is to propose a design fire depending on the type of system (low pressure, high pressure), water flow rate (5-15 mm / min), type of fire (buses, trucks) and its openness (Roof), and quantify the impact on tunnel structure. To do that, we need to conduct further experiments in model scale to find out how much the design fire can be reduced in relation to a free-burning fire. Experience from previous model scale fire suppression tests could be used as guidance [2-4].

Nowadays when a new water-based fire suppression system is planned to be installed in a tunnel, full scale tests are always in demand. However, there is no accepted standard of performing water-based fire suppression tests in tunnels. The absence of a test protocol that describes how these systems should be tested for a given tunnel makes it difficult for authorities or tunnel owners to make a good assessment of the performance of a fire suppression system. By proposing a SP method for testing fire suppression systems in tunnels, the purpose is to be able to meet this need.

The main objective of the tests is to investigate the performance of water-based fire suppression systems in tunnel fires under different conditions, and further to develop and propose different criteria to evaluate the performance of different systems. In addition, one special purpose is to obtain valuable information for the full scale fire suppression tests that were carried out in the Runehamar tunnel in 2013 [5].

2 Scaling theory

The Froude scaling technique has been applied in this project. Although it is impossible and in most cases not necessary to preserve all the terms obtained by scaling theory simultaneously, the terms that are most important and most related to the study are preserved. The thermal inertia of the involved material, turbulence intensity and radiation are not explicitly scaled, and the uncertainty due to the scaling is difficult to estimate. However, the Froude scaling has been used widely in enclosure fires. Our experience of model tunnel fire tests shows there is a good agreement between model scale and large scale test results on many focused issues [6-11].

The model tunnel was built in a scale of 1:4, which means that the size of the tunnel is scaled geometrically according to this ratio. The scaling of other variables such as the heat release rate, flow rates and the water flow rate can be seen in Table 1.

Table 1 A list of scaling correlations for the model tunnel.

Type of unit	Scaling model*	Eq. number
Heat Release Rate (HRR) (kW)	$\frac{Q_F}{Q_M} = (\frac{L_F}{L_M})^{5/2}$	Eq. (1)
Volume flow (m^3/s)	$\frac{\dot{V}_F}{\dot{V}_M} = (\frac{L_F}{L_M})^{5/2}$	Eq. (2)
Velocity (m/s)	$\frac{u_F}{u_M} = (\frac{u_F}{u_M})^{1/2}$	Eq. (3)
Time (s)	$\frac{t_F}{t_M} = (\frac{L_F}{L_M})^{1/2}$	Eq. (4)
Energy (kJ)	$\frac{E_F}{E_M} = (\frac{L_F}{L_M})^{3}$	Eq. (5)
Mass (kg)	$\frac{M_F}{M_M} = (\frac{L_F}{L_M})^{3}$	Eq. (6)
Temperature (K)	$T_F = T_M$	Eq. (7)
Water flow rate (L/min)	$\frac{\dot{q}_{w,F}}{\dot{q}_{w,M}} = (\frac{L_F}{L_M})^{5/2}$	Eq. (8)
Water density (mm/min)	$\frac{\dot{q}''_{w,F}}{\dot{q}''_{w,M}} = (\frac{L_F}{L_M})^{1/2}$	Eq. (9)
Pressure difference (Pa)	$\frac{P_F}{P_M} = \frac{L_F}{L_M}$	Eq. (10)
Water droplet (µm)	$\frac{d_F}{d_M} = (\frac{L_F}{L_M})^{1/2}$	Eq. (11)

*Assume the ratio of heat of combustion $\Delta H_{c,M} / \Delta H_{c,F} = 1$. L is the length scale. Index M is related to the model scale and index F to full scale (L_M=1 and L_F=4 in our case).

3 Experimental Setup

The scaling ratio is 1:4, that is, the geometry ratio between model scale and full scale tunnel is 1:4.

3.1 Model tunnel

The model tunnel itself was 15 m long, 2.8 m wide and 1.4 m high, see Figure 1 and Figure 2. The scaling ratio is 1:4. This suggests that the corresponding full scale dimensions were 60 m long, 11.2 m wide and 5.6 m high, respectively. In some tests, the model tunnel width was changed to 1.88 m, corresponding to 7.5 m in full scale.

The model, including the floor, ceiling and one of the side walls, was constructed using non-combustible, 15 mm thick Promatect H boards. Several windows (30 cm ×30 cm) are placed on one side of the tunnel. The model tunnel was built on a platform and the tunnel floor was 0.8 m above the floor level of the lab. An axial fan was used to produce the flows inside the tunnel. A 1.2 m long tunnel section with nets was used as static box to smooth the flows.

The end of the tunnel was set below a smoke hood through which the smoke was exhausted to the central system.

Figure 1 A photo of the model tunnel (Dimensions in mm).

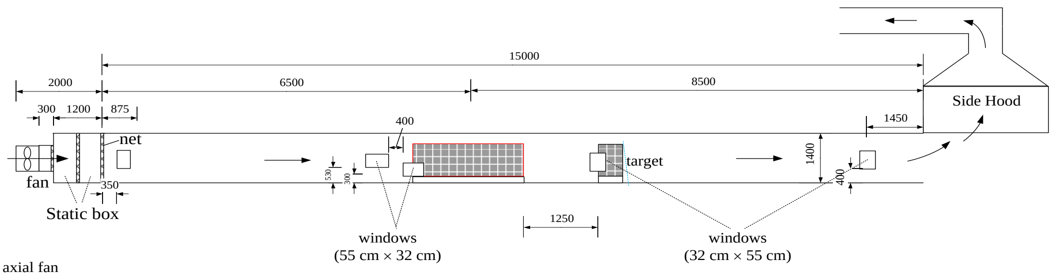


Figure 2 A schematic drawing of the model tunnel (Dimensions in mm).

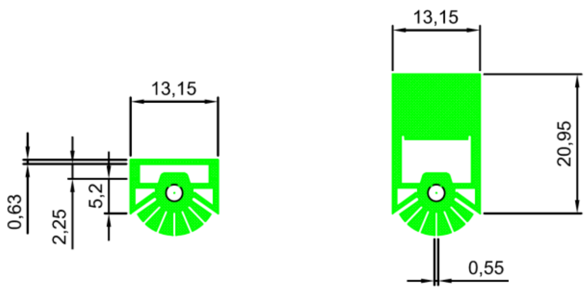
3.2 Water spray system

In most of the tests, the water spray system was designed to cover a region of 12.5 m, corresponding to 50 m in full scale. To investigate the effect of length of the fire suppression section (sprinkler length section) on its performance, in some of the tests, the system was shorten to 7.5 m, corresponding to 30 m in full scale.

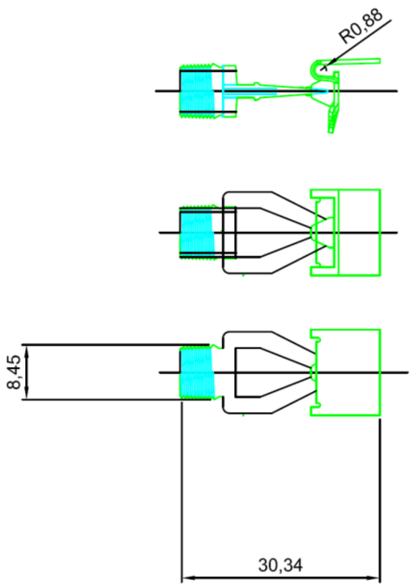
In the tests, three types of nozzles were tested in the tests, including one scaled T-Rex nozzle and two normal nozzles.

3.2.1 T-Rex nozzles

Three-dimensional geometry of the full scale T-Rex nozzle was obtained after a laser scan. The corresponding geometry of the T-Rex nozzles in 1:4 scale is shown in Figure 3. The T-Rex nozzles in model scale have a K factor of 22.5, corresponding to 360 in full scale.



(a) Front of outlet



(b) Normal to the outlet (side view)

Figure 3 Geometry of the model scale T-Rex nozzles (Dimensions in mm).

After the geometry was obtained by the laser scan, a powerful 3D printer was used to print out the steel T-Rex nozzles used in the tests, see Figure 4.

Figure 4 A photo of a 1:4 T-Rex nozzle that is made of steel.

A total of 10 couples of T-Rex nozzles, i.e. N1 to N10, were placed along the centre line of the tunnel, see Figure 5. All the T-Rex nozzles were placed 10 cm below the ceiling.

The water spray system with the T-Rex nozzles is shown in Figure 5. The pipes have a diameter of 3 cm. The interval between the nozzles are 1.25 m, corresponding to 5 m in full scale. The nozzles are distributed symmetrically relative to the centre of the fuel load.

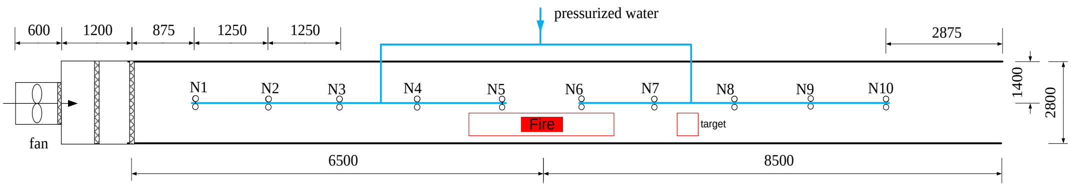


Figure 5 Tests with T-Rex nozzles (Top view).

3.2.2 Two normal full cone nozzles

The two normal nozzles used in the tests are Lechler 460.726 and 460.846 with a cone angle of 90^{o}, see Figure 6. The K factors are 4.77 and 9.47, respectively, corresponding to 76 and 152 in full scale. For simplicity, these two nozzles are called K5 and K9 respectively. To obtain 5 mm/min in the model scale tests, the operating nozzle pressures were around 1.76 bar and 0.32 bar, respectively, corresponding to 7 bar and 1.3 bar in full scale. It can be known that the K5 nozzles might be classified as low pressure water mist nozzles and K9 as conventional water spray nozzles.

Figure 6 Two Lechler Series 460 nozzles used in model scale tests.

The two normal nozzles are placed in three lines, see Figure 7. The main pipe had a diameter of 5 cm. All the normal nozzles, i.e. K5 and K9, were placed 17.5 cm below the ceiling.

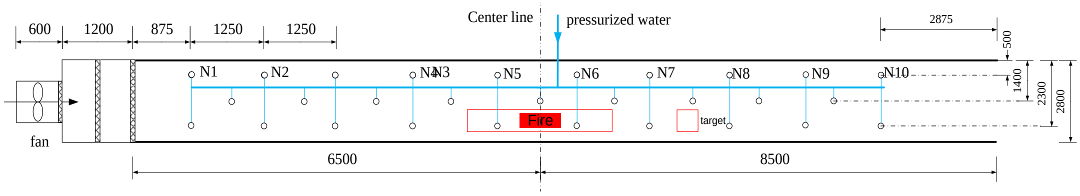


Figure 7 Tests with normal nozzles (Top view).

During the tests, the total water flow rate and the pressure in the main supply pipe and the pressure close to one nozzle were measured.

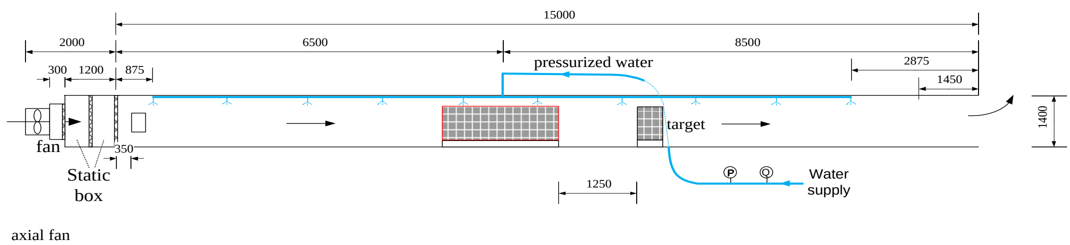


Figure 8 Water supply system for tests with normal nozzle (Side view).

3.2.3 Activation time

The activation time is a key parameter for the performance of any fire suppression system. The influence of activation time on fire suppression is a very interesting research topic, however, the activation time should not be too far away from reality.

The Swedish Transport Administration has set the goal of detecting a 0.5 to 1 MW fire under 5 to 7 m/s within 1 min in reality. This requirement is hard to fulfilled in tunnels with such high ventilation, if only heat detection systems are used. Note that heat detection is widely used in the tunnel. In building fires, the typical automatic sprinkler has activation temperatures of 68 °C and 141 °C. A measured ceiling gas temperature of 141 °C is used as the criteria for fire detection in the tests, that is, a tunnel fire is detected after a gas temperature of 141 °C is measured by one of the ceiling thermocouples (T5 to T9). The corresponding fire is expected to be large enough to be detected easily by most of the detectors, e.g. line type heat detectors, infrared flame detectors and smoke detectors. In other words, for safety reasons the activation criterion was chosen to be conservative. Further, note that generally in reality a fire suppression system is not activated immediately after the fire detection, due to that it takes some time for the tunnel operators to respond to the situation. This delay of activation is also simulated. By default, it is set to be 1 min in full scale, corresponding to 0.5 min in 1:4 model scale. In the tests, different delay time was tested. In other words, the performance of the fire suppression systems using different activation time was investigated.

3.3 Ventilation system

An axial fan was attached to the upstream end of the tunnels to produce the longitudinal flow. The fan was BRV 710 with a diameter of approx. 0.71 m. It can produce a maximum longitudinal flow of 1.88 m/s in the model tunnel, corresponding to 3.76 m/s in full scale. In most of the model scale tests, the longitudinal ventilation velocity in the tunnel was set to be 1.5 m/s, corresponding to 3 m/s in full scale.

3.4 Fire load

The HGV mock-up was simulated using piles of wood pallets, as shown in Figure 9 for wide tunnel and in Figure 10 for narrow tunnel. 1/2 standard Europe wood pallets (pine) were used as fuels, see Figure 11. The fuels were placed on a Promatect board above a steel frame.

The front and back side of the fire load were always covered by steel plates. In some of the tests, steel plates were also used to cover the top of the fire load.

To test the fire spread, one pile was placed 1.25 m away from the end of the HGV mock-up, i.e. 5 m in full scale. In each test, 50 pallets were used, together with 10 pallets for the target. The target was not covered.

The total maximum heat release rate was estimated to be 3.6 MW corresponding to 115 MW in full scale. The maximum heat release rate for the main fuel load was estimated to be 3 MW, corresponding to 96 MW in full scale (approximately 100 MW fire load).

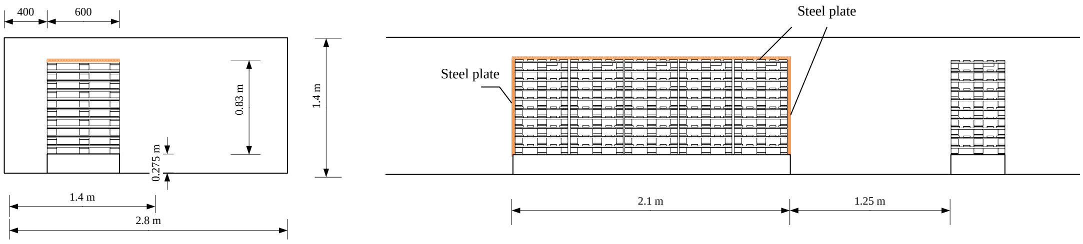


Figure 9 Fuel arrangement.

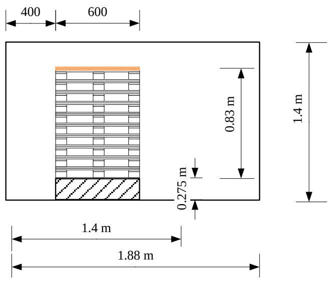


Figure 10 Fuel arrangement for narrow tunnel tests.

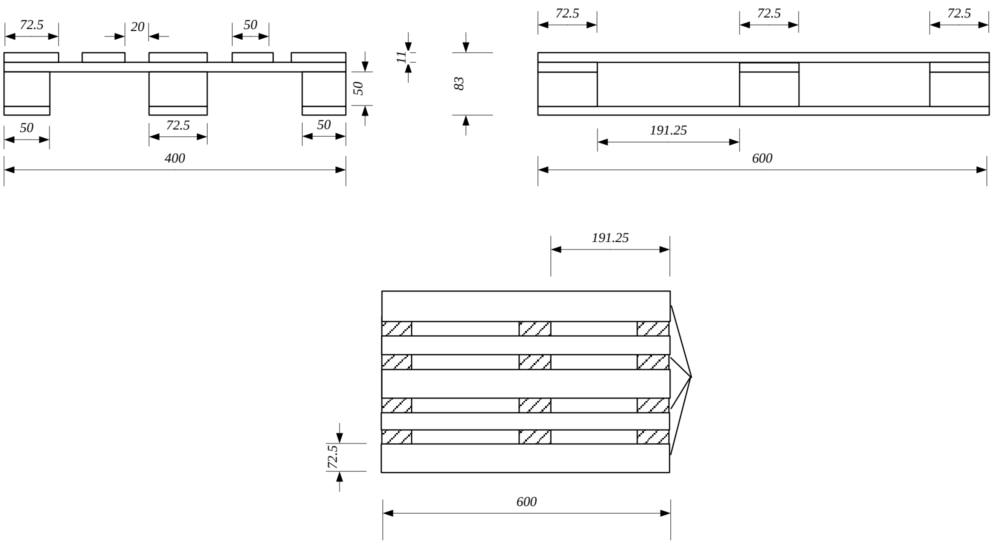


Figure 11 Detailed drawing of the wood pallet.

3.5 Ignition source

Two heptane pool with geometries of 10 cm × 10 cm were placed at the bottom of the first wood pallet upstream of the fuel load, see Figure 12. They produced a total heat release rate of around 15 kW, corresponding to 0.5 MW in full scale.

Figure 12   Placement of two ignition sources attached together.

3.6 Measurement

In total, 21 thermocouples, 2 plate thermometers, 5 bi-directional pressure tubes, and 4 gas analyses were placed at the center line of the tunnel.

All ceiling thermocouples were placed 10 cm below the ceiling, except at Pile A and Pile B. Two plate thermometers are attached to the ceiling.

At Pile B, the gas analysis probes were placed at the centreline of the tunnel, and the bi-directional tubes and thermocouples were placed horizontally 5 cm from the gas analysis.

The heat release rates could be estimated using the oxygen consumption method[12, 13]:

$$Q = 14330 \sum \dot{m}_i \left(\frac{X_{0,O_2}\left(1 - X_{CO_2,i}\right) - X_{O_2,i}\left(1 - X_{0,CO_2}\right)}{1 - X_{O_2,i} - X_{CO_2,i}} \right) \quad (12)$$

where Q is the heat release rate (kW), $\dot{m}_i$ is the mass flow rate of the ith layer, X_{0,O_2} is the volume fraction of oxygen in the incoming air (ambient) or 0.2095, X_{0,CO_2} is the volume fraction of carbon dioxide in the incoming air (ambient) or $X_{0,CO_2} \approx 0.00033$, carbon dioxide, X_{O_2} and X_{CO_2} are the volume fractions of oxygen and carbon dioxide measured by a gas analyser (dry) at the measuring station downstream of the fire. Since the gas temperatures at the measurement station were not very high in the tests with fire suppression, the humidity was considered to have quite limited influence on the estimation of the heat release rates and thus ignored.

There are also other calorimetry methods available to determine the heat release rate, such as CO/CO_2 method developed by Tewarson [14] and utilized in tunnel fires by Grant and Drysdale [13, 15]:

$$Q = 12500 \frac{M_{CO_2}}{M_a} \Delta X_{CO_2} \dot{m}_a + 7500 \frac{M_{CO}}{M_a} \Delta X_{CO} \dot{m}_a \qquad (13)$$

where M_{CO_2} =44g, M_{CO} =28g and M_a =28.95g. X_{CO_2} and X_{CO} are the increases above ambient, i.e. the ‘background’ levels should be subtracted from these measured values.

