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Model Scale Railcar Fire Tests

Brandforskprojekt 404-011

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Abstract

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A series of tests have been performed in a model of a typical passenger train compartment (railcar). The tests were carried out on a scale of 1:10. The main purpose of the tests was to investigate if it is possible to calculate the heat release rate for a flashed over train compartment with simple mathematical expressions derived for ordinary compartment fires. The combustion that takes place outside the windows was considered in the study. The parameters that were varied include: the ventilation, the fuel loads and the type of interior surface material. In all tests, one door was open and the number of windows varied from all windows closed, to all windows open. The ignition took place in the corner of the model compartment opposite the door opening. The tests show that the fire development inside the model railcar is mainly controlled by the ventilation. The number of windows opened was found to be crucial for the fire development although the fuel load and the type of interior surface material did affect the fire development. The peak Rate of Heat Release (RHR) was about the same when all the windows were open at the time of ignition, independent of interior surface materials used. Different types of surface interior material resulted in different initial fire growth rates.

Key words: model scale, passenger railcar, fire development, RHR, train, fire

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Förord

På uppdrag av BRANDFORSK har SP Brandteknik genomfört modellskaleförsök i skala 1:10 med en tågvagn. Bakgrunden är att man har misstänkt att brandeffekterna från EUREKA-försöken har varit för låga på grund av den fuktiga miljön eller att brandgaserna som omger tåget kan påverka brandeffekten. Det har även funnits en misstanke att fönstren kan ha en avgörande roll för brandutvecklingen. Dessutom så ville man se om man teoretiskt kan beräkna brandeffekten i en övertänd vagn med enkla matematiska uttryck.

Ett stort tack till Magnus Bobert vid SP Brandteknik som har sammanställt observationerna från försöken (Appndix A) och plottat datan från försöken (Appendix B). Magnus har även ritat Figur 5. Ett stort tack till Michael Magnusson, Markus Lönnmark och Ari Palo-Oja vid SP Brandteknik som byggde och instrumenterade modellen.

Summary

Five tests have been performed in a model of a typical passenger train compartment (railcar). The tests were carried out in a scale of 1:10. The parameters varied were the number of windows that were opened, the fuel loads and the type of interior surface material. In all tests one door was open, and the number of windows varied from all windows closed, to all window opened. The model was constructed using non-combustible, 12 mm think, boards (Promatect H). The density of the boards was 870 kg/m^3, the heat capacity was 1,13 kJ/kg K and heat conduction was 0,19 kW/m K. It only considered the geometrical aspects of a railcar body (external measures of the steel body, windows and door opening). Seats and other details of the railcar were not considered.

The roof was made removable to allow replacement of inside surface materiel in the model between tests. The surface material that covered the walls, ceiling and floor consisted of plywood (see Figure 4) and corrugated cardboard, respectively. The main idea was to simulate different type of combustible surface material in a railcar. The materials chosen had different characteristics concerning flammability and thermal inertia.

The model scale tests show that the fire development is controlled to great extend by the ventilation. Therefore, the fire size depends on the railcar body integrity (steel, aluminium or glass fibre) and whether the windows and doors are intact. The surface interior material also has a great impact on the initial rate of fire growth. The fire development will also depend on the amount of combustible material inside the railcar compartment. The burn out time of the fuel has certain importance in the case when the windows do not fall out or shatter easily. Consequently, the openings, the flammability and the thermal response of the interior material and the total fuel mass determine the peak rate of heat release (RHR) and the time to reach it.

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1 Introduction

The fire development in passenger railcars has not yet been fully explored. The reason is that the number of large scale tests of passenger railcars that have been carried out is rather limited [1-5]. Large scale tests with railcars are expensive and such railcars are not usually easily available. The EUREKA 499 test program [1] in 1991 to 1992 in Norway included the only passenger railcars experimentally burned in a tunnel to date. The Rate of Heat Release (RHR) was measured for numerous types of passenger railcars, both steel and aluminium body railcars [6-8].

The peak RHRs obtained in the EUREKA 499 tests with steel body railcars were relatively low in comparison to a theoretically calculated peak RHRs in a fully developed compartment fire (post-flashover fire) [9-11]. Therefore, it is of interest to explore and understand why there is a discrepancy between the theoretically and experimentally obtained RHR. This is important when determining a design fire in a tunnel fire safety project.

Peacocks et al [3, 12-15] carried out a thorough investigation of the fire behaviour of American passenger railcars. The study, which included both small and large scale tests, demonstrated that a strong correlation exists between the Cone Calorimeter [16] data of interior material and flammability and smoke emission data obtained from other tests. This is a concept that has been introduced into American regulations [17].