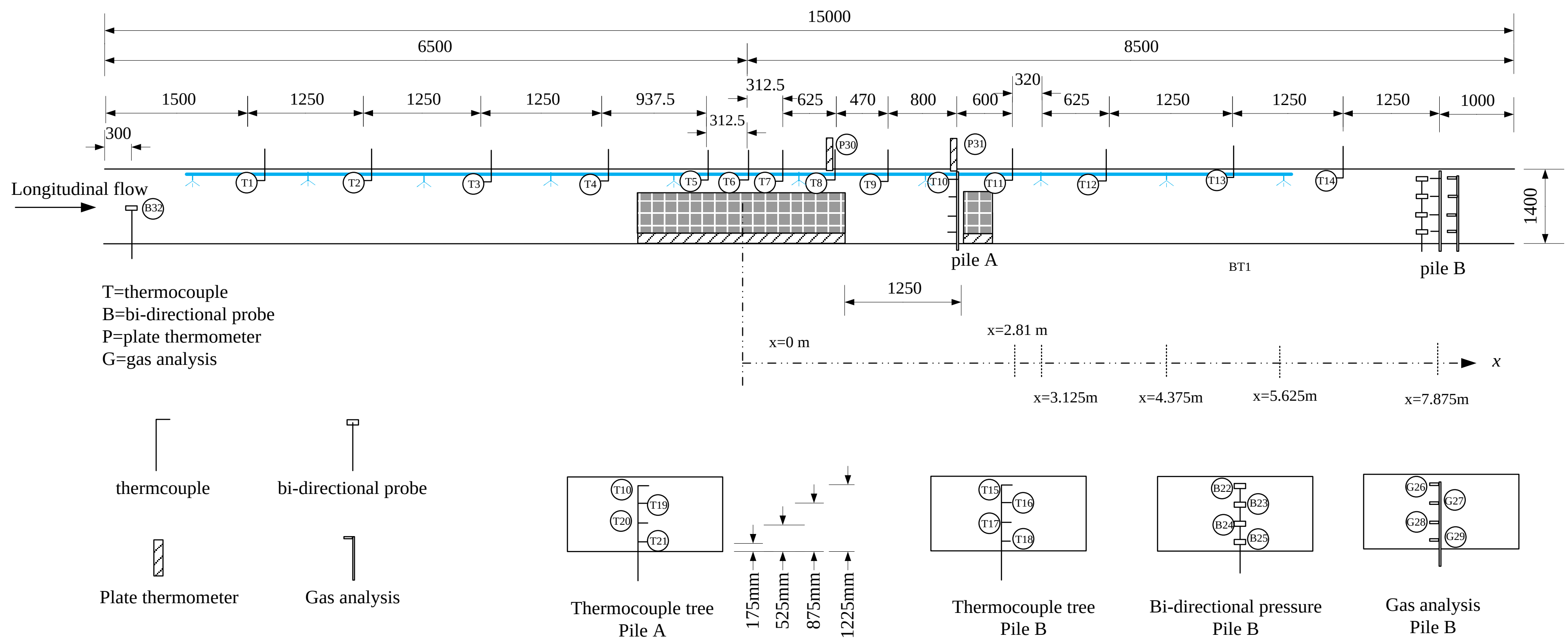


Figure 13 *The layout and identification of instruments in the series of tests (dimensions in mm).*

4 Test procedure

The parameters tested include fuel load covers, activation time, water flow rate, nozzle type, ventilation velocity, length of suppression system and width of tunnel.

A summary of tests carried out in this project is listed in Table 2. In all the tests except Test 9, the front and end faces of the fuel load were covered by 0.75 mm steel plates.

In test 9, the front cover was placed for ignition during the early 2 min and removed after 2 min. In some tests, the ceiling was also covered. By default the top cover was a 0.75 mm steel plate, but in Test 7 a 3 mm thick plywood cover was used to investigate the effect of combustible covers.

In tests 14 to 18, the water spray system was shortened to 7.5 m, corresponding to 30 m in full scale. In tests 16 to 18, the 2.8 m wide tunnel was changed to 1.88 m by moving one of the side walls, see Figure 10.

In tests 16 to 18, the model tunnel width was changed to 1.88 m, corresponding to 7.5 m in full scale. All the instruments were moved to the centre line of the narrow tunnel.

In Test 8, the gas analysis failed and thus the test was repeated in Test 8b.

Table 2 Summary of tunnel fire tests with fire suppression.

Test no.	Ventilation velocity	Activation time 141°C + delay time	Water flow rate	Ceiling cover	Nozzle	Water spray length	Others
	m/s	min	mm/min			m	
1	1.5	0.5	5	No	K5	12.5	
2	1.5	0.5	5	Yes	K5	12.5	
3	1.5	1	5	No	K5	12.5	
4	1.5	2	5	No	K5	12.5	
5	1.5	4	5	No	K5	12.5	
6	0.5	1	5	No	K5	12.5	
7	1.5	0.5	5	Yes	K5	12.5	Plywood cover
8	1.5	1	2.5	No	K5	12.5	
8b	1.5	1	2.5	No	K5	12.5	repeat Test 8
9	1.5	0.5	5	No	K5	12.5	No end blocks
10	1.5	0.5	7.5	Yes	K5	12.5	
11	1.5	0.5	5	Yes	K9	12.5	
12	1.5	0.5	5	Yes	T-Rex	12.5	
13	1.5	2	5	Yes	T-Rex	12.5	
14	1.5	2	5	Yes	T-Rex	7.5	
15*	1.5	-	-	Yes	-	-	Free-burn
16	1.5	2	5	Yes	T-Rex	7.5	Narrow tunnel
17	1.5	0.5	5	Yes	T-Rex	7.5	Narrow tunnel
18	1.5	2	5	Yes	T-Rex	7.5	Narrow tunnel

*Free burn test.

In all the tests, the measured humidity of the wood pallets was mainly in a range of 9 % to 10 %, except in Test 18 where only the first 2 piles near the ignition source had a humidity in a range of 9 % to 10 %, and the other piles, including the target pile, had a humidity of around 18 %.

In each tests, the measurements were started 2 min before ignition. Two cameras were used to record the tests with one placed inside the tunnel close to the fan and another outside the window beside fuel.

5 Test results

Short tests notes are presented in Appendix A. Note that the ignition was at 2 min in the notes. For each test, some photos of the fires before and after activation of the fire suppression are also presented in Appendix B.

Further, all the detailed test data can be found in Appendix C. In the tests, the time 0 corresponds to ignition. Heat fluxes data are not presented since in most of the tests the water spray wetted the plate thermometer which caused failure of measurement.

5.1 Heat release rate

The maximum heat release rates, Q_{max}, are presented in Table 3, together with the activation time, t_{act}, and the corresponding activation heat release rate, Q_{act}.

In the tests with fire suppression, the activation of water spray systems affected the measurement of oxygen especially in the decay period. Therefore, the heat release rate is estimated using the CO2/CO technique. The difference between the oxygen consumption method and CO2/CO technique in estimation of heat release rates before fire suppression has been compared and little difference has been found. Therefore, the method can be expected to be reliable.

In the free-burn test 15, the instruments at Pile B failed after around 34 min and the latter HRR curve was reconstructed using the gas temperature according to Li et al's maximum gas temperature models. This methodology has been used in the Metro project and proven to be credible. The reconstructed curve was in the decay period and thus has no influence on the maximum heat release rate and the curve at early stage.

5.2 Maximum gas temperature

All the measured maximum ceiling gas temperatures are presented in Table 3. Note that all ceiling thermocouples were placed 10 cm below the ceiling, except at Pile A and Pile B where the ceiling thermocouples were placed 17.5 cm below the ceiling. In Table 3, the locations are defined relative to the centre of the fire load and a minus sign indicates upstream of the fire and a positive one corresponds to downstream.

Maximum gas temperatures measured by thermocouple trees at Pile A and Pile B are presented in Table 4.

5.3 Maximum gas concentration

The measured maximum gas concentrations measured at Pile B are presented in Table 5. Note that they are volume fractions.

5.4 Fire spread

In the free-burn test 15, the target was ignited at 13.2 min and burn out after the test. In all the other tests with fire suppression systems, the target was well protected and not ignited (even not charred).

Table 3 Test data related to heat release rate and maximum ceiling gas temperature.

Test no.	u_o	$\dot{q}_w$	Q_{max}	t_{act}	Q_{act}	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	T11	T12	T13	T14	T15
	m/s	mm/min	kW	min	kW	°C	°C	°C	°C	°C	°C	°C	°C	°C	°C	°C	°C	°C	°C	°C
						x=-5m*	-3.75	-2.5	-1.25	-0.3125	0	0.31	0.94	1.41	2.21	2.81	3.75	5.00	6.25	7.50
1	0.5	5	283	4.25	259	20.6	20.5	21.0	25.8	382.1	247.3	23.1	176.8	145.5	90.4	98.9	84.0	69.3	78.3	55.0
2	0.5	5	1150	4.68	261	19.7	19.3	20.0	37.0	946.9	816.2	725.3	902.6	682.1	347.3	354.7	293.0	238.1	206.7	157.4
3	1	5	434	5.37	410	20.1	20.2	20.8	25.2	516.3	303.3	273.2	214.3	183.8	105.9	110.4	92.0	98.5	97.7	66.8
4	2	5	798	6.47	482	19.7	20.1	21.5	39.2	718.8	557.1	496.6	365.5	320.3	220.7	243.6	203.0	167.9	164.4	108.6
5	4	5	869	8.20	576	20.6	21.4	23.4	114.6	926.0	865.9	785.3	770.3	664.3	422.7	403.0	334.5	260.4	255.9	158.4
6	1	5	299	4.72	253	149.6	173.5	252.8	454.6	246.9	179.0	230.4	278.6	206.0	98.4	145.3	121.5	105.8	100.6	56.0
7	0.5	5	1074	4.38	231	20.2	19.9	20.3	34.8	793.0	903.8	767.6	863.0	545.1	283.8	307.1	216.5	146.5	126.4	90.3
8	1	2.5	**	4.67	**	17.8	18.0	19.4	54.0	815.7	880.9	902.5	761.7	695.2	562.9	450.4	355.1	285.9	271.8	192.1
8b	1	2.5	1650	5.28	333	17.5	17.6	18.8	42.0	826.6	812.3	922.1	836.6	912.8	566.8	441.0	359.4	277.2	267.6	224.0
9	0.5	5	1410	3.02	130	17.9	17.9	18.9	52.2	669.1	830.0	914.6	812.7	636.5	384.5	344.6	247.8	199.7	183.7	156.6
10	0.5	7.5	831	3.92	221	17.1	17.1	17.7	27.3	870.5	598.4	480.8	466.7	256.8	104.1	135.4	100.0	65.0	70.2	52.9
11	0.5	5	857	4.40	235	18.5	18.3	18.8	36.2	837.4	928.8	959.1	699.2	391.4	284.9	273.0	226.3	195.9	174.2	155.5
12	0.5	5	177	3.73	104	18.9	18.8	19.0	21.9	98.7	116.4	132.9	189.0	170.2	100.8	97.0	76.3	64.3	57.8	36.3
13	2	5	413	5.87	407	18.8	19.0	19.7	31.9	424.2	448.0	409.4	356.4	262.1	116.4	159.1	170.6	166.4	145.4	121.2
14	2	5	341	5.63	310	18.6	18.6	19.3	28.2	378.1	381.5	341.5	307.6	240.9	101.5	126.2	132.9	157.7	131.1	99.3
15	-	-	3560	-	-	30.1	31.5	95.3	673.3	958.4	979.1	951.3	973.2	947.7	870.1	865.0	825.9	730.6	622.3	564.8
16	2	5	1075	3.70	176	19.2	19.4	20.1	26.7	427.1	531.9	680.7	774.4	795.2	165.1	498.6	506.6	363.0	320.1	321.9
17	0.5	5	102	2.42	102	18.4	18.3	18.4	20.6	219.3	177.2	146.9	63.3	51.7	21.5	77.5	65.6	46.8	41.4	41.4
18	2	5	785	3.83	199	18.9	18.9	19.2	28.0	704.8	505.9	689.9	799.7	759.8	94.1	446.9	384.0	297.6	277.5	220.4

* -5 indicates a location 5 m upstream of the fire relative to the centre of the fuel load.
** No measurement of HRR before 36 min due to technical failure.
"-" free-burn test.

Table 4 Maximum gas temperatures measured at Pile A and Pile B.

Test no.	Pile A (x=2.21 m)				Pile B (x=7.5 m)			
	T10	T19	T20	T21	T15	T16	T17	T18
	122.5cm	87.5cm	52.5cm	17.5cm	122.5cm	87.5cm	52.5cm	17.5cm
	^oC	^oC	^oC	^oC	^oC	^oC	^oC	^oC
1	90.4	54.6	23.9	24.4	55.0	33.9	27.9	23.1
2	347.3	61.3	26.3	49.9	157.4	84.8	36.7	27.6
3	105.9	65.5	22.5	24.2	66.8	33.7	27.2	23.6
4	220.7	83.9	22.8	28.2	108.6	41.9	30.8	28.2
5	422.7	116.2	28.1	38.2	158.4	47.3	38.0	35.4
6	98.4	28.7	30.2	29.1	56.0	28.8	28.1	28.6
7	283.8	55.2	22.5	36.9	90.3	55.8	32.6	28.3
8	562.9	55.9	27.3	32.0	192.1	68.8	37.9	25.0
8b	566.8	57.8	24.0	28.3	224.0	108.5	50.0	20.3
9	384.5	118.2	22.5	33.6	156.6	72.2	32.7	21.8
10	104.1	65.4	27.8	24.4	52.9	32.0	27.7	27.7
11	284.9	61.8	20.9	29.2	155.5	65.9	29.2	21.3
12	100.8	48.9	19.4	13.9	36.3	28.5	23.0	20.2
13	116.4	61.2	20.8	19.8	121.2	36.3	24.8	21.5
14	101.5	52.0	22.2	20.8	99.3	33.3	23.5	21.3
15	870.1	648.1	396.1	586.7	564.8	488.3	298.4	108.6
16	165.1	439.2	28.2	46.9	321.9	229.8	98.6	42.9
17	21.5	37.6	18.3	18.6	41.4	26.7	20.1	19.2
18	94.1	446.5	25.7	37.3	220.4	130.6	68.0	35.9

Table 5 Maximum gas concentrations measured at Pile A and Pile B.

Test no.	CO2 (%)				CO (%)			
Test no.	G26	G27	G28	G29	G26	G27	G28	G29
	122.5cm	87.5cm	52.5cm	17.5cm	122.5cm	87.5cm	52.5cm	17.5cm
1	0.32	0.26	0.18	0.17	0.051	0.060	0.033	0.014
2	1.53	1.01	0.58	0.29	0.319	0.188	0.097	0.034
3	0.59	0.34	0.23	0.19	0.077	0.057	0.031	0.018
4	0.36	1.68	0.28	0.25	0.044	0.160	0.043	0.024
5	0.40	1.86	0.39	0.35	0.062	0.154	0.056	0.027
6	0.70	0.81	0.37	0.84	0.101	0.153	0.094	0.111
7	0.95	1.40	0.48	0.27	0.111	0.144	0.058	0.029
8	0.44	2.30	0.24	0.08	0.050	0.385	0.026	0.004
8b	0.87	3.36	0.36	0.10	0.072	0.373	0.027	0.006
9	1.24	2.43	0.44	0.16	0.161	0.264	0.053	0.018
10	0.51	0.61	0.54	0.55	0.064	0.075	0.071	0.066
11	2.87	0.59	0.20	0.09	0.211	0.057	0.015	0.005
12	0.36	0.21	0.10	0.07	0.057	0.044	0.010	0.005
13	1.88	0.18	0.10	0.07	0.176	0.036	0.006	0.006
14	1.33	0.17	0.11	0.08	0.096	0.039	0.009	0.005
15	16.5	5.97	2.01	0.43	1.041	0.104	0.100	0.024
16	5.25	2.19	0.81	0.25	0.477	0.255	0.094	0.050
17	0.36	0.15	0.09	0.08	0.046	0.028	0.006	0.009
18	3.58	1.13	0.55	0.21	0.552	0.201	0.071	0.035

6 Analysis of test results

In the following analysis, we focus on the influence of different parameters on the performance of the fire suppression systems. These parameters include the activation time delay, water flow rate, nozzle type, ceiling coverage, ceiling coverage material, end blocks, ventilation velocity, sprinkler section length and tunnel cross section. At first, the results from the free-burn test are presented. By default, in the following analysis, the ventilation velocity is 1.5 m/s, the water flow rate 5 mm/min, the tunnel width 2.8 m, and the sprinkler section length 12.5 m.

6.1 Free-burn test

Figure 14 shows the heat release rate in the free-burn test 15. The maximum heat release rate is 3.56 MW, corresponding to 114 MW in full scale. Note that the designed maximum heat release rate for the main fuel load and the target is 3.6 MW in model scale and 115.2 MW in full scale. These values match very well.

It is shown in Figure 14 that the fire grew up slowly at the early stage and after 10 min the heat release rate rose rapidly to 2.35 MW within 3 min. Then the target was ignited. At this moment, the majority of the main fuel load was involved in burning with the exception of the part close to the fuel base. After this, the fire continued to grow up at a slightly slower rate until 21.9 min when it reached the maximum heat release rate of 3.56 MW. At this moment, the whole fuel load and the target were burning and the ceiling flame extended to a location on the downstream side corresponding to about 5.5 m from the fuel centre.

Note that in the fire suppression tests, the heat release rates approximately follow the same curve as shown in Figure 14 before activation. Given that the longitudinal velocity was mostly 1.5 m/s, the time when the maximum ceiling gas temperature reached 141 ^{o}C was approximately 3.5 to 4 min, corresponding to a heat release rate of approximately 190 kW (6 MW in full scale). The systems were activated at various delayed times after this.

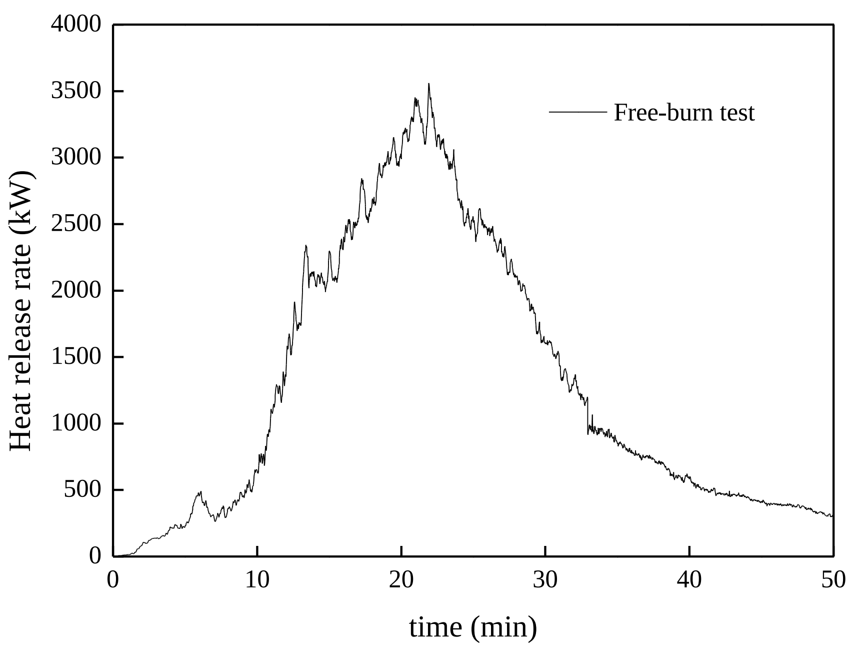


Figure 14 Heat release rate in the free-burn test 15.

6.2 Effect of activation time

In the following, the effect of activation time on the performance of the fire suppression systems is analysed for tests without ceiling coverage and with ceiling coverage respectively.

6.2.1 Tests without ceiling coverage – K5 nozzles

Figure 15 shows the influence of the activation time delay on the performance of the fire suppression system with the K5 nozzles in the tests without ceiling coverage. Comparing tests 1, 3, 4 and 5 shows that the fires in tests 1, 3 and 4 with an activation delay of 0.5 min, 1 min and 2 min were suppressed immediately after activation, and the fire in test 5 with an activation delay of 4 min was also suppressed but took much longer time to extinguish. The main reason could be that the fire suppression system is much more efficient in suppressing the fire by pre-wetting the un-burnt fuel surfaces to prevent further flame spread, rather than by extinguishing the existing burning surfaces. Further, the solid fuel fires were burning in three dimension and thus took some time to have effect on the deepest fuel surfaces and the heat release rate after activation.

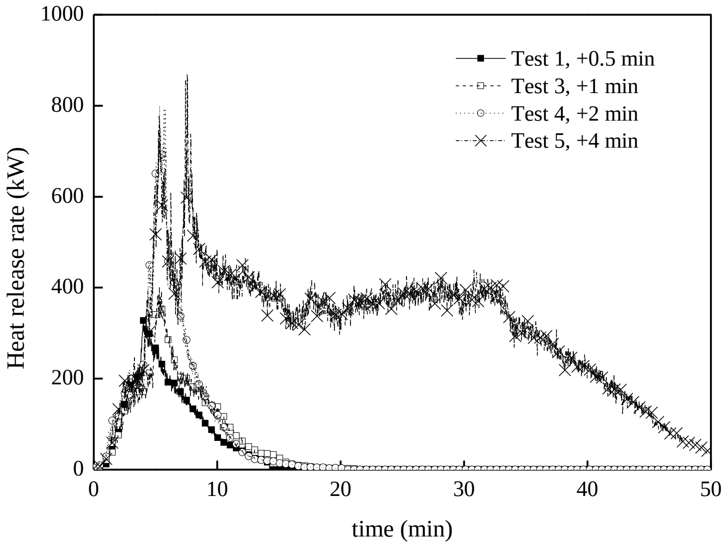


Figure 15 Effect of activation time on heat release rate in K5 tests without ceiling coverage.

6.2.2 Tests with ceiling coverage – T-Rex nozzles

Figure 16 shows the influence of the activation time delay on the performance of the fire suppression system with the T-Rex nozzles in the tests with ceiling coverage and wide tunnel. The maximum heat release rate is 177 kW in test 12 with an activation delay of 0.5 min and 413 kW in test 13 with an activation delay of 2 min. Clearly, the late activation results in a much greater maximum heat release rate, however, the fires were suppressed efficiently in both tests after activation of the fire suppression system.

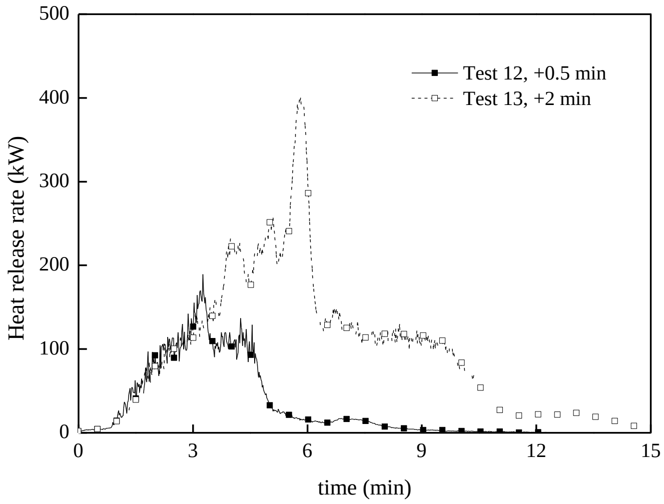


Figure 16 Effect of activation time on heat release rate in T-Rex tests without coverage (wide tunnel).

Figure 17 shows the effect of the activation time delay on the performance of the fire suppression system with the T-Rex nozzles in the narrow tunnel tests with ceiling coverage. Note that test 18 is a repeat of test 16 with the only difference that the wood pallets had a higher moisture content with the exception of the first 2 piles. Clearly, it shows that the fire in test 17 with an activation delay of 0.5 min was suppressed efficiently. However, the fires in 16 and 18 with an activation delay of 2 min were not efficiently suppressed, and the heat release rates increased continually to approx. 1 MW in test 16 and 0.8 MW in test 18.

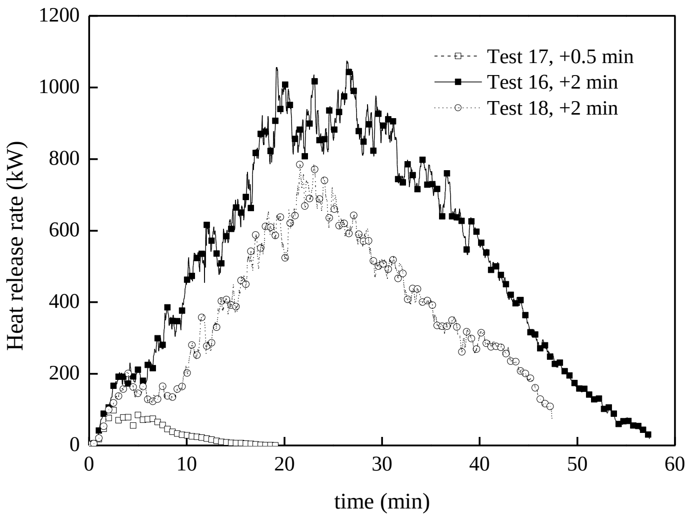


Figure 17 Effect of activation time on heat release rate in T-Rex tests with ceiling coverage (narrow tunnel).

It can be concluded that the activation time plays an important role in fire suppression. For a late activation, the fire could approximate a fully developed fire and result in catastrophic consequences. In these cases, the fires are much more difficult to suppress and further the benefit from a fire suppression system becomes small.

In order to reduce the heat release rate and suppress the fire rapidly, the fire suppression system should be activated as early as possible in case of a fire accident.

6.3 Effect of water flow rate

In the following, the effect of water flow rate on the performance of the fire suppression systems is analysed for tests without ceiling coverage and with ceiling coverage respectively.

6.3.1 Tests without ceiling coverage – K5 nozzles

Figure 18 shows the effect of water flow rate on heat release rate in K5 tests without ceiling coverage. In both tests shown in Figure 18, the activation had a delay of 1 min. Clearly it shows that in test 8b with a water flow rate of 2.5 mm/min the fire suppression system did not suppress the fire efficiently after activation, and the fire continued to grow up until around 42 min when it reaches the maximum heat release of approx. 1.5 MW, 46 % of the maximum heat release in a free-burn test. In test 3 with 5 mm/min, the fire was suppressed immediately after activation and the heat release rate decreases rapidly.

The results shown here indicate that the water flow rate of 2.5 mm/min (5 mm/min in full scale) is not high enough to efficiently suppress such a fire without ceiling coverage. Instead, the water flow rate of 5 mm/min (10 mm/min in full scale) is able to suppress such a fire efficiently. This could also indicate that in such a scenario, increasing the water flow rate to a greater value, e.g. 10 mm/min (20 mm/min in full scale), does no significant improvement to the performance of the fire suppression system since 5 mm/min (10 mm/min in full scale) has already been able to suppress the fire efficiently. Note that these conclusions are drawn from the tests without ceiling coverage.

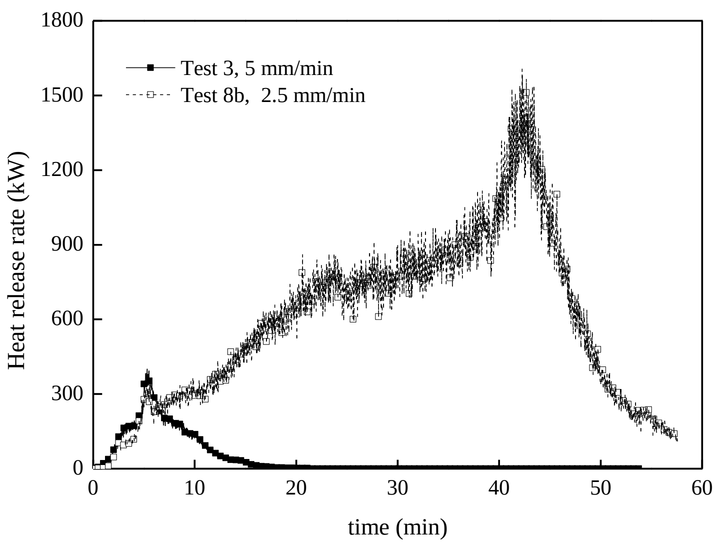


Figure 18 Effect of water flow rate on heat release rate in K5 tests without ceiling coverage.

6.3.2 Tests with ceiling coverage – K5 nozzles

Figure 19 shows the effect of water flow rate on heat release rate in the K5 nozzle tests with ceiling coverage and an activation delay is 0.5 min. The maximum heat release rate in test 10 with 7.5 mm/min decreases by 28 % relative to test 2. Note that the water flow rate is 1.5 times greater in test 10 compared to tests 2 and 7. Compared these values to the maximum HRR in the free-burn test, the maximum heat release rates in the suppression tests with 5 mm/min was 32 % of that in a free-burn test, and the maximum heat release rates in tests with 7.5 mm/min was 23% of that in a free-burn test. This indicates that an increase of 50 % in the water flow rate from 5 mm/min to 7.5 mm/min only results in a decrease in the maximum heat release rate of approximately 9 % of that in a free-burn test. In other words, the influence of the water flow rate on the fire development in the tests with ceiling coverage is insignificant for the tested water flow rate ranging from 5 mm/min to 7.5 mm/min, corresponding to 10 mm/min to 15 mm/min in full scale.

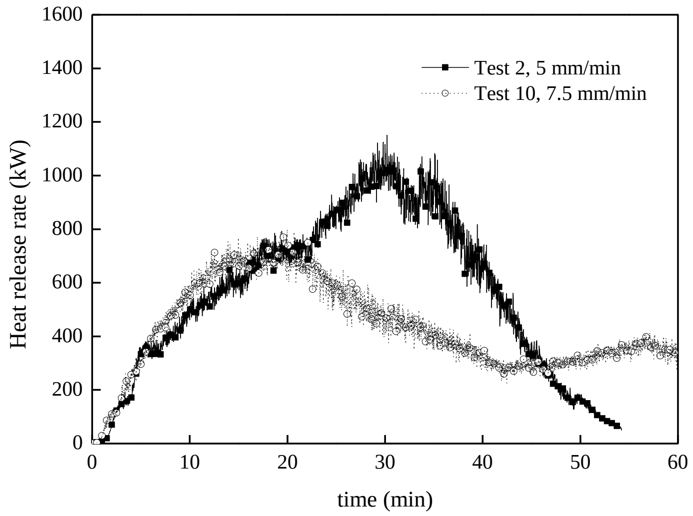


Figure 19 Effect of water flow rate on heat release rate in K5 tests with coverage.

6.4 Effect of nozzle types

Figure 20 shows the influence of nozzle types on the performance of the fire suppression systems in the tests with ceiling coverage and an activation delay of 0.5 min. Clearly, the T-Rex system efficiently suppressed (extinguished) the fire in these tests with ceiling coverage, and its performance was much better than K5 and K9 systems. On the other hand both K5 and K9 systems controlled the fires. The maximum heat release rate for the K5 system was 32 % of that in a free-burn test, and 24 % of that in a free-burn test for the K9 system. Although the difference between K5 and K9 is insignificant, it can still be seen that the K9 system discharging larger droplets performed slightly better than the K5 system. Note that the T-Rex nozzles which performed better than the other two systems discharged even larger droplets. Although the droplets were discharged in a different way for the T-Rex nozzles, it could still be concluded that the nozzle type with large droplets slightly performs better in suppression of vehicular fires with ceiling coverage.

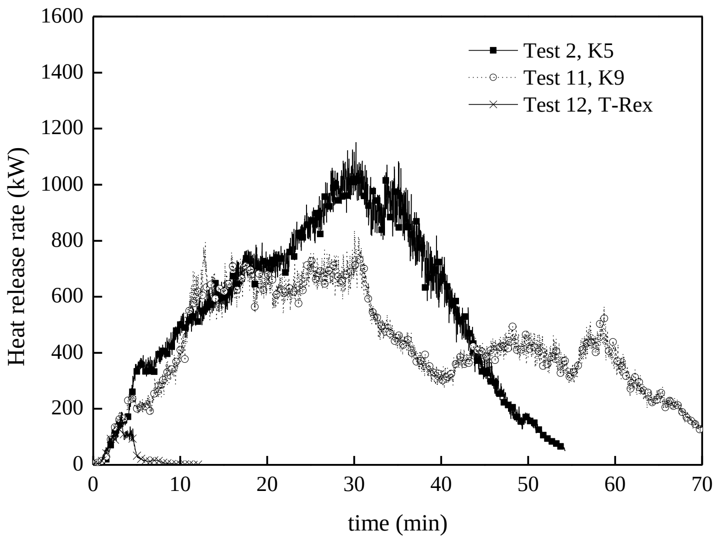


Figure 20 Effect of nozzle types on heat release rate in the tests with ceiling coverage and activation delay of 0.5 min.

Further, it can be seen from Table 3 that even for a delay of 2 min, the fire with ceiling coverage was successfully suppressed by the T-Rex system immediately after activation. The test data show that the T-Rex system can effectively suppress the fires, except in the tests with the narrow tunnel and an activation delay of 2 min. It can be concluded that in the tested scenarios, the T-Rex system with larger droplets performs better than the other two systems with normal nozzles.

6.5 Effect of ceiling coverage

Figure 21 shows the effect of the ceiling cover on top of the fuel load on the performance of the fire suppression system with K5 nozzles. Clearly, it shows that in the test without ceiling coverage, the fires were effectively suppressed. In contrast, in the test with steel ceiling coverage, the fire was not efficiently suppressed and the fire continued to grow up to approximately 1.15 MW, 32 % of the maximum heat release rate in the free-burn test. The main reason is that the surface cooling is the main mechanism of an effective suppression of this type of fire, however, in the tests with ceiling coverage on the top of the fuels, most of the water spray cannot discharge water directly to the fuel surfaces and take heat away from the fuels, instead the water sprays only impinged on the ceiling cover and cooled the plate. It can be concluded that the fire with a ceiling coverage is much more difficult to suppress and corresponds to a worse scenario and thus the steel ceiling cover was used in most of the tests.

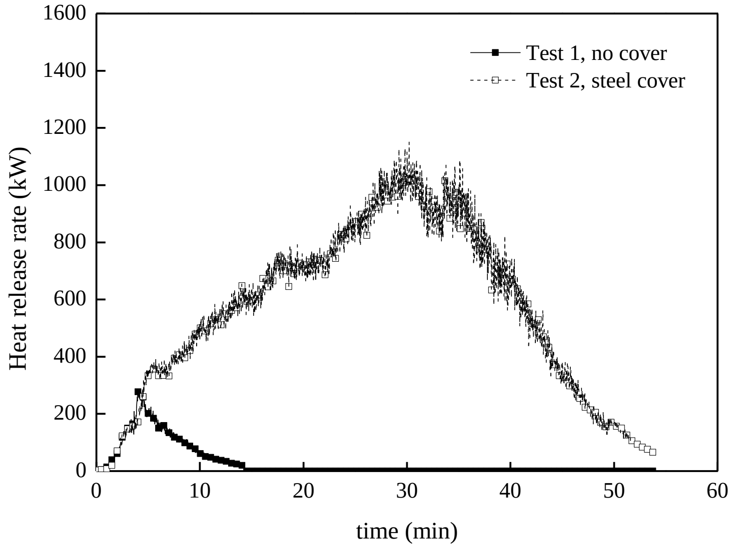


Figure 21 Effect of ceiling coverage on heat release rate in the tests with K5 nozzles.

6.6 Effect of ceiling coverage materials

Figure 22 shows the test results with different ceiling coverage materials and a delay of 0.5 min. In test 2 the top cover of the main fuel load was a steel plate and a plywood plate in test 7. Comparing test 2 and test 7 shows that the heat release rate curve obtained from the tests with the combustible plywood ceiling cover was approximately equivalent to that with the non-combustible steel ceiling. The main reason is that the water spray discharged to the top surface of the ceiling cover significantly cooled down its surface temperature. Therefore the temperature on the bottom side of the cover was also significantly lowered down. The overall effect is that only a small piece of the combustible plywood ceiling (less than 10 %) was burnt and most of the plywood cover was only charred on the bottom side in test 7. Note that the process activation was simulated well in the tests by use of the commonly-used heat detection algorithm (or even conservative in some tests), therefore the scenario simulated should be quite realistic. Therefore, in the tested scenarios, the effect of ceiling coverage materials is not significant. In other words, a thick combustible ceiling cover could be equivalent to an uncombustible ceiling cover.

Assuming that the ceiling plate is very thin and highly combustible, e.g. thin tarpaulin, the ceiling cover above the initial fire source could burn out before the activation of a fire suppression system. Therefore the results could be completely different, and the scenario could be more similar to the scenario without ceiling coverage.

In any case, this indicates that the influence of ceiling coverage materials is insignificant in such a tunnel fire with a suppression system with the exception that the ceiling cover is very thin and highly combustible such as thin tarpaulin. This could be applied to general cases.

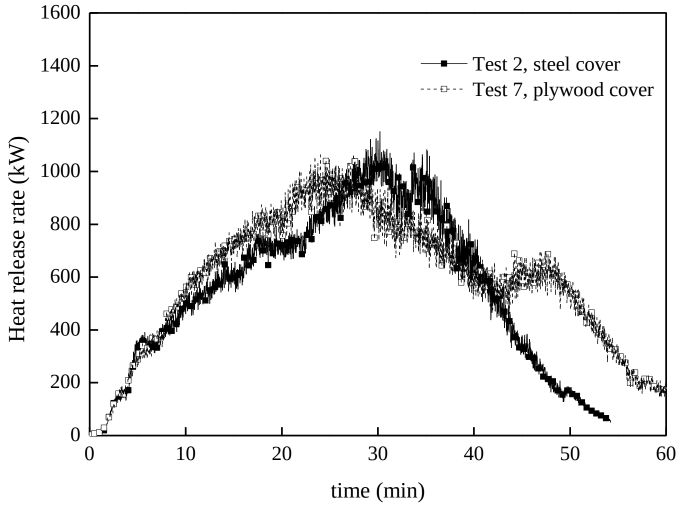


Figure 22 Effect of ceiling coverage materials on heat release rate in the tests.

6.7 Effect of end blocks

Figure 23 shows the effect of end blocks on the performance of the fire suppression system with an activation time delay of 0.5 min. Note that both tests were carried out without ceiling coverage. Cleary, there exists a huge difference between the tests. The fire in test 1 with end blocks was suppressed immediately after activation, however, the fire in test 9 without end blocks had a maximum heat release rate of 1.4 MW. This suggests that high ventilation significantly increases the fire growth rate (see Figure 23) and thus increase the difficulty in fire suppression for fuels directly exposed to wind. For fuels with end blocks, the fire develops much more slowly and could be easily suppressed. According to this, a suggestion can be made to the vehicle industry that the heavy good vehicles should all have steel end blocks.

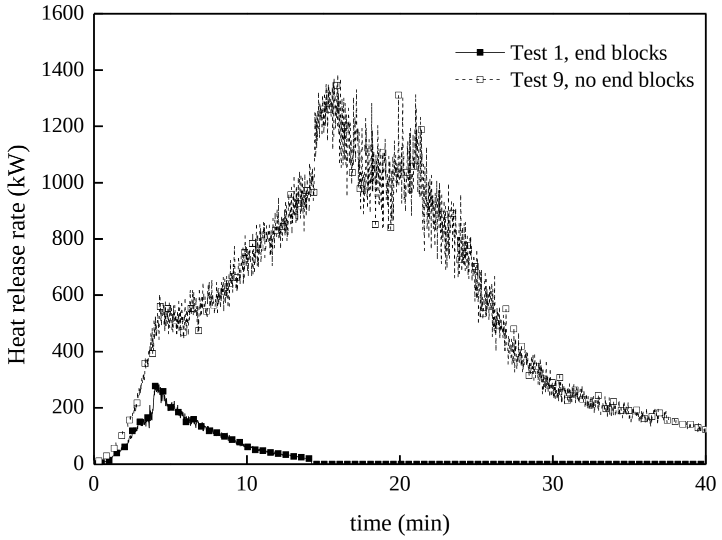


Figure 23 Effect of end blocks on heat release rate in the tests without ceiling coverage.

6.8 Effect of ventilation velocity

Figure 24 shows the effect of ventilation velocities on the performance of the fire suppression with the K5 nozzles and an activation delay of 1 min. The tests correspond to Test 3 and test 6, both without ceiling coverage. Clearly, the fire was suppressed in both tests. Under low ventilation, heat based fire detection systems can be triggered much earlier and fire suppression was activated earlier. Thus the heat release rate was smaller at the activation time. Also note that the fire grows up more slowly in test 6 with a ventilation velocity of 0.5 m/s.

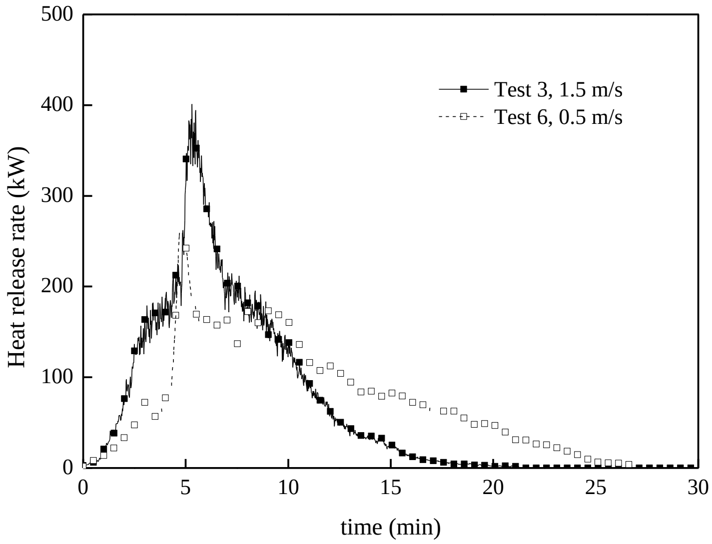


Figure 24 Effect of ventilation velocity on heat release rate in the K5 tests without ceiling coverage and activation delay of 1 min.

6.9 Effect of sprinkler section length

In some tests, the water spray system was shortened to 7.5 m, corresponding to 30 m in full scale. Figure 25 shows the influence of the sprinkler section lengths on the performance of the fire suppression systems with T-Rex nozzles (12.5 m long or 7.5 m long sprinkler section). Clearly, the heat release rate curves are approximately the same, and both fires were suppressed in the tests. This suggests that the longer sprinkler section does not improve the performance of the system, and the key sprinkler section corresponds to the section covering the fire source. In other words, the cooling effect of the sprinklers far away from the fire source is rather limited, at least for large droplet nozzles such as T-Rex.