A large research project on fire safety in trains (FIRESTARR) was carried out recently in Europe [18]. The FIRESTARR project was jointly funded by the European Commission and Industry. The main objectives were to identify the fire risks in European trains, to define the most relevant fire scenarios, to select the most suitable test methods for the assessment of reaction-to-fire behaviour and to propose a classification system for structural, furniture and electrotechnical material in trains.

Despite the numerous investigations and experimental activities that have been performed, there is still a lack of knowledge about which parameters affect the fire development in railcars. Ingason and Lönnermark [19] listed in a report to the Swedish Rail Administration the parameters that are thought to be important for the fire development in railcars. These include:

- body type (steel, aluminium, glass-fibre etc),
- fire resistance features of the windows,
- geometry of the openings (windows and doors),
- flammability and amount of interior material,
- initial moisture content of the interior material,
- construction of railcar joints,
- air velocity within the tunnel, and
- geometry of the tunnel cross-section.

The role of the openings and interior surface materials on the RHR in a passenger railcar needs to be investigated systematically. Large scale tests do not allow significant variation when investigating the influence of different parameters on the RHR. An alternative way to investigate parameter effects is to carry out model scale tests. Such tests can give answers to the physical behaviour of railcar fires under a variety of conditions. The results from such tests can be linked to large scale tests by using scaling laws [20]. This technique has been used for decades in fire research and can give a good indication of the levels of peak RHRs in large scale. There are limitations when concerning turbulence, thermal inertia of materials, incident heat radiation effects and fire spread, but this type of tests can give an indication of the principal fire behaviour in a railcar fire. In the analysis of the test data presented here, an order of magnitude comparison is made to large scale tests that have been performed in tunnels. To facilitate such a comparison, an overview of RHR data from large scale tests carried out in tunnels is presented in the following section.

The data presented in this report can be of importance for modelling work, such as presented by Lattimer and Beyler [11], where a post-flashover fire model was used to predict the RHR of a fully-developed fire inside of a railcar with plastic windows that burn away as the fire develops.

2 Overview of large scale tests in tunnels

In the following an overview is given of RHR data obtained from large-scale fire tests carried out. The literature describes very few measurements of RHRs for rail- and subway cars. The majority of the tests reported are from the EUREKA 499 test series [1]. In Table 1, a summary of the results from tests with RHR data is given and in Figure 1 a plot of available RHR as a function of time is given.

Table 1 Large scale experimental data on fully developed fires in railcars [21, 22].

Test nr	Type of vehicle, test series, test nr, u=longitudinal ventilation m/s	Calorific value (GJ)	Peak RHR (MW)	Time to peak RHR (min)	Reference
Rail					
1	A Joined Railway car; two half cars, one of aluminium and one of steel, EUREKA 499, u=6-8/3-4 m/s	55	43	53	Steinert [8]
2	German Intercity-Express railway car (ICE), EUREKA 499, u=0.5 m/s (steel body)	63	19	80	Steinert [8]
3	German Intercity passenger railway car (IC), EUREKA 499, u=0.5 m/s (steel body)	77	13	25	Ingason et al [6]
4	British Rail 415, passenger railway car*)	NA	16	NA	Barber et al. [23]
5	British rail Sprinter, passenger railway car, fire retardant upholstered seatings*)	NA	7	NA	Barber et al. [23]
Subway					
6	German subway car, EUREKA 499, u=0.5 m/s (aluminium body)	41	35	5	Ingason et al [6]

*) The original test report is confidential and no information is available on test set-up, test procedure, measurement techniques, ventilation, etc.

The test results presented in Table 1 and Figure 1 are based on tests with single passenger railcars. The peak RHR is found to be in the range of 7 to 43 MW and the time to reach the peak RHR varies from 5 to 80 minutes. If the fire were to spread between the railcars, the total RHR and the time to reach a peak RHR would be much higher than the values given here. One should recall, however, that it is not realistic to sum the RHR for each railcar, as the first car would not necessarily reach the peak RHR at the same time as the later ones.

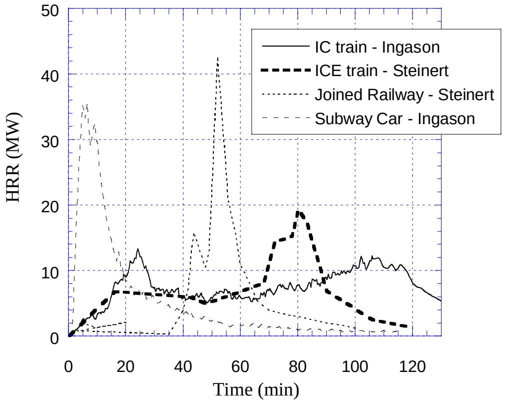

Figure 1 The RHR for the railcar tests presented in Table 1.