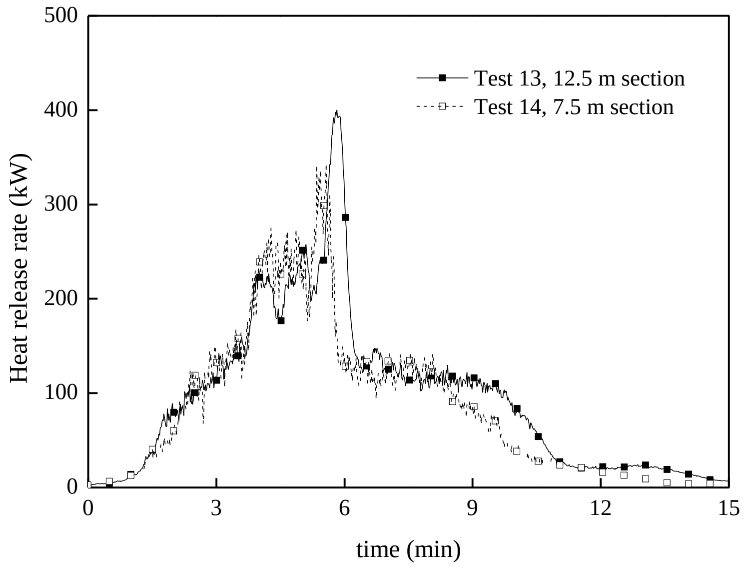


Figure 25 Effect of sprinkler section length on heat release rate in the tests.

6.10 Effect of tunnel cross section

Figure 26 shows the heat release rate curves in the T-Rex tests with a tunnel width of 2.8 m (wide tunnel) and 1.88 m (narrow tunnel) and an activation delay of 2 min. Note that test 18 is a repeat test of test 16 except that some piles of pallets had higher humidity in test 18. In Test 14 with a normal cross-section, the fire was extinguished immediately after activation. However, in tests 16 and 18 with the 1.88 m tunnel width, the fire was not efficiently suppressed. The main reason could be that in the vicinity of the fire source, the fuels together with end blocks blocked the tunnel cross section and thus increased the local gas velocity, which stimulates the fire growth and make the fire more difficult to suppress. Note that in the narrow tunnel, the blockage ratio is greater than that in the wide tunnel.

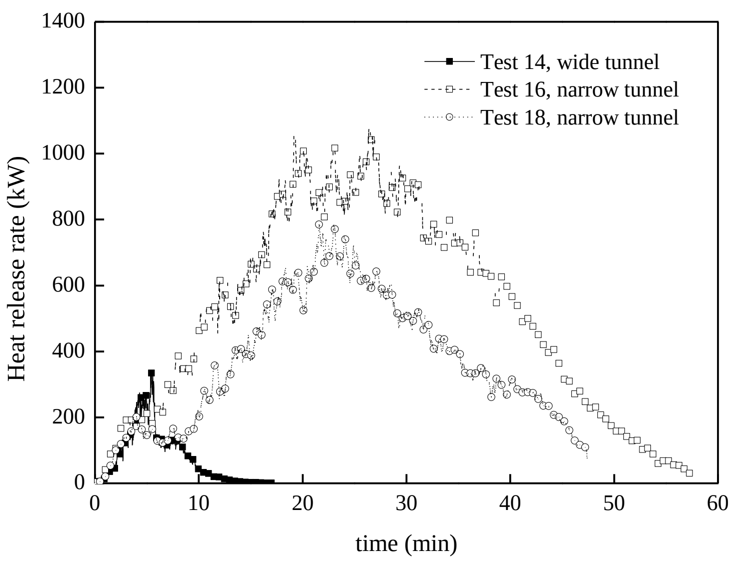


Figure 26 Effect of tunnel cross section on heat release rate in the tests.

Figure 27 shows the heat release rate curves in the T-Rex tests with a tunnel width of 2.8 m (wide tunnel) and 1.88 m (narrow tunnel) with the activation delay of 0.5 min. Clearly it shows that both fires were effectively suppressed immediately after activation and the maximum heat release rates were lower than 200 kW. Further, the influence of tunnel width on the performance of the fire suppression system appears to be weak in the tests with the activation delay of 2 min, on contrary to the cases with the activation delay of 0.5 min.

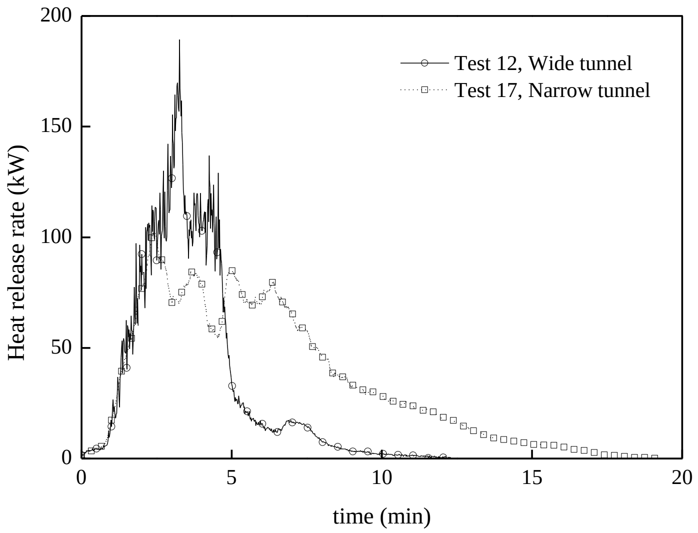


Figure 27 Effect of tunnel cross-section on heat release rate in the tests with activation delay of 0.5 min.

6.11 Guidance for the design fire

A key interest of the study is the design fire for a tunnel with a water-based fire suppression system. As analyzed in the above sections, the performance of a fire suppression system depends mainly on fuel load covers, activation time, water flow rate, nozzle type, ventilation velocity and sprinkler section length and tunnel width.

In order to give a general idea of the design fire with fire suppression, all the heat release rate curves in tests with fire suppression were plotted together with the curve obtained from the free-burn test, see Figure 28. Clearly, the heat release rates in the tests with any type of fire suppression is at a much lower level than that in the free-burn test. The maximum heat release rates in tests with fire suppression is less than 50 % of that in the free-burn test. Note that these tests covers a wide range of scenarios, i.e. referring to different nozzle types, ventilation velocities, activation time, with or without ceiling coverage. If we ignore the test with water flow rate of 2.5 mm/min (5 mm/min in full scale) and the test without end blocks, i.e. test 8b and test 9 (two curves with the peak value over 1.4 MW in Figure 28), the results show that the maximum heat release rates in tests with fire suppression is less than 30 % of that in the free-burn test.

This indicates that for a normal deluge water spray system operated at a water flow rate of approximately 10 mm/min (or not lower than this value), 50 % of the maximum heat release rate in the free-burn test (test without fire suppression) could be considered as the design fire or the maximum heat release rate with fire suppression. If the burning vehicle has steel end blocks, 30 % of the total HRR without fire suppression could be considered as the design fire. These results correspond to full scale activation delay less than 4 min after a gas temperature of 141 ^{o}C was measured beneath the ceiling (heat detection), or the activation heat release rate not over 16 MW.

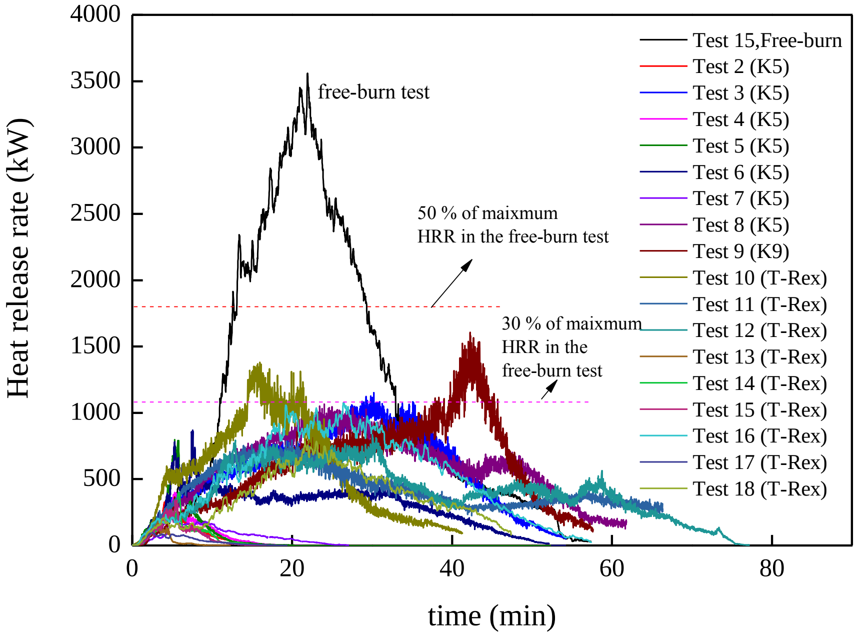


Figure 28 *A summary of the heat release rate curves from the tests. The dash line corresponds to 50 % of the maximum heat release rate in the free-burn test.*

7 Summary

A total of 18 tests were carried out in the 1:4 model scale tunnels with water-based fire suppression systems together with one free-burn test. The key parameters including fuel load covers (ceiling cover and end blocks), activation time, water flow rate, nozzle type, ventilation velocity, sprinkler section length and tunnel width were tested. Three types of nozzles were used in the tests, including two normal nozzles K5 (K-factor 5) and K9 and one special nozzle T-Rex.

The results show that the activation time plays an important role in fire suppression efficiency. For a late activation, the fire could approximate a fully developed fire and result in catastrophic consequences. In these cases, the fires are much more difficult to suppress and further the benefit from a fire suppression system becomes limited. In order to reduce the heat release rate and suppress the fire efficiently, the fire suppression system should be activated as early as possible.

The water flow rate influences the performance of a fire suppression system in a tunnel fire without ceiling coverage significantly and the water flow rate of 5 mm/min (10 mm/min in full scale) is efficient to extinguish the fire, but 2.5 mm/min (5 mm/min in full scale) is not great enough which resulted in a maximum heat release rate of 46 % of that in a free-burn test. However, the influence of water flow rate on the performance of a fire suppression system with ceiling coverage is insignificant.

The fire suppression systems using normal nozzles cannot effectively suppress the fire with ceiling coverage, however, the nozzles K9 discharging larger droplets performs slightly better. In these tests with the two normal nozzles (K5 and K9), the maximum heat release rate were reduced to around 23 % to 32 % of that in a free-burn test for water flow rate of 5 mm/min to 7.5 mm/min (50 % change), corresponding to 10 mm/min to 15 mm/min in full scale, respectively. This indicates that within the range of water flow rate tested, an increase of 50 % in water flow rate only results in a decrease in the maximum heat release rate of approximately 9 % of that in a free-burn test. As a comparison, the fire suppression systems using T-Rex nozzles with a water flow rate of 5 mm/min (10 mm/min in full scale) effectively suppressed the fires, except in the tests in the narrow tunnel with an activation time delay of 2 min. It can be concluded that in the tested scenarios, the T-Rex system with larger droplets performs better than the other two systems with normal nozzles.

The ceiling coverage plays an important role in fire suppression. The fire with a ceiling coverage is much more difficult to suppress and corresponds to the worse scenario compared to the case without ceiling coverage. In the tests with ceiling coverage, the fires were difficult to suppress using normal nozzles. Only the T-Rex nozzles performed well in corresponding situations. Further, the ceiling coverage materials generally may not affect the performance of the fire suppression system since in the tests even a thin combustible cover (3 mm plywood board) was protected well by the fire suppression system after activation. Note that the activation time was simulated well in the tests by use of the commonly-used heat detection algorithm (or even conservative in some tests), therefore the scenario simulated should be quite realistic. In other words, the combustible covers normally used may probably not burn out before the activation of a fire suppression system and will probably be protected well by the fire suppression system, with the exception that the ceiling cover is very thin and highly combustible such as thin tarpaulin.

Without the end blocks (in front and at the end of the fuels), the fuels were directly exposed to wind, and the high ventilation significantly increased the fire growth rate and thus increased the difficulty in fire suppression. For fuels with end blocks, the fire develops much more slowly and could be more easily suppressed. According to this, a suggestion can be made to the vehicle industry that the heavy good vehicle trailers should all have steel end blocks.

Tunnel ventilation affects the performance of a fire suppression system by influencing the fire development. Further, under low ventilation conditions, heat or smoke fire detection systems can be triggered much earlier and thereby the fire suppression system can be activated earlier. Therefore, the fire under low ventilation was more easily suppressed due to both the low heat release rate at the activation time, and the slow fire growth.

The decrease of sprinkler section length from 12.5 m to 7.5 m (50 m to 30 m in full scale) did not affect the performance of the fire suppression system with large droplets nozzles (T-Rex), and the key sprinkler section corresponds to the section covering the fire source. In contrast, the tunnel cross-section shows some influence on the performance of the fire suppression system. For early activation, the tunnel width shows no influence. However, for the activation delay of 2 min, the fire in the narrow tunnel was not efficiently suppressed. The main reason could be that close to the fire source, the fuels together with end blocks increased the local gas velocity by obstruction, which stimulates the fire growth and make the fire more difficult to suppress.

Fire spread to a target placed 1.25 m from the rear end of the main fire load (5 m in full scale) was prevented in all the tests with fire suppression. In the free-burn test 15, the target was ignited at 13.2 min (approx. 1.6 MW in model scale and 50 MW in full scale) and burn out after the test.

A key interest of the study is the design fire for a tunnel with a water-based fire suppression system. From the analysis of test data, it is concluded that for a normal deluge water spray system operated at a water flow rate of approximately 10 mm/min (or not lower than this value) in a realistic tunnel, 50 % of the maximum heat release rate in the free-burn test (test without fire suppression) could be considered as the design fire or the maximum heat release rate with fire suppression. If the burning vehicle has steel end blocks, 30 % of the total HRR without fire suppression could be considered as the design fire. These results correspond to full scale activation delay less than 4 min after a gas temperature of 141 ^{o}C was measured beneath the ceiling (heat detection), or the activation heat release rate was not over 16 MW in full scale. Comparison of these results to full scale test data will be carried out to further verify the findings.

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Appendix A Test notes

Test 1

Date: 29/5-13
Moisture: 8.8 – 9.7 – 10.0 (three random points)

Chronology
00:00 start
02:00 Ignition
04:50 heptane out (probably little eariler)
05:15 Half of the first pallet pile is on fire
05:42 141°C ceiling gas temperature
06:12 Water on
07:12 the hood ventilation in the hall increased to 70 000 m^3/h
07:30 The fire starts to decrease in size
08:10 1.81 bar – tuned down to set value
09:00 The fire is almost out
10:12 Even less of a fire
15:00 Sprinkler is turned off
15:40 Small embers are manually extinguished

Test 2

Date: 30/5-13
Moisture: 9.2 – 9.6 – 10.0 (three random points)

Chronology
00:00 Start
02:00 Ignition time
04:15 Heptane out
05:15 Half of the first pallet pile is on fire
06:10 141°C ceiling gas temperature
06:40 Water on, 7 seconds later the water has reached full effect.
09:15 The water has low effect on the fire
10:15 The fire has grown larger
11:40 Two entire piles of pallets are burning
14:41 The fire seems to focus on the center of the pallet piles
15:52 Flames hit the ceiling
17:20 One pile collapsed
19:30 The front plate loosened and a collapse occurred
25:10 Another collapse
31:15 The water affects the areas that the water hits. When the pallets collapsed, the water can hit more burning materials collapsed on the floor.
35:00 The tunnel roof has to be cooled due to ignition of one of the beams
39:00 Small fire left
40:39 last plate fell and the fire was extinguished

Test 3

Date: 30/5-13
Moisture: 9.1 – 9.2 – 9.6 (three random points)

Chronology

00:00 Start
02:00 Ignition time
03:50 The fire climbs along the plate
04:20 The heptane is out
05:07 Half of the first pallet row is on fire
06:22 141^{o}C ceiling gas temperature
07:25 Water on
11:25 The water has a clear effect
14:10 The plate covers a small fire
17:00 Water turned off

Test 4

Date: 30/5-13
Moisture: 9.8 – 10.0 – 10.2 (three random points)

Chronology
00:00 Start
02:00 Ignition time
04:14 The heptane is out
06:28 141 ^{o}C ceiling gas temperature
08:28 Water on
08:59 Water has a great effect
10:12 The fire has been reduced, and ceiling temperature is under 100 ^{o}C
14:20 Almost no visible flames
15:30 No visible flames

Test 5

Date: 30/5-13
Moisture: 9.7 – 9.8 – 10.6 (three random points)

Chronology
00:00 Start
02:00 Ignition time
04:22 The heptane is out
06:12 141^{o}C ceiling gas temperature
08:12 2 minutes until the water is turned on (400 ^{o}C)
09:12 1 minute until water (600 ^{o}C)
10:12 The water is turned on (860 ^{o}C)
20:50 There are still some flames left
21:10 Suppression controls the fire but doesn’t extinguish it
39:40 One row of pallets collapsed
42:50 There are a few flames existing above the cover
49:30 No flames left
52:00 Water off

Test 6

Date: 30/5-13
Moisture: 9.9 – 10.6 – 11.0 (three random points)

Chronology
00:00 Measurement start

02:00 Ignition time
03:50 The fire extends along the plate
04:30 The heptane is out
05:15 Backlayering in the tunnel
05:43 141^{o}C ceiling gas temperature
06:43 Water on
07:49 Flames pulsates and hits the roof, no more backlayering
14:48 No more flames on the roof, still some flames left
15:44 Some smoke outside the hood (very small amount)
27:00 Water off

Test 7

Date: 30/5-13
Moisture: 9.9 – 10.7 – 11.1 (three random points)

Chronology
00:00 Measurement start
02:00 Ignition time
03:08 Pallets caught fire
04:00 The heptane is out
05:55 141^{o}C ceiling gas temperature
06:23 Water on
09:00 5000 m^3/h in the roof ventilation
21:37 Small collapse
23:37 7000 m^3/h in the roof ventilation
35:20 Small collapse
66:00 Water off

Test 8

Date: 30/5-13
Moisture: 7.9 – 8.6 – 10.8 (three random points)

Chronology
00:00 Measurement start
02:00 Ignition time
02:30 Pallets burning
04:32 One heptane container is out, the other container 4:55
06:18 141 ^{o}C ceiling gas temperature
07:18 Water on
08:30 89 l/min – 0.35 bar
21:40 Minor collapse
32:18 Collapse
42:20 The fire is slowly dying, still large though
46:10 The steel plate yielded from the roof
53:50 Small flames left
55:00 Water off

Test 9

Date: 30/5-13
Moisture: 8-9 % (three random points)

Chronology

00:00 Measurement start
02:00 Ignition time
04:00 Heptane out plus the side plates were tipped
04:31 141^{o}C ceiling gas temperature
05:01 Water on
07:30 175 l/min – 1.48 bar
18:00 Collapse
28:50 Collapse
40:00 Water off

Test 10

Date: 30/5-13
Moisture: 8.6 – 9.3 – 9.9 (three random points)

Chronology

00:00 Measurement start
02:00 Ignition time
03:40 Large fire
04:30 The heptane is out
05:25 141 ^{o}C ceiling gas temperature
05:55 Water on
07:20 264 l/min
30:50 Small collapse
45:25 The ventilation in the hall ceiling is increased to 90 000 m^{3}/h due to a lot of smoke.
72:00 Water off

Test 11

Date: 30/5-13
Moisture: 10.0 – 10.0 – 10.1 (three random points)

Chronology

00:00 Measurement start
02:00 Ignition time
02:45 Pallets are burning on their own
04:31 The heptane is out
05:53 141 ^{o}C ceiling gas temperature
06:24 Water on
07:58 175 l/min
21:30 900 ^{o}C – top value
58:15 Seems to be slowing down
67:30 Collapse
75:00 Water off

Test 12

Date: 30/5-13
Moisture: 8.6 – 9.2 – 9.3 (three random points)

Chronology

00:00 Measurement start
02:00 Ignition time
04:17 Heptane out
05:14 141 °C ceiling gas temperature
05:44 Water on
07:00 15-16 °C beneath ceiling, the fire is very small
10:00 Water off

Test 13

Date: 30/5-13
Moisture: 8.5 – 8.9 **-** 9.2 – 10.5 (four random points)

Chronology
00:00 Measurement start
02:00 Ignition time
04:20 Heptane out
05:52 141°C ceiling gas temperature
07:52 Water on, 440°C
08:40 176 l/min
14:10 The fire is totally out
15:00 Water off

Test 14

Date: 30/5-13
Moisture: 8.9 – 8.9 – 10.2 – 10.7 (four random points)

Chronology
00:00 Measurement start
02:00 Ignition time
04:20 Heptane out
05:38 141°C ceiling gas temperature
07:38 Water on, 280 °C
09:10 105.9 l/min
13:20 Very small fire left
15:00 Water off

Test 15

Date: 30/5-13
Moisture: 8.9 – 9.8 – 10.2 (three random points)

Chronology
00:00 Measurement start
02:00 Ignition
04:24 Heptane out
15:10 The target is ignited
18:27 Small collapse
18:57 The entire target is on fire
19:38 Collapse
19:48 Big collapse which ignites the plywood on the floor
20:00 The effect and temperature are the highest values, a plate from the roof loosens as well.

20:55 The other plywood is ignited but the fire fades out within a couple of seconds
24:19 The target collapses
24:40 Smaller collapse
25:00 Another collapse
26:10 Huge collapse, the steel plate bends. From this point on, the fire decreases a lot.
28:00 The ventilation is increased to 90 000 m^3/h
55:00 Extinguishment

Test 16
Date: 30/5-13
Moisture: 8.9 – 9.3 – 9.5 (three random points)

Chronology
00:00 Measurement start
02:00 Ignition
03:42 141°C ceiling gas temperature
05:42 Water on
11:34 0.26 bar
33:25 Small collapse
55:00 Water off – extinguishment.

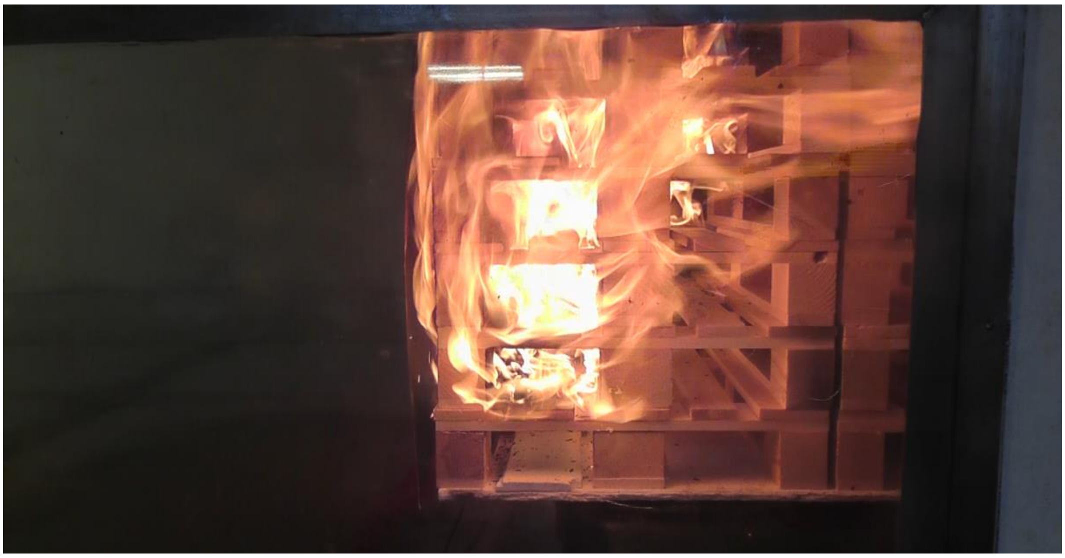
Test 17
Date: 30/5-13
Moisture: 9.4 – 9.7 – 9.9 (three random points)

Chronology
00:00 Measurement start
02:00 Ignition
03:55 141 °C ceiling gas temperature
04:25 Water on
08:50 0.26 bar
15:55 No visible flames
18:00 Water off

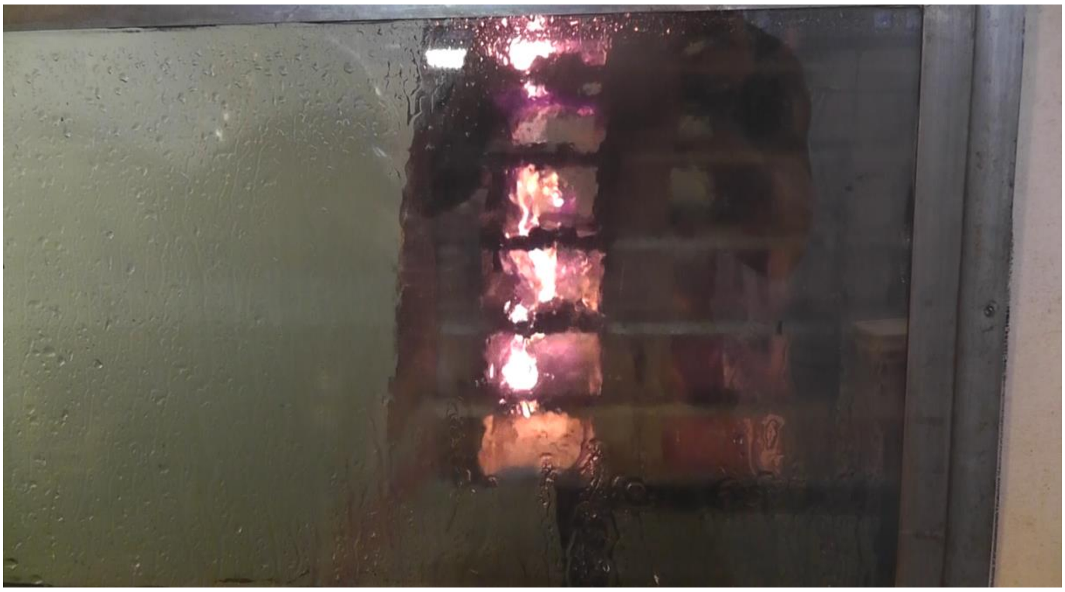
Test 18
Date: 30/5-13
Moisture: 8.7 – 9.4 – 11.1 (three random points) for the first 2 piles
The other piles had a humidity of around 18 %.

Chronology
00:00 Measurement start
02:00 Ignition
03:50 141°C ceiling gas temperature
05:50 Water on
27:20 Collapse
47:00 Water off

Appendix B Test photos



(a) Before suppression



(b) 3.3 min after suppression

Figure B1 Test photos, side window, Test 1.

(a) Before suppression

(b) 3 min after suppression

Figure B2 Test photos, side window, Test 2.

(a) Before suppression

(b) 3 min after suppression

Figure B3 Test photos, Test 3.

(a) Before suppression

(b) 2 min after suppression

Figure B4 Test photos, Test 4.

(a) Before suppression

(b) 3 min after suppression

Figure B5 Test photos, Test 5.

(a) Before suppression (backlayering)

(b) 3 min after suppression

Figure B6 Test photos, Test 6.

(a) Before suppression

(b) 3 min after suppression

Figure B7 Test photos, Test 7.

(a) Before suppression

(b) 3 min after suppression

Figure B8 Test photos, Test 8.

(a) Before suppression

(b) 3 min after suppression

Figure B9 Test photos, Test 8b.

(a) Before suppression

(b) 3 min after suppression

Figure B10 Test photos, Test 9.

(a) Before suppression

(b) 3 min after suppression

Figure B11   Test photos, Test 10.

(a) Before suppression

(b) 3 min after suppression

Figure B12   Test photos, Test 11.

(a) Before suppression

(b) 1 min after suppression

Figure B13 Test photos, Test 12.

(a) Before suppression

(b) 1 min after suppression

Figure B14 Test photos, Test 13.

(a) Before suppression

(b) 1.5 min after suppression

Figure B15 Test photos, Test 14.

(a) 5 min after ignition

(b)   10 min after ignition

(c) 20 min after ignition

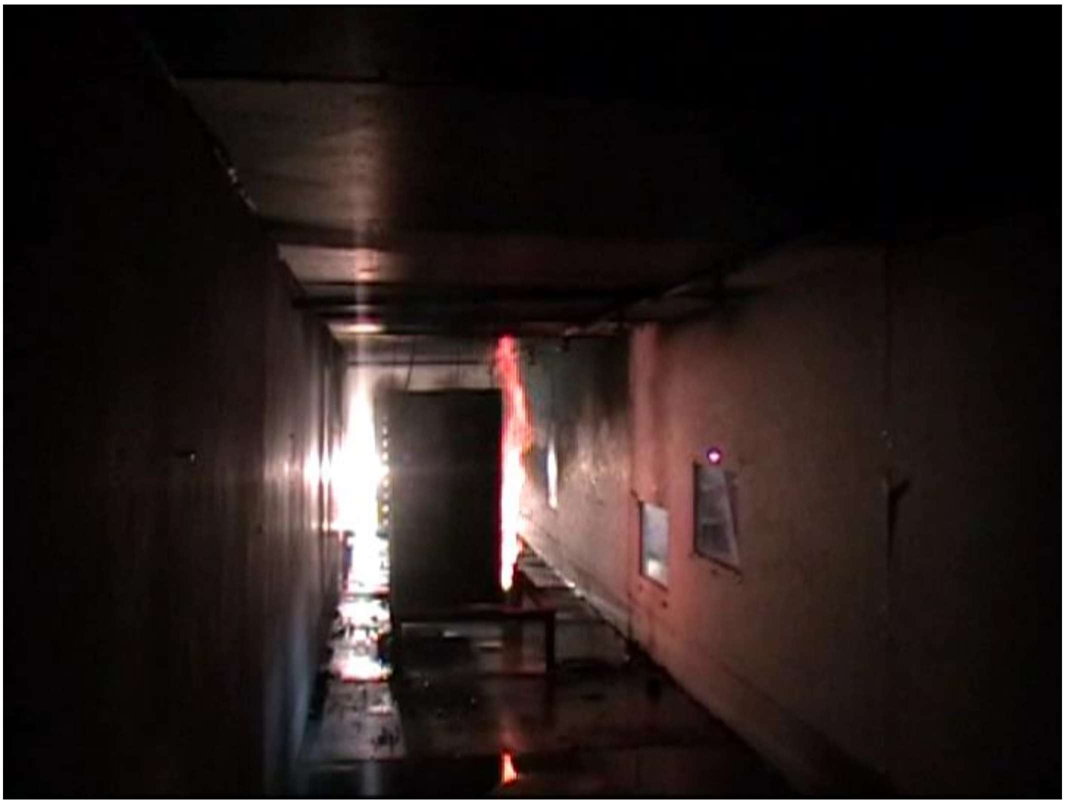
(d) 40 min after ignition

Figure B16 Test photos, Test 15.

(a) Before suppression

(b) 3 min after suppression

Figure B17 Test photos, Test 16.



(a) Before suppression

(b) 3 min after suppression

Figure B18   Test photos, Test 17.

(a) Before suppression

(b) 3 min after suppression

Figure B19 Test photos, Test 18.

Appendix C Test results

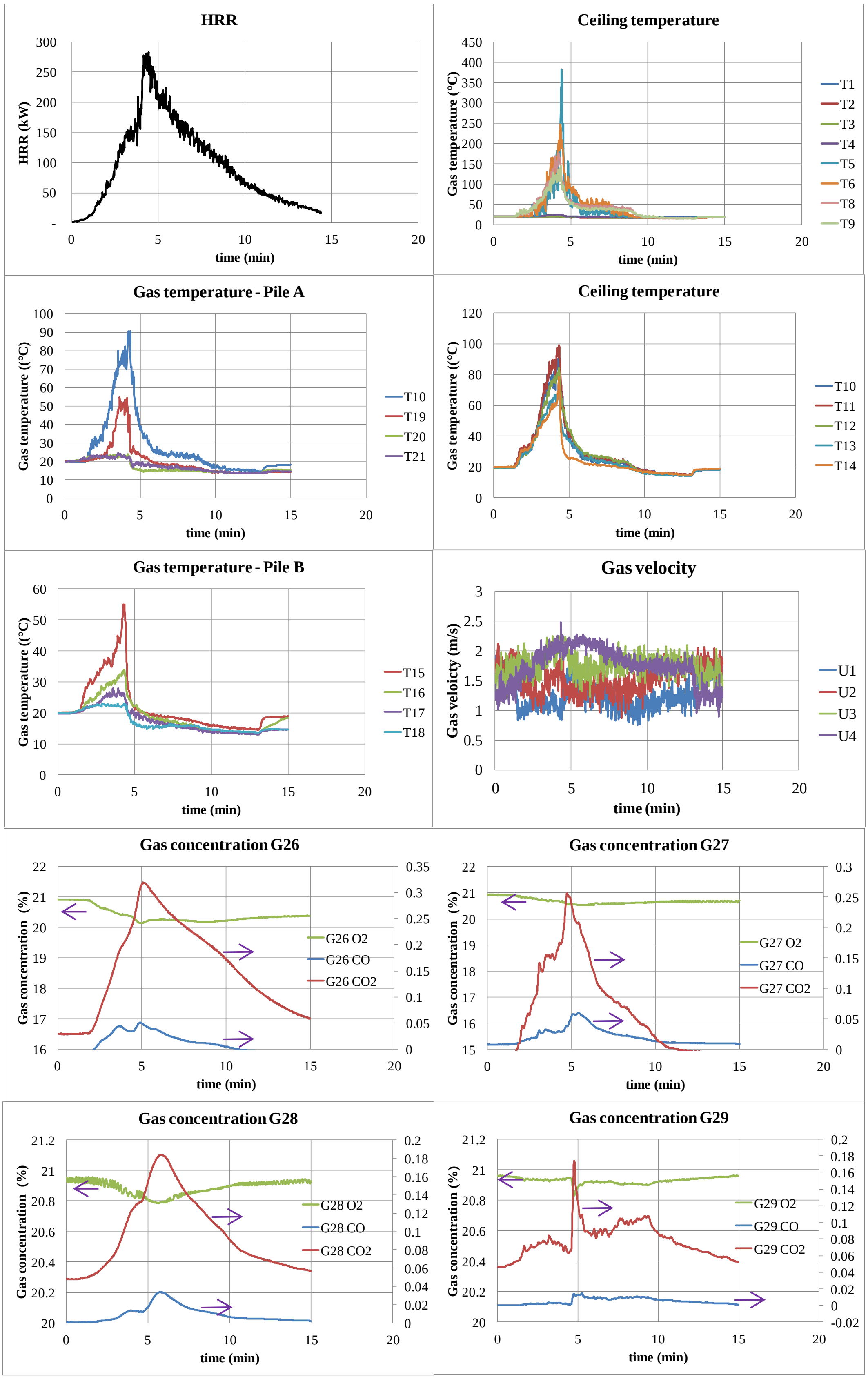


Figure C1 Test Results Test 1.

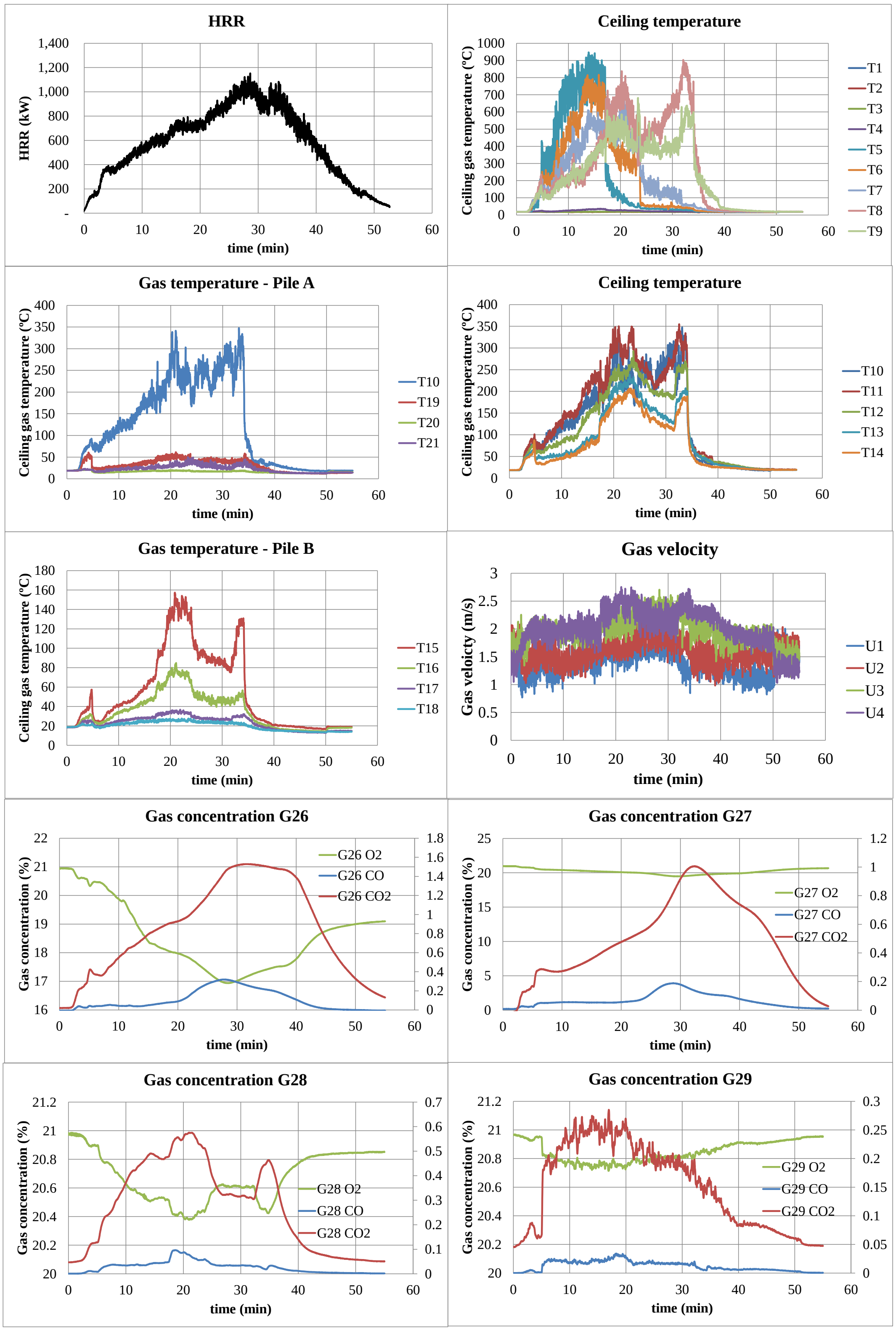


Figure C2 Test Results Test 2.

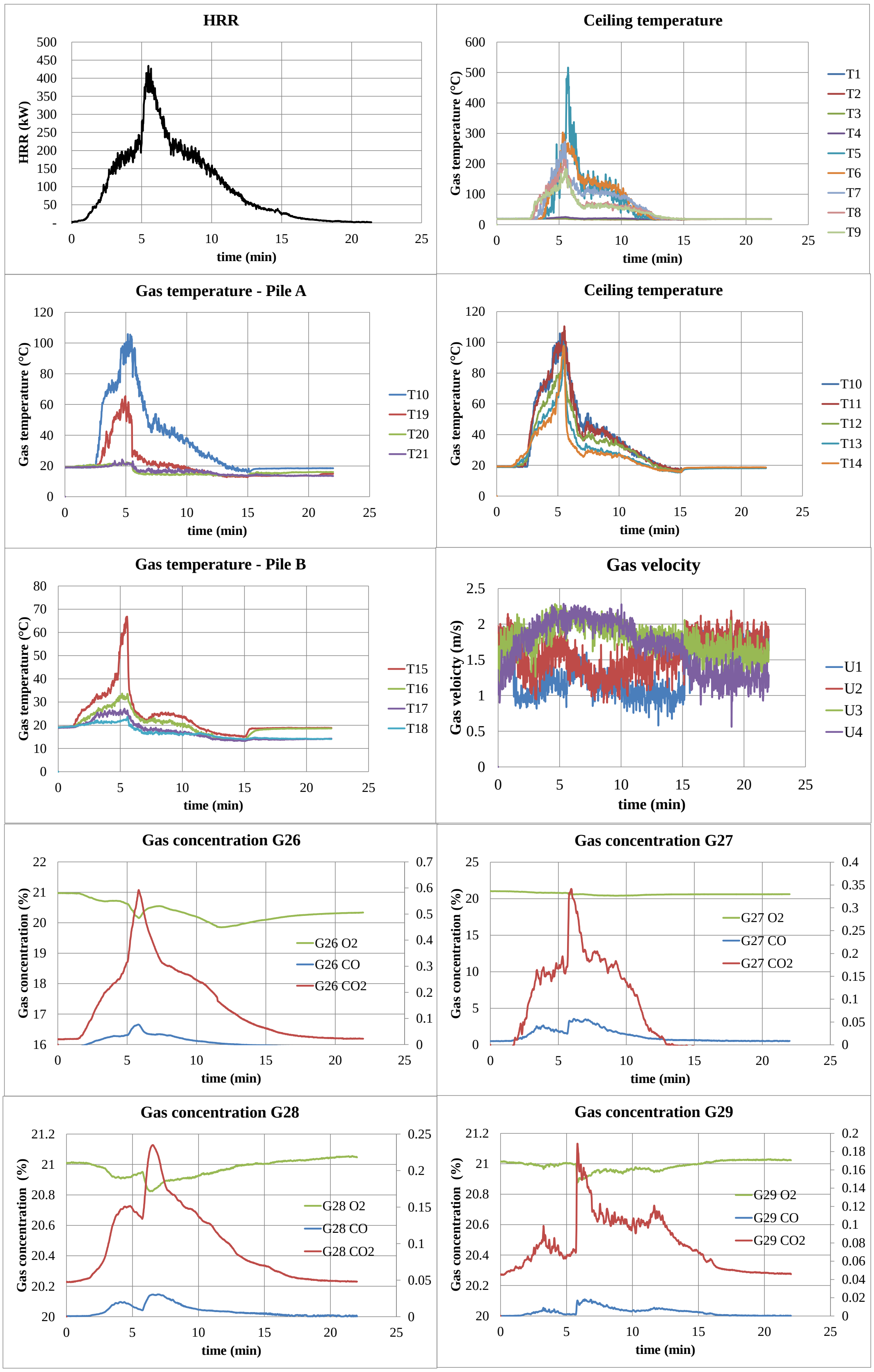


Figure C3 Test Results Test 3.