3 Theoretical considerations

It is of interest to determine the peak RHR in a ‘post-flashover’ steel body railcar located inside a tunnel and to investigate the influence of the geometrical shape of the railcar. The geometry of a railcar is considerably different from ordinary compartments. Flashover in a compartment has been explained as a thermal instability, caused by the energy generation rate increasing faster with temperature than the rate of aggregated energy losses [24]. Usually this phenomenon occurs during a short period and results in rapid increase of RHR, gas temperatures and production of combustion products. After a flashover has occurred in a compartment, the rate of heat release will develop to produce temperatures of 900 - 1100 ºC. The period after flashover is called the post-flashover stage or the fully-developed fire period. During this period the RHR is dictated by the oxygen flow through the openings and the fire is therefore said to be ‘ventilation controlled’[9]. The heat released depends upon the relative quantities of air available within the compartment. The air mass flow rate through the opening, $\dot{m}_a$, can be expressed in general terms [25] as:

$$\dot{m}_a = \rho_a \cdot \delta \cdot \sqrt{g} \cdot A_0 \cdot \sqrt{h_0} \qquad (1)$$

where δ is a proportionality constant which is a weak function of temperature, A_0 is the area of the opening (m^2) and h_0 is the height of the opening (m). The value of δ has been estimated to be 0.08 for pre-flashover fires and 0.13 for post-flashover fires [25, 26]. The value of $\rho_a \cdot \delta \cdot \sqrt{g}$ in the pre-flashover case (fuel-controlled) is 0.3 (kg/s $m^{-5/2}$) and 0.5 (kg/s $m^{-5/2}$) in the post-flashover (ventilation controlled) case assuming the density, ρ_a, is equal to 1.22 kg/m^3 and g equal to 9.81 m/s^2. The term $A_0\sqrt{h_0}$ is better known as the ’ventilation factor’ and originates from Bernoulli’s equation applied to density flow through a single opening [9].

Assuming that each kg of oxygen used for combustion produces about 13.1 x 10^3 kJ [27, 28] and that the mass fraction of oxygen in air is 0.231 we can approximate the maximum RHR that is possible within a compartment during the ventilation controlled stage. If we use the values given earlier in combination with equation (1), i.e., 13.1 × 10^3 × 0.231 × $\dot{m}_a$ where $\dot{m}_a = \delta\rho_a\sqrt{g}A_0\sqrt{h_0}$, we obtain the maximum RHR, Q_{max} (kW), within the compartment ($\delta\rho_a\sqrt{g}$ =0.5 kg/s $m^{-5/2}$) as:

$$Q_{\max} \approx 1500 A_0\sqrt{h_0} \qquad (2)$$

Here it is assumed that all the oxygen entering the compartment is consumed within the compartment. In many cases the rate at which air enters the compartment is insufficient to burn all the volatiles vaporising within the compartment and the excess volatiles will be carried through the opening with the outflowing combustion products. This is normally accompanied by external flaming outside the opening such as the one in figure 2.

(photo Tomas Karlsson)

Figure 2 A fully developed fire in a passenger railcar.

Equation (2) may underestimate the maximum RHR within the tunnel as excess volatiles are burned outside the railcar. Bullen and Thomas [29] have showed that the amount of excess fuel burning outside the openings is mainly dependant on the fuel surface area and the ventilation factor $A_0\sqrt{h_0}$. Thus, assuming that this factor is relatively constant for this type of geometry (a railcar) the maximum RHR according to equation (2) can be multiplied by a factor η determined from experiments.

$$Q_{\max} = \eta 1500 A_0 \sqrt{h_0} \tag{3}$$

An important question to answer here is why the RHR was so low in the EUREKA 499 tests for the steel bodied railcars. The estimated ventilation factor $A_0\sqrt{h_0}$ for tests 2 and 3 in Table 1 is 34 $m^{5/2}$. Thus, equation (2) gives Q_{max}=51 MW, which is considerably higher than the 13 MW and 19 MW that were actually measured.

One could expect that it is due to the windows. The fire development was probably controlled by the how the windows shattered during the tests. This can be partly observed when looking at the ceiling temperature development inside the Intercity (IC) railcar (test 3 in Table 1), see Figure 3. It can be seen that the peak temperatures inside the railcar moves along the ceiling as the fire spreads from left to the right. This indicates that the fire development is dominated by how the window shattered and in what sequence.