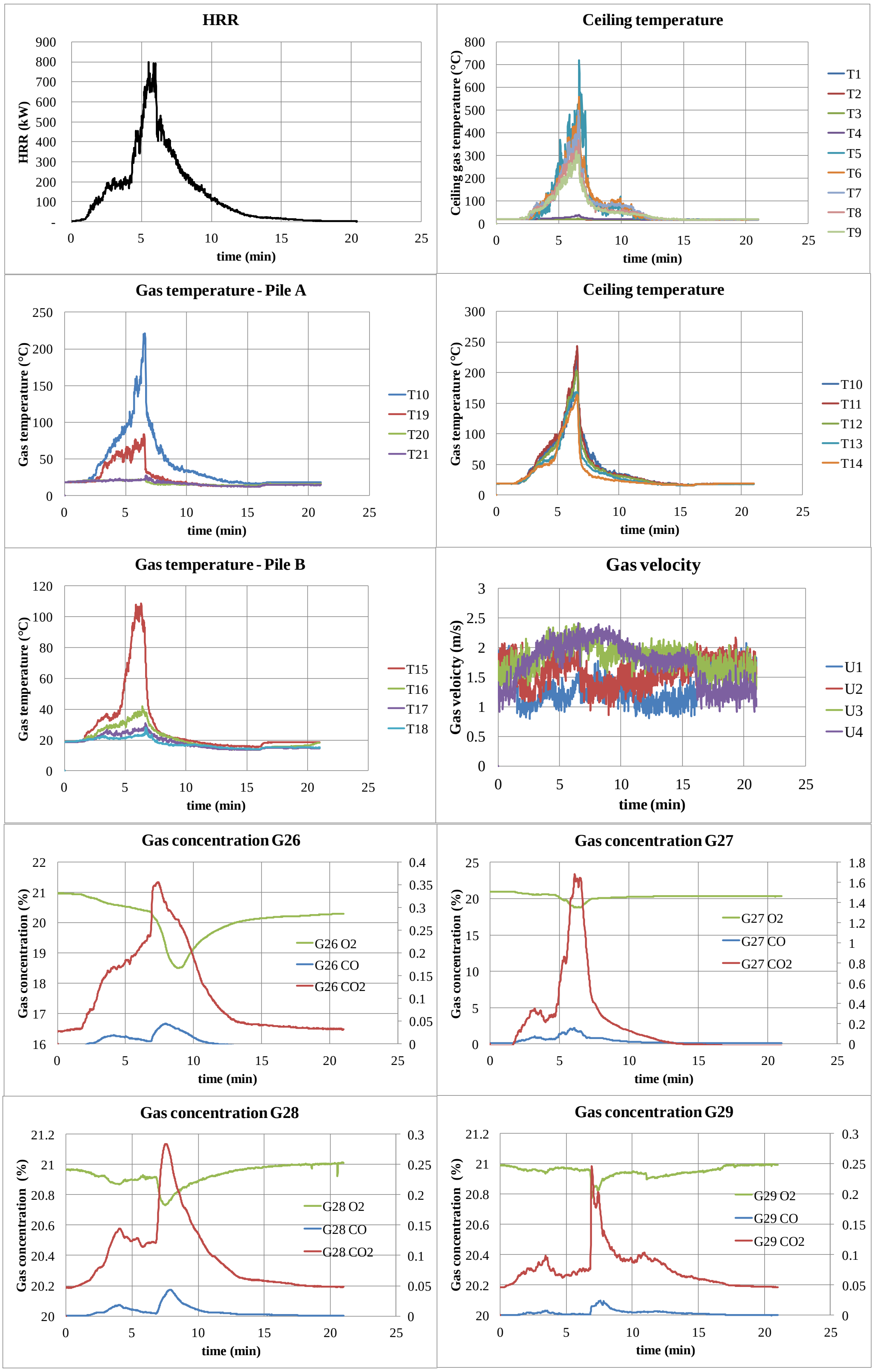


Figure C4 Test Results Test 4.

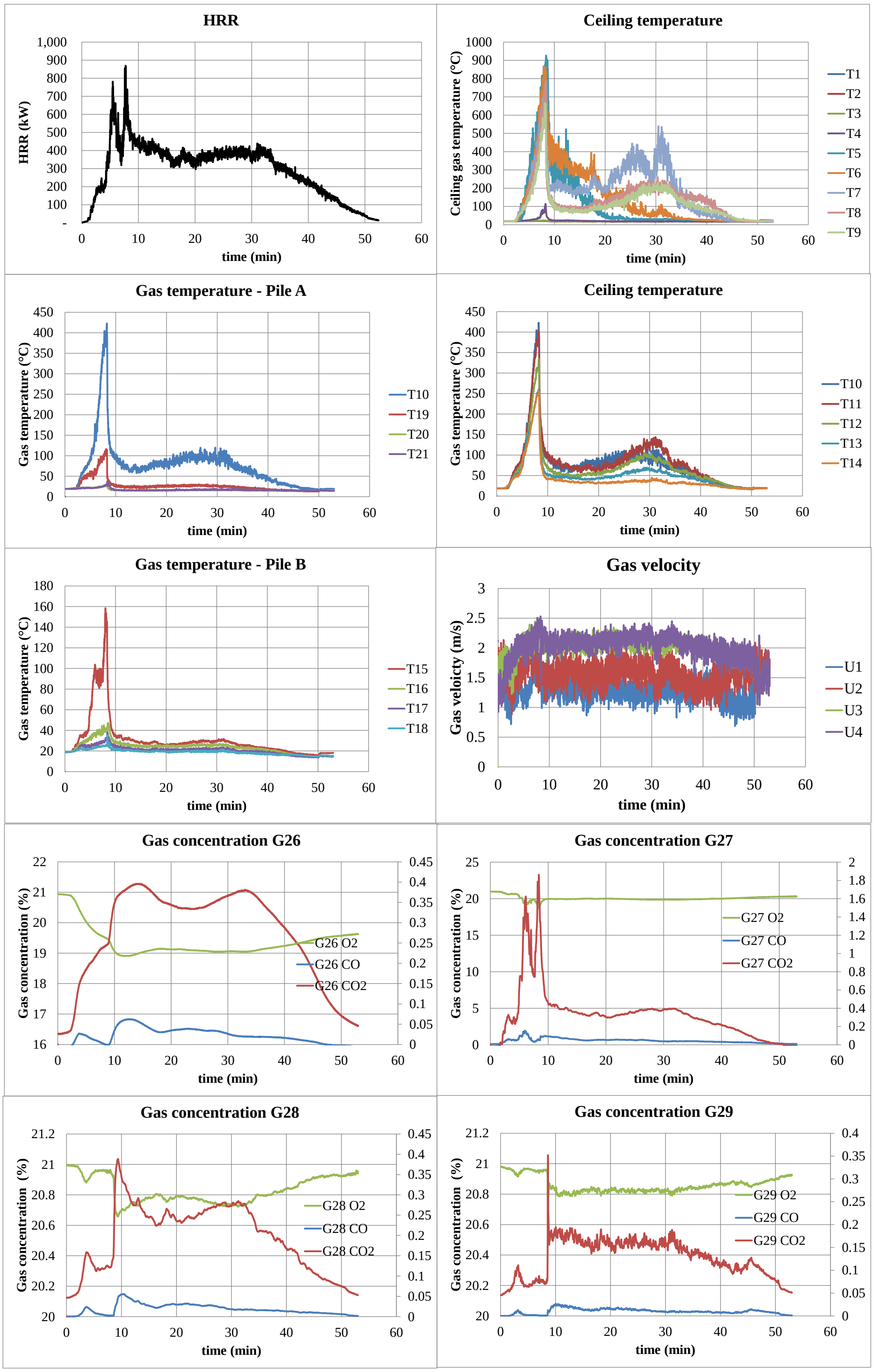


Figure C5 Test Results Test 5.

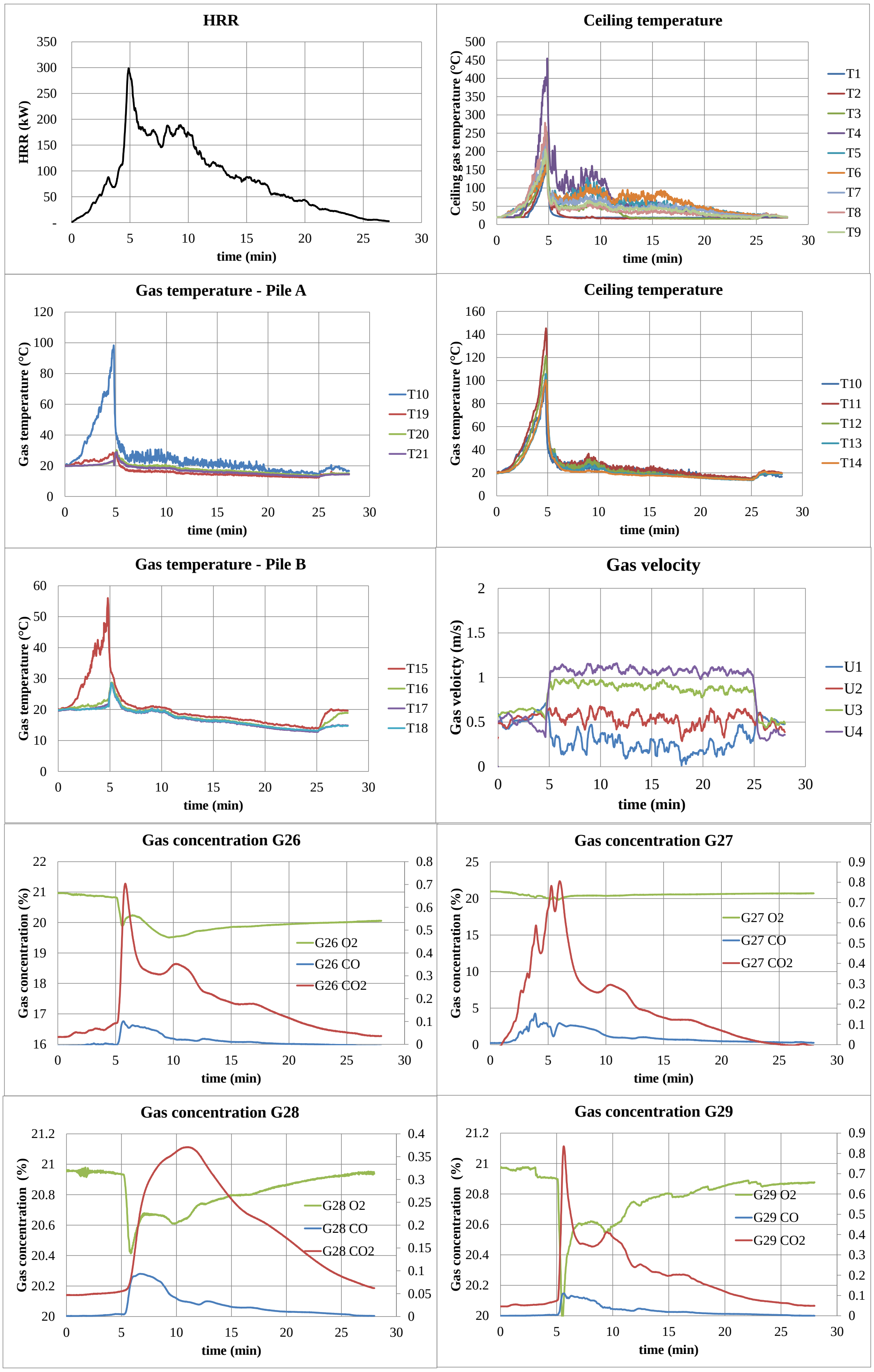


Figure C6 Test Results Test 6.

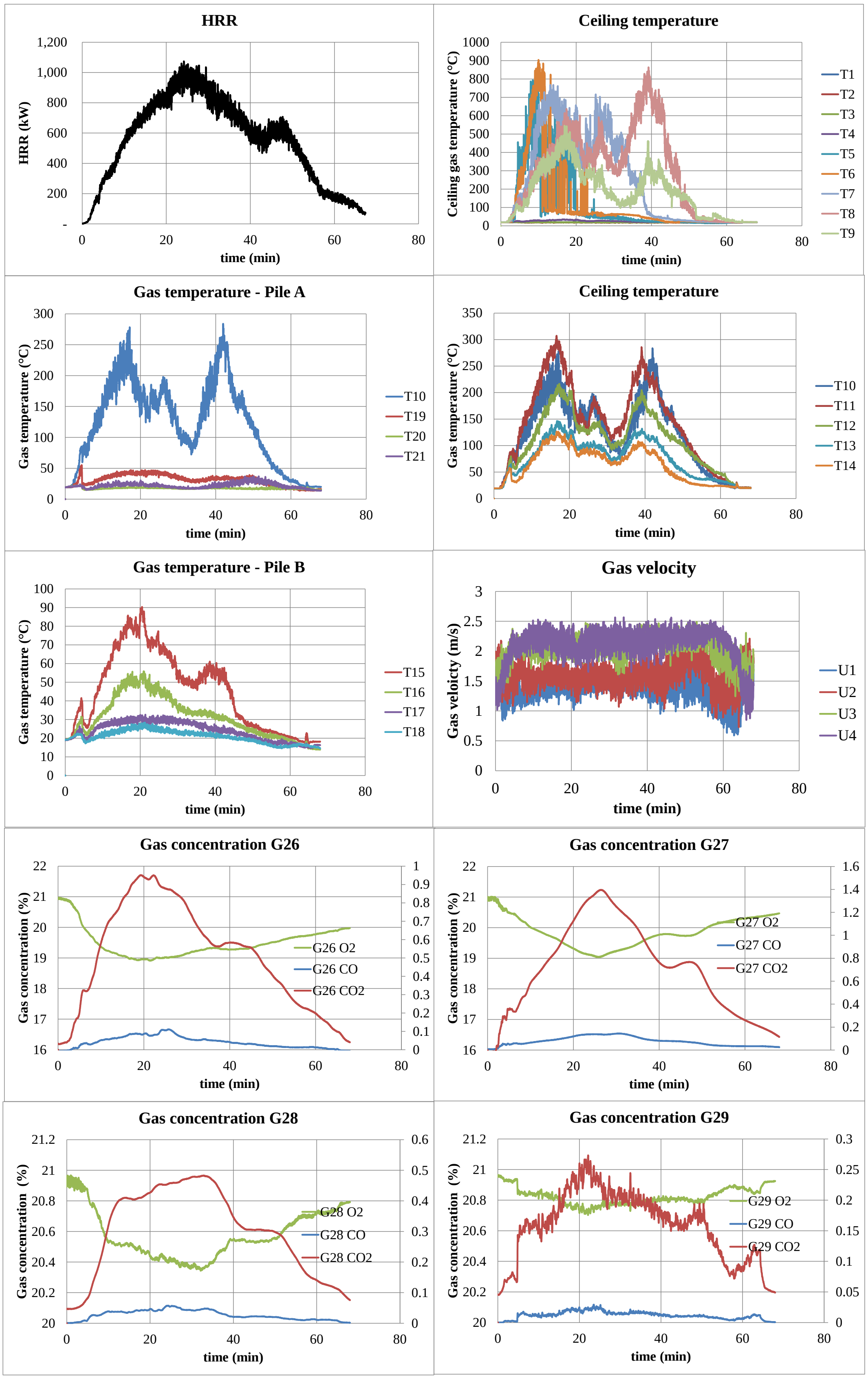


Figure C7 Test Results Test 7.

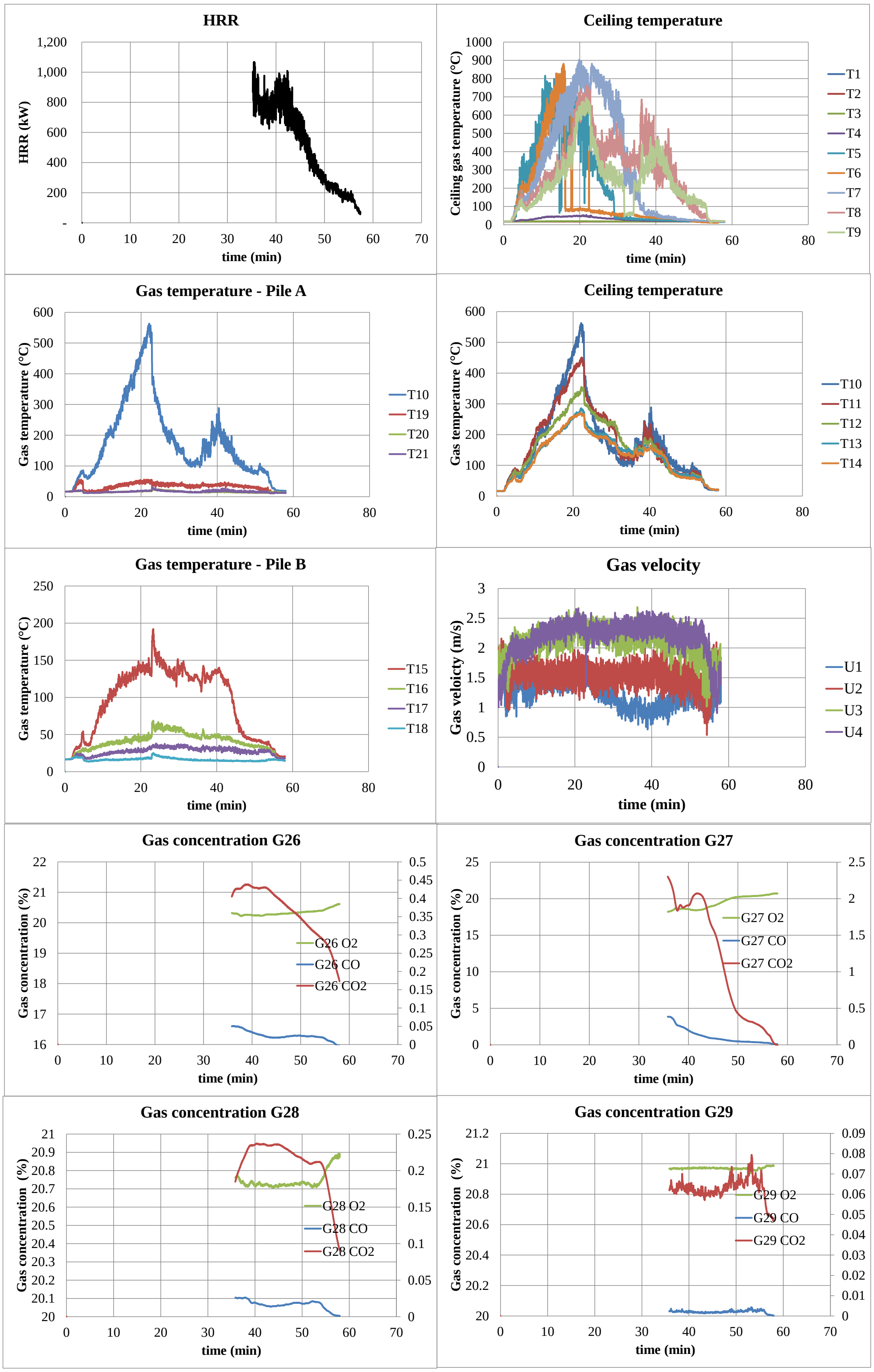


Figure C8 Test Results Test 8.

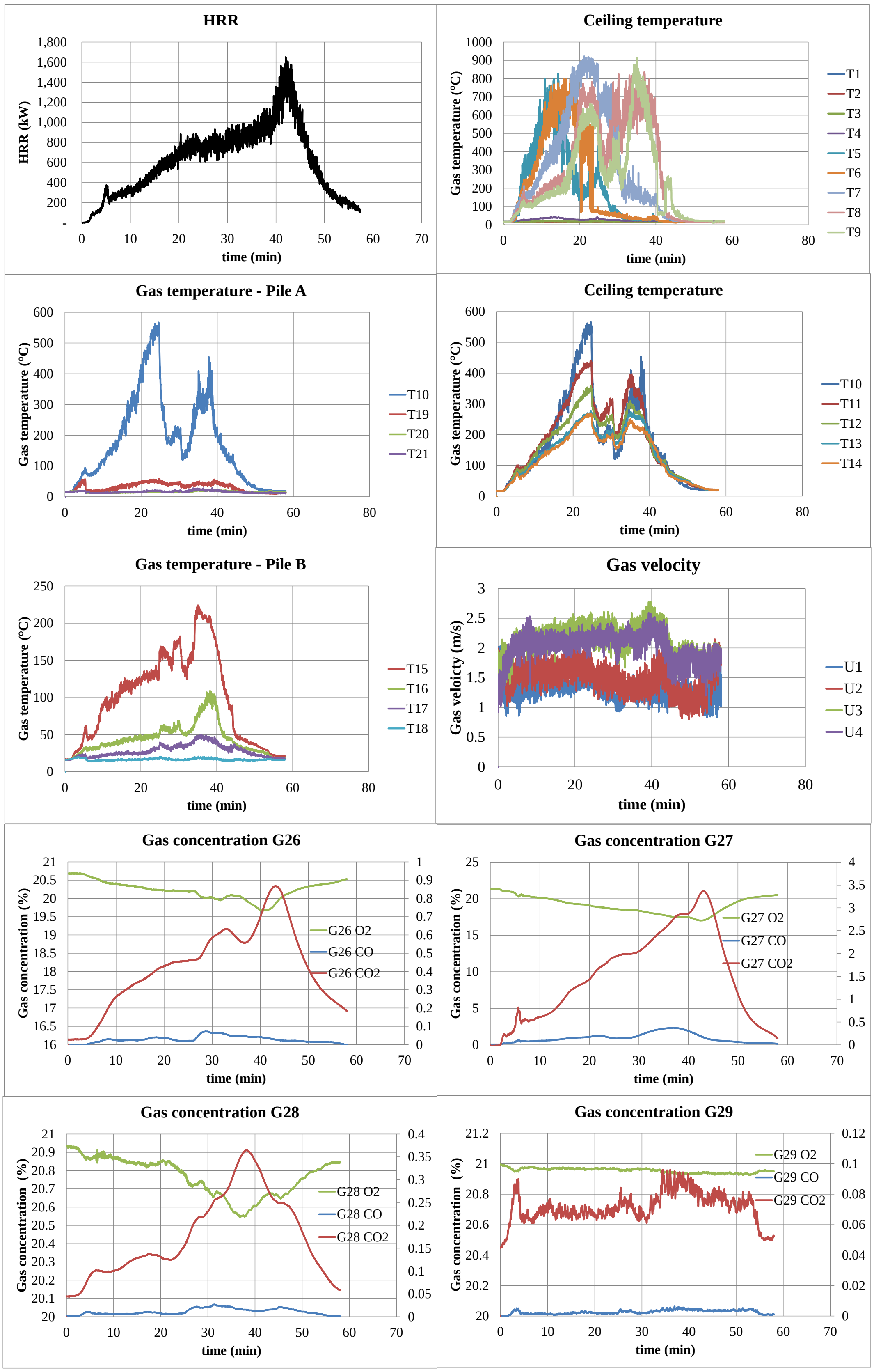
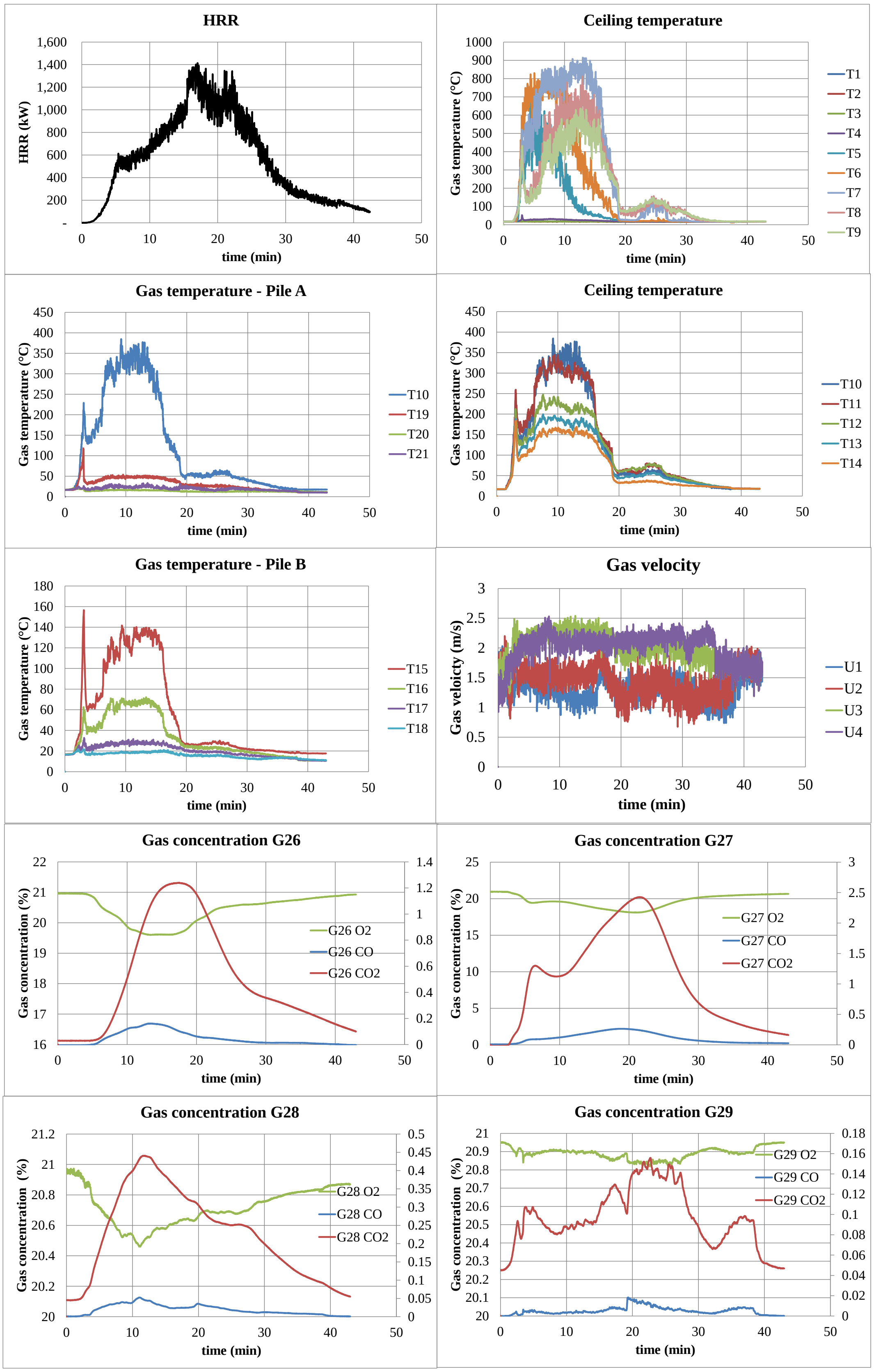


Figure C9 Test Results Test 8b.



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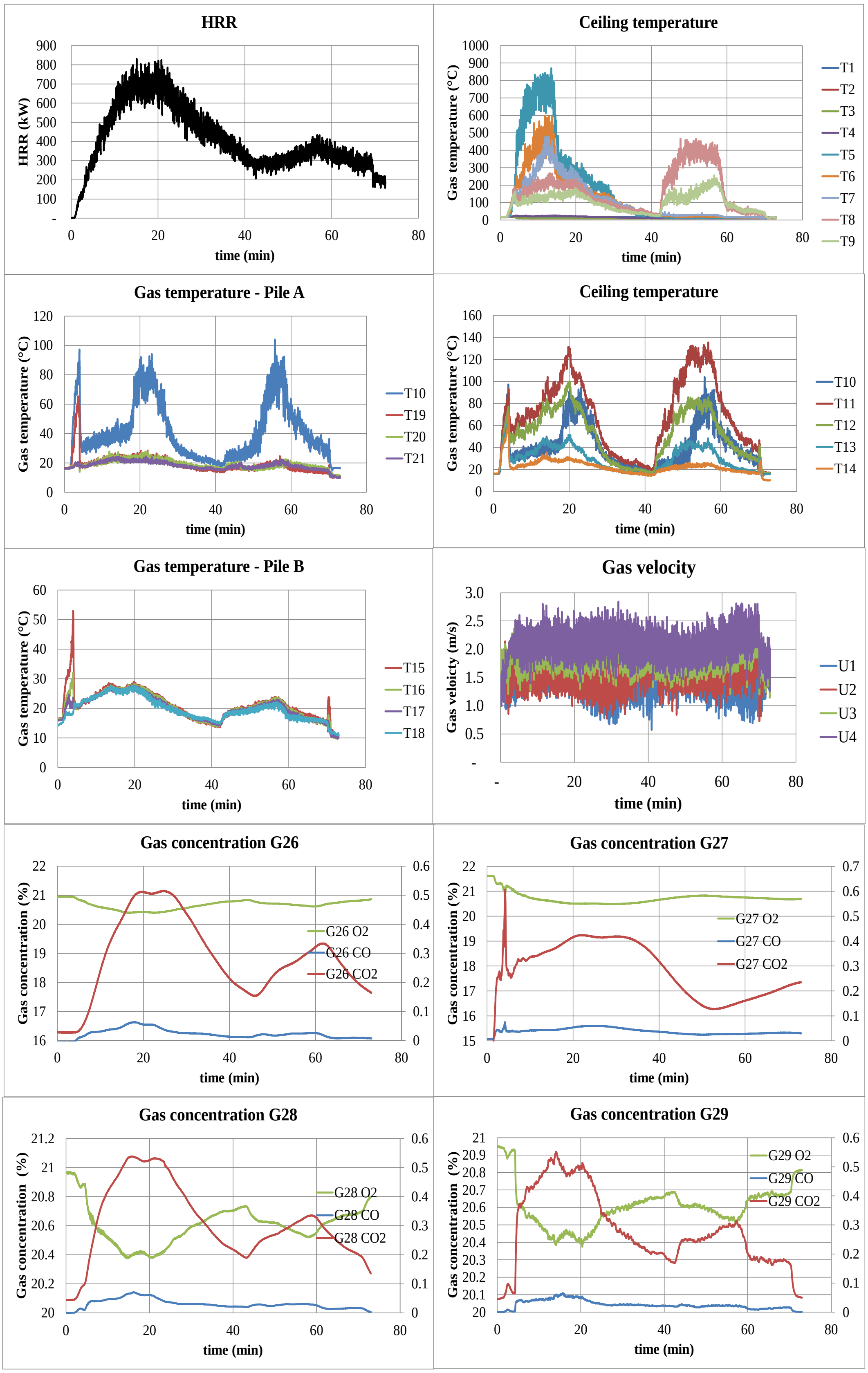

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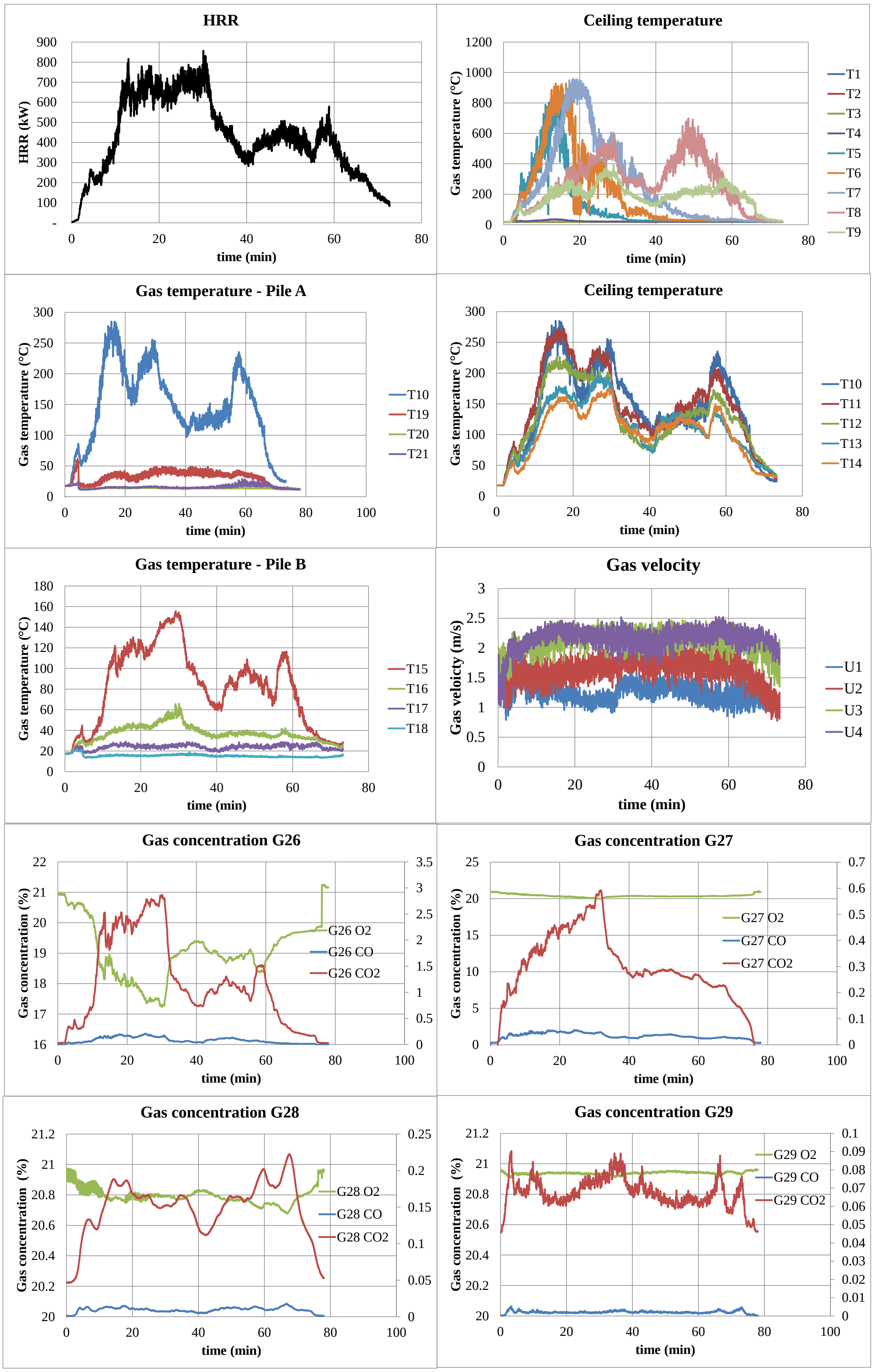

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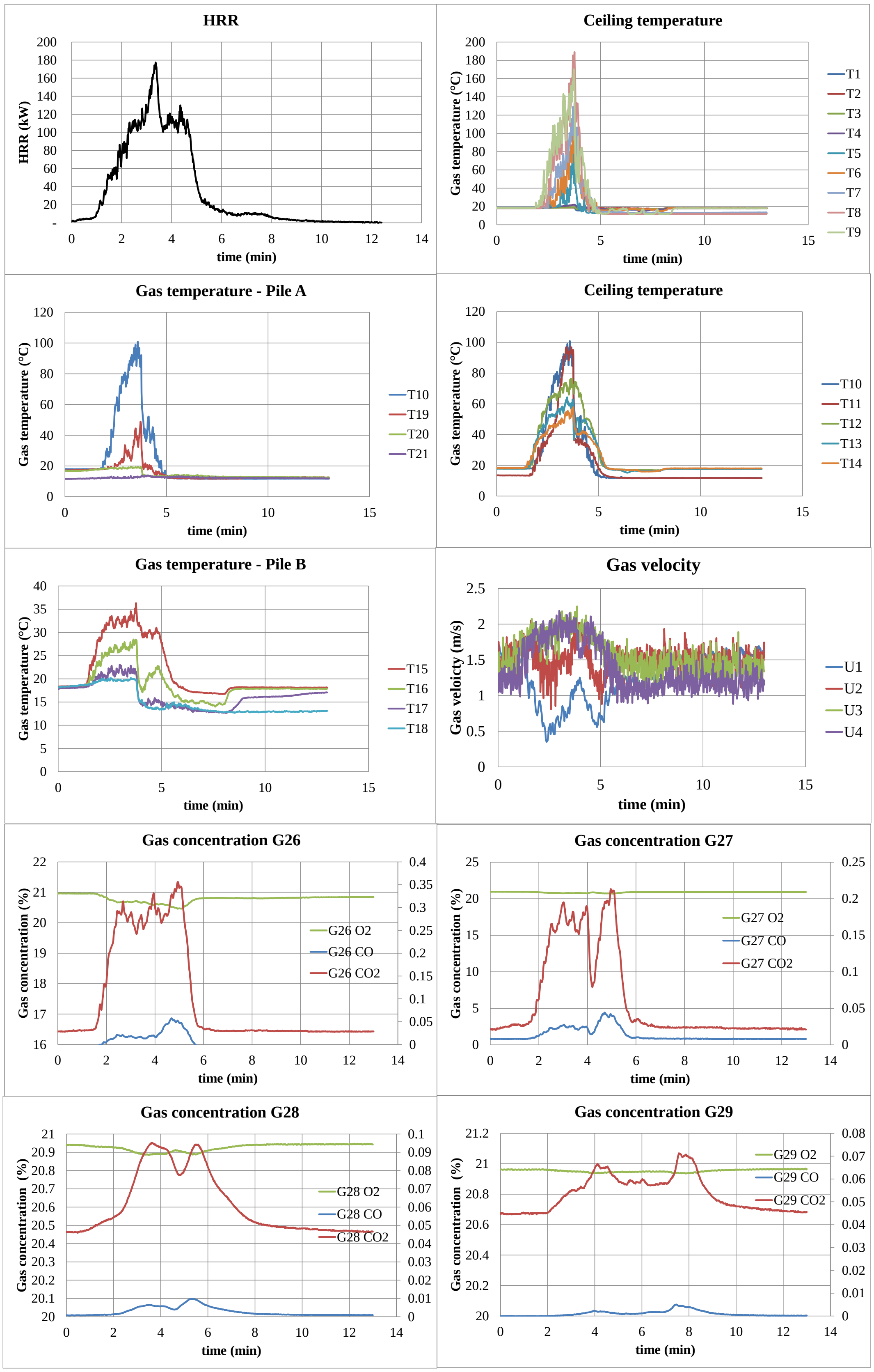

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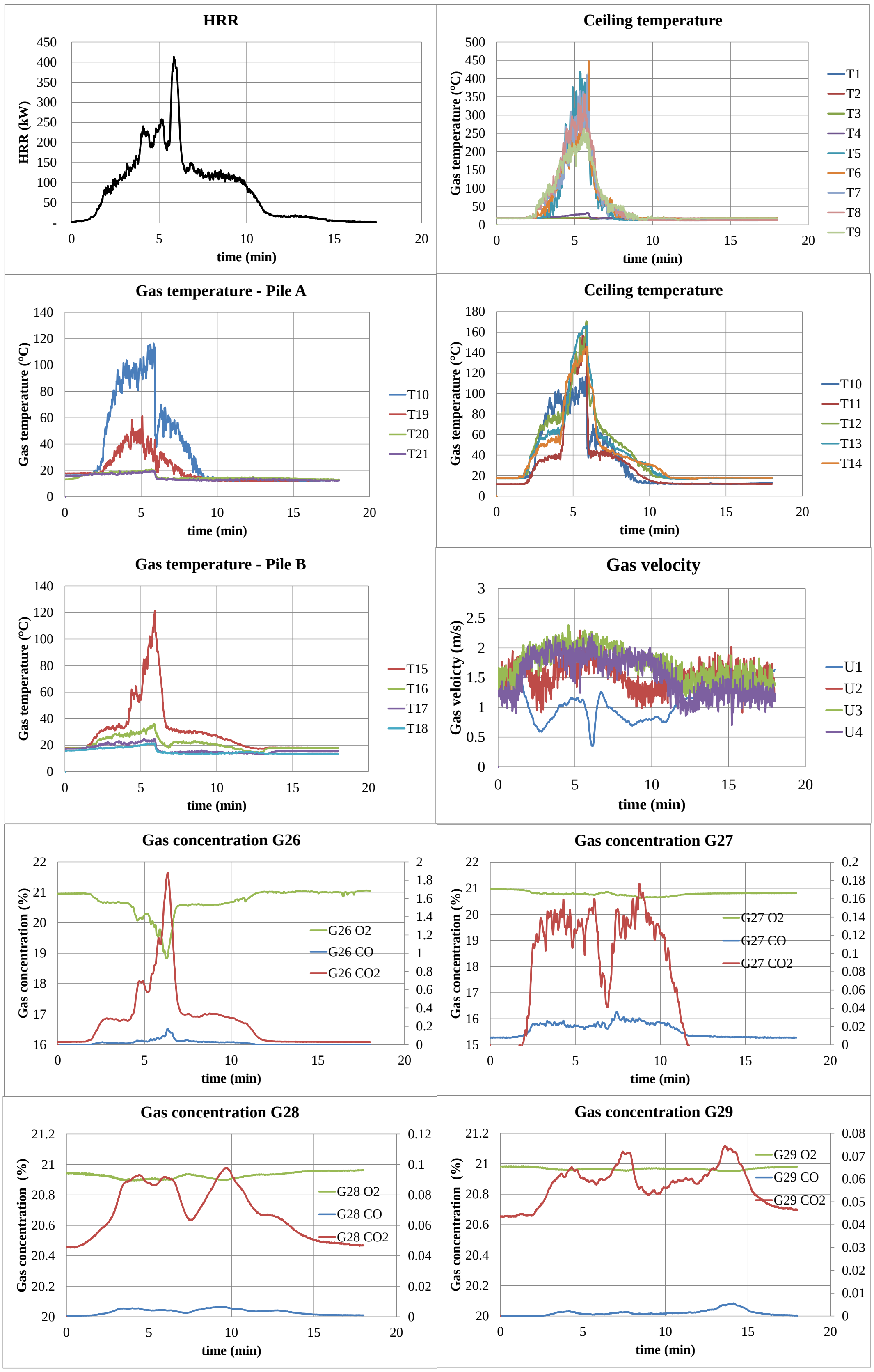
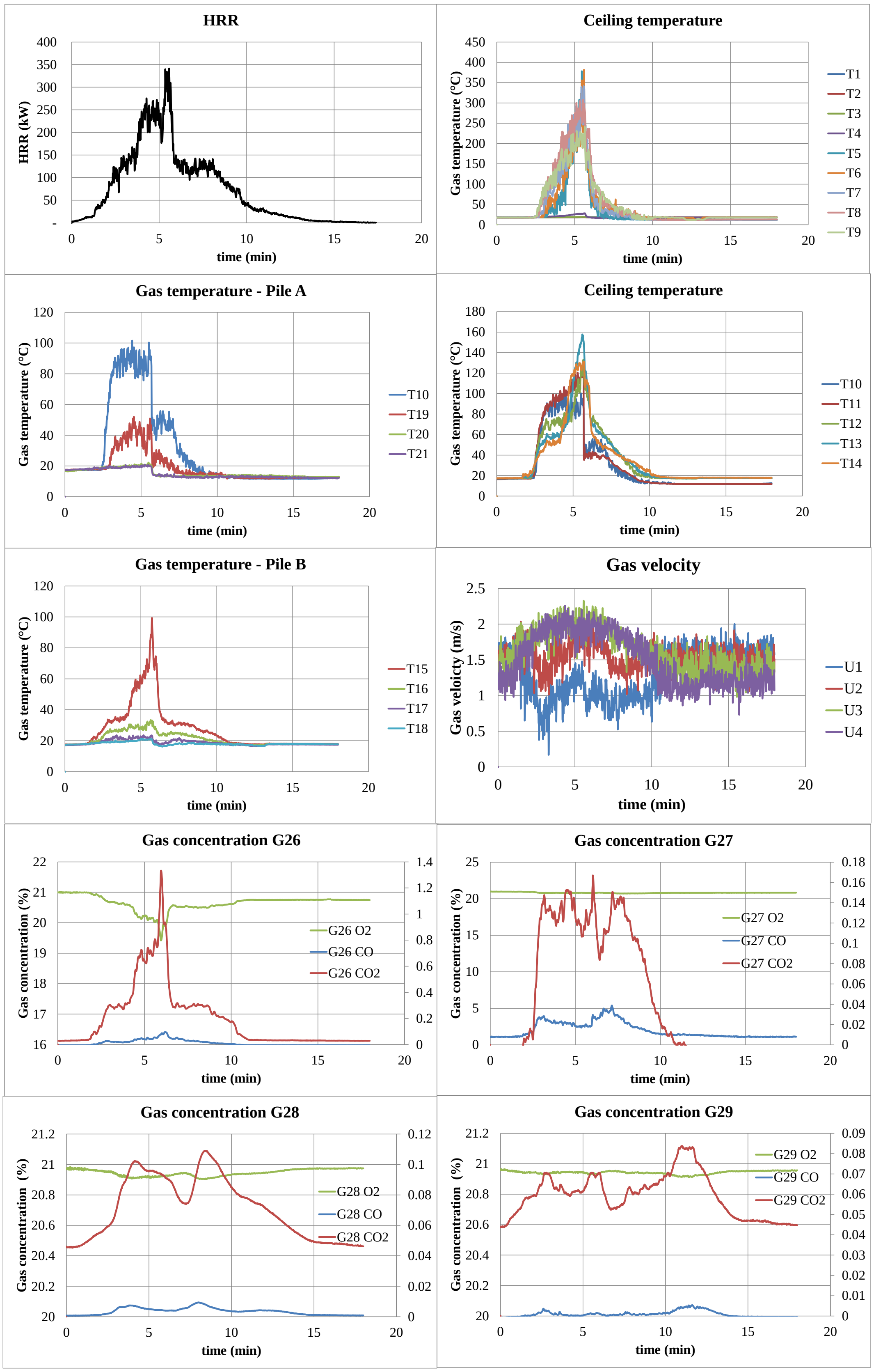


Figure C14 Test Results Test 13.



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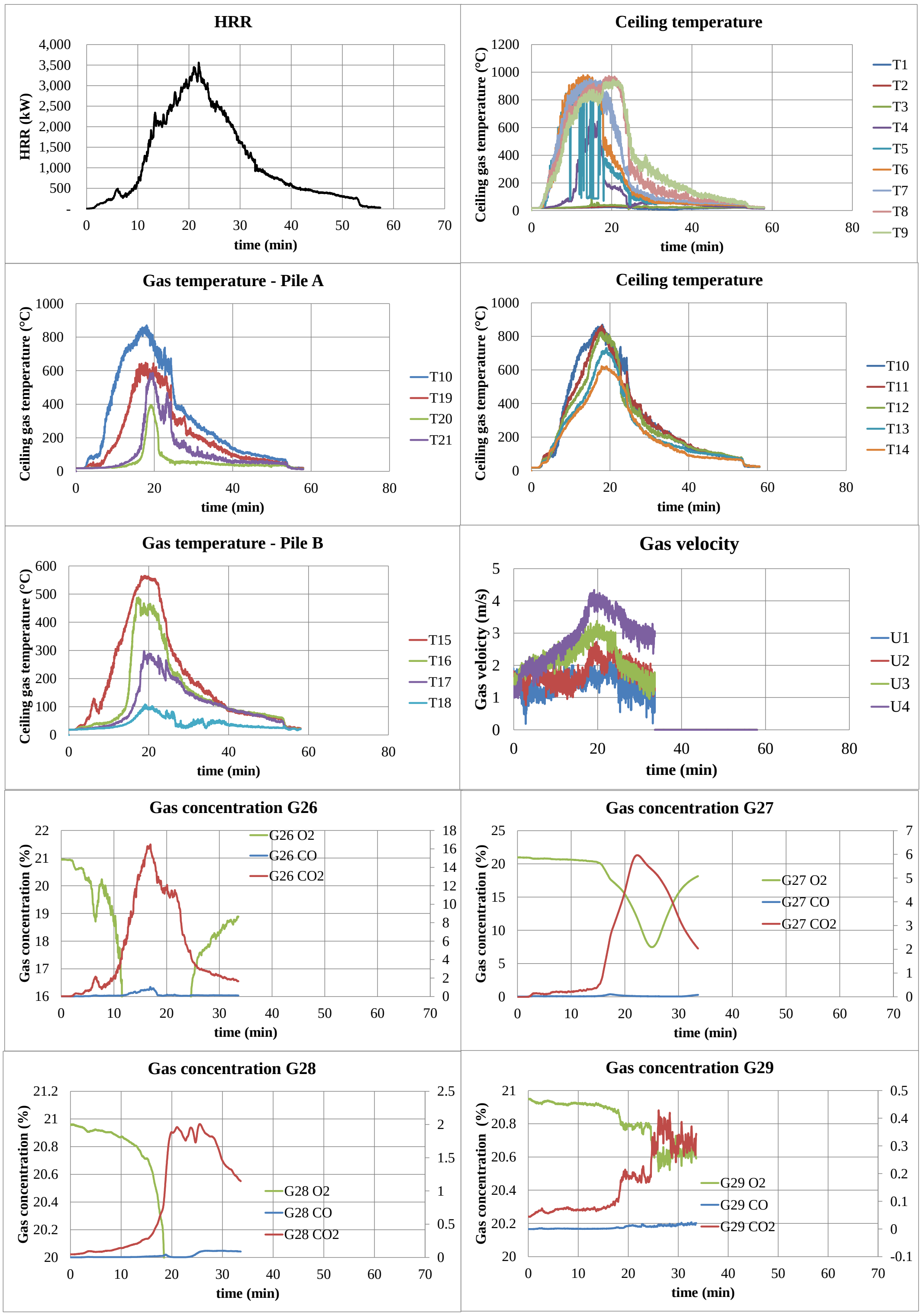

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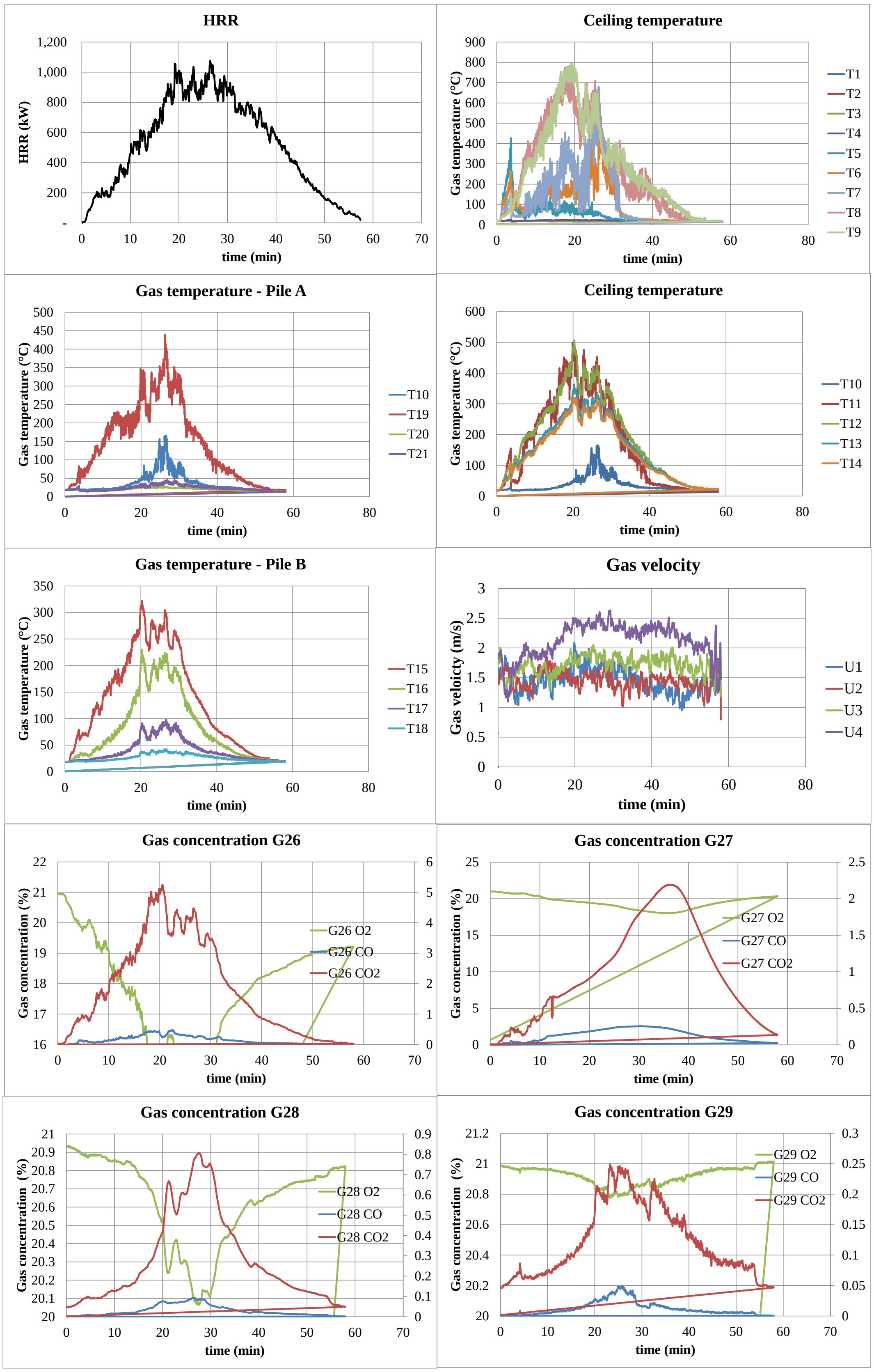

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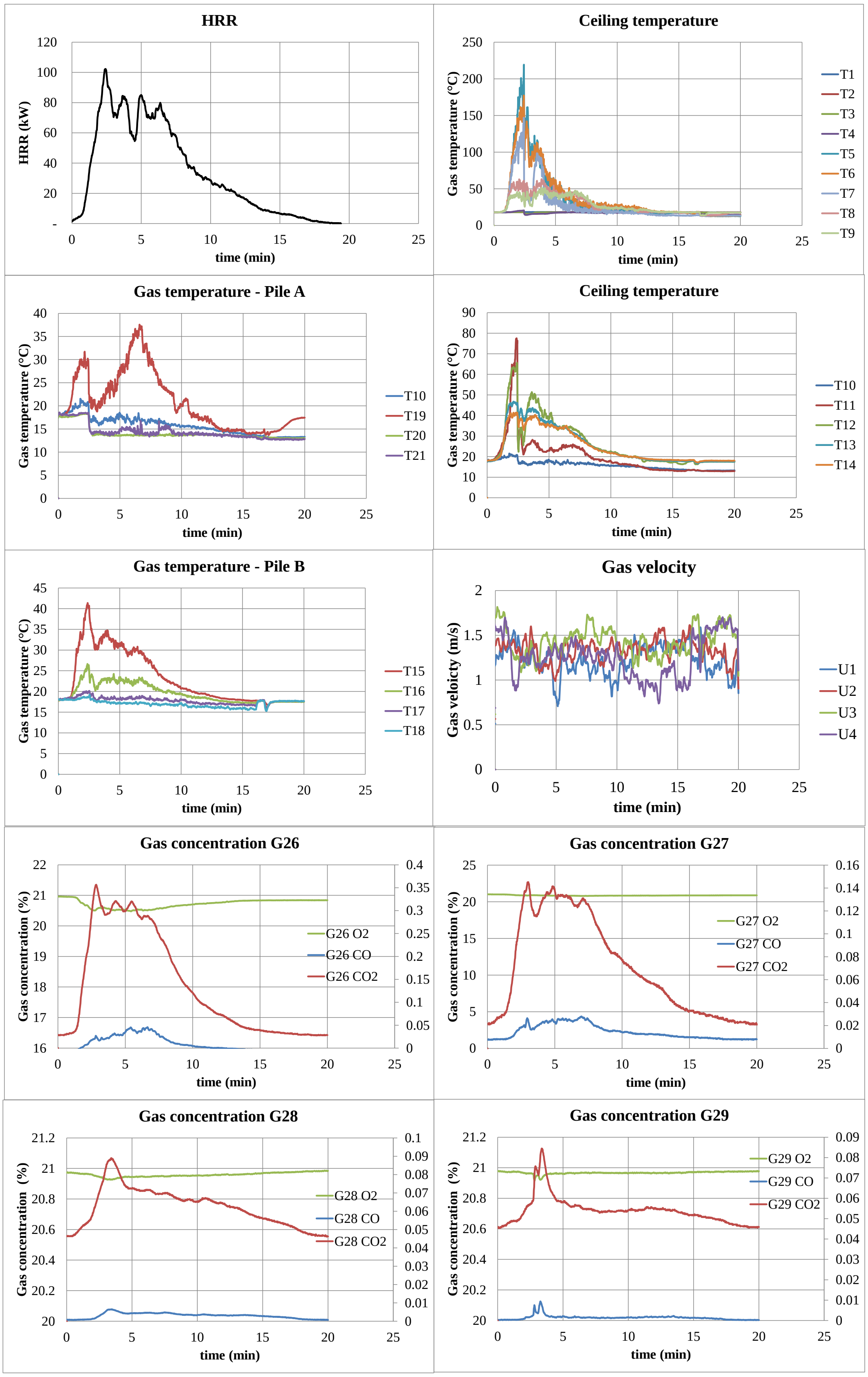

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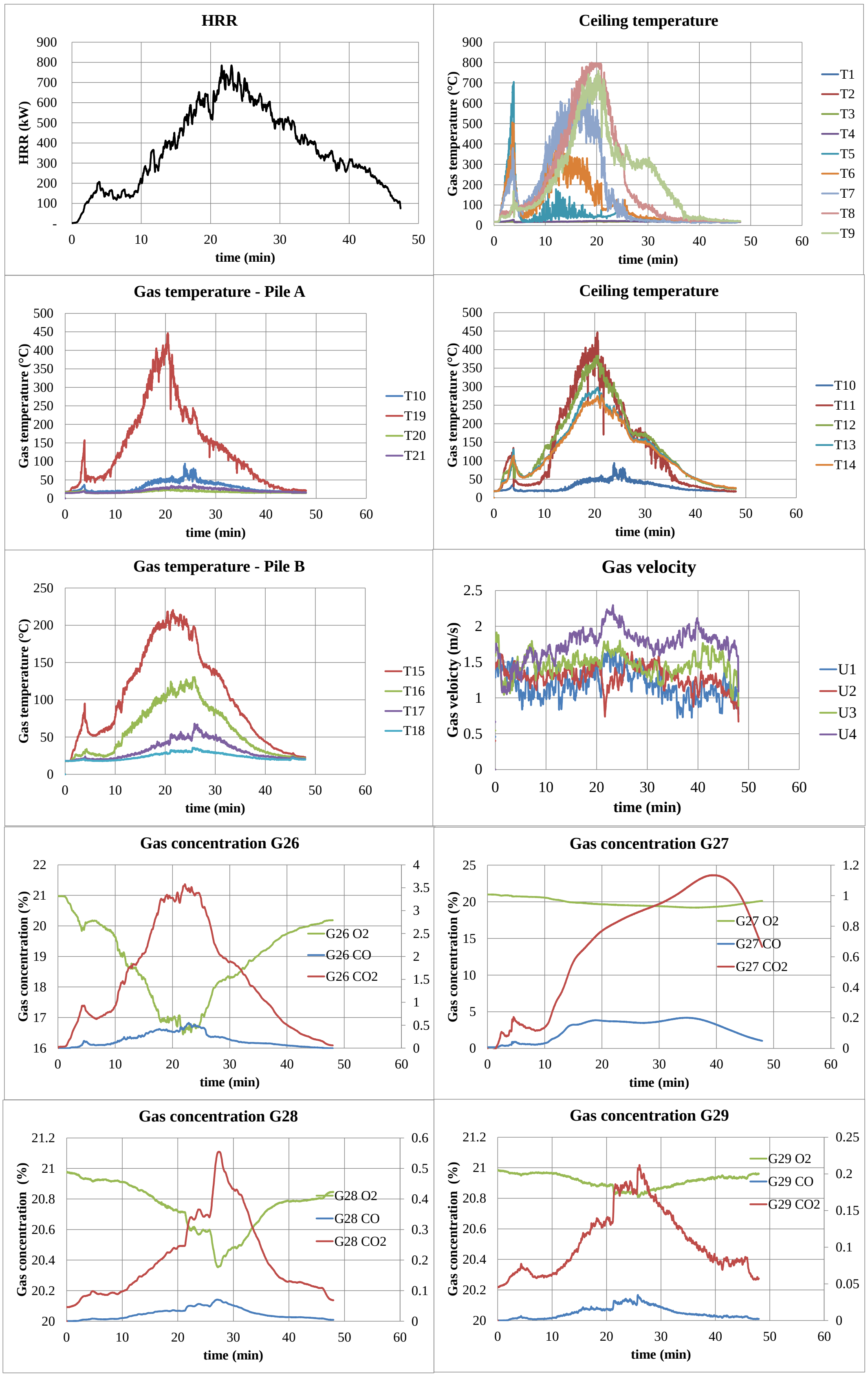

Figure C19 Test Results Test 18.

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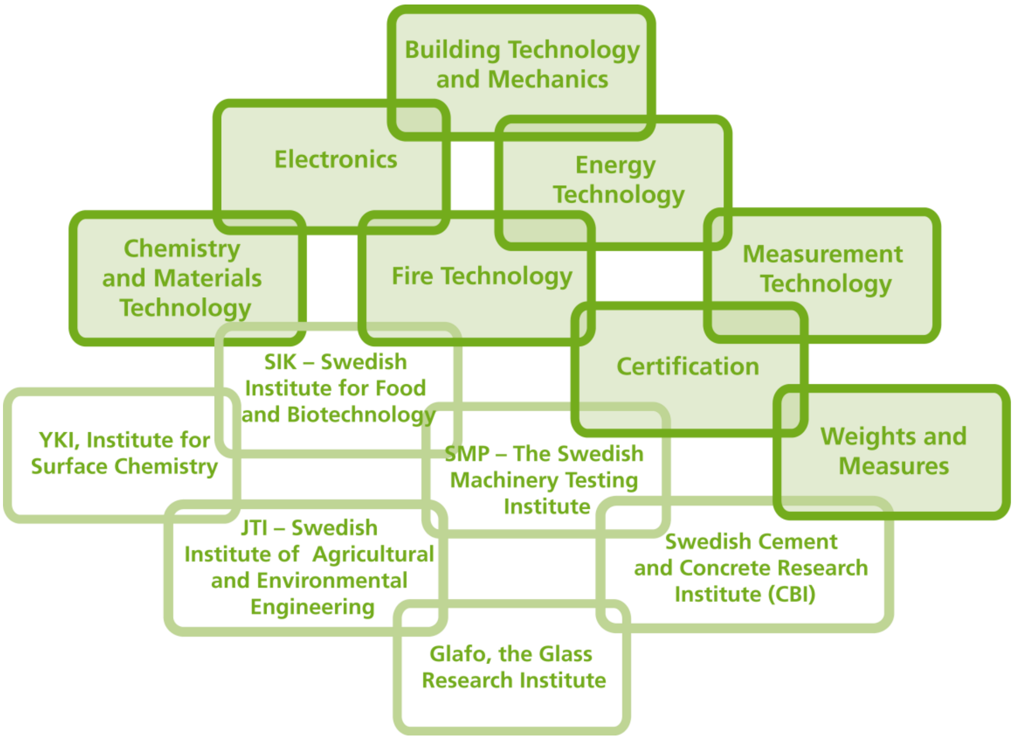

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