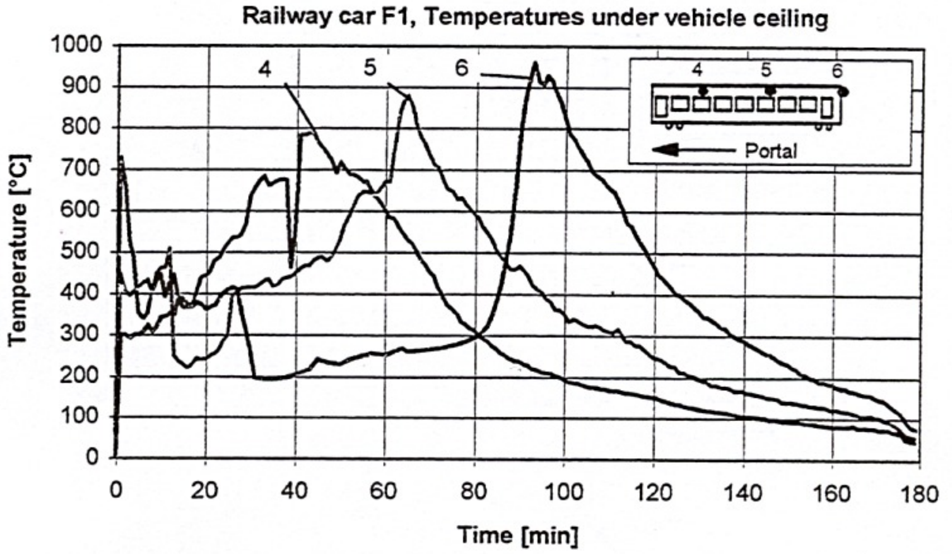

Figure 3 The temperature development inside the Intercity (IC) railcar test in the EUREKA 499 test programme [1].

This description of how the fires have progressed is partly confirmed by the results obtained by Lattimer and Beyler [11]. Their model is based on simple post-flashover considerations. They were able to predict the peak RHR which ranged from 14 – 41 MW for intercity and subway type of railcars. They showed that the peak RHR was sensitive to the initial number of doors opened, the time at which windows fell out and the fire properties of the interior materials.

The railcar model presented here was built to scale 1:10, which means that the size of the compartment is scaled geometrically according to this ratio. A Froude scaling technique is considered here [20, 30-33]. We do not consider the influence of the material thermal inertia and radiation effects on fire spread. We scale the RHR, the time, the energy and mass. The RHR will scale according the following equation:

$$Q_F = Q_M \left(\frac{L_F}{L_M} \right)^{5/2} \tag{4}$$

where L is the length scale and index M is related to the model scale and index F to full scale (L_M=1 and L_F=10 in our case). The time scale can be obtained with the following equation:

$$t_F = t_M \left(\frac{L_F}{L_M} \right)^{1/2} \tag{5}$$

where t is the time in seconds or minutes. The total energy released in the fire can be obtained with the following equation:

$$E_F = E_M \left(\frac{L_F}{L_M} \right)^{3} \frac{\Delta H_{c,M}}{\Delta H_{c,F}} \tag{6}$$

where E is the total heat content in MJ or GJ and ΔH_c is the heat of combustion. The total mass of the fuel can be scaled according to the following equation:

$$m_F = m_M \left(\frac{L_F}{L_M} \right)^3 \tag{7}$$

where m is the total mass of the fuel in kg.

A detailed description of the model is given in the following section.

4 Test set-up

The test set-up consisted of a 1:10 geometrically similar scale model of a Swedish intercity passenger railcar of type X2000. In Figure 4, a photo of the test-setup taken prior to the first test is shown. The ceiling has not been mounted at the time the photo was taken. The model was placed under a hood system which collected all the combustion gases.

4.1 Description of the model

The model was constructed using non-combustible, 12 mm think, boards (Promatect H). The density of the boards was 870 kg/m^3, the heat capacity was 1,13 kJ/kg K and heat conduction was 0,19 kW/m K. The roof was made removable to allow replacement of inside surface material in the model between tests. The surface material that covered the walls, ceiling and floor consisted of plywood (see Figure 4) and corrugated cardboard, respectively. The main idea was to simulate different types of combustible surface material in a railcar without specific consideration of scaling the thermal response of the material. The material chosen had different flammability and thermal inertia characteristics. The total energy and mass was scaled.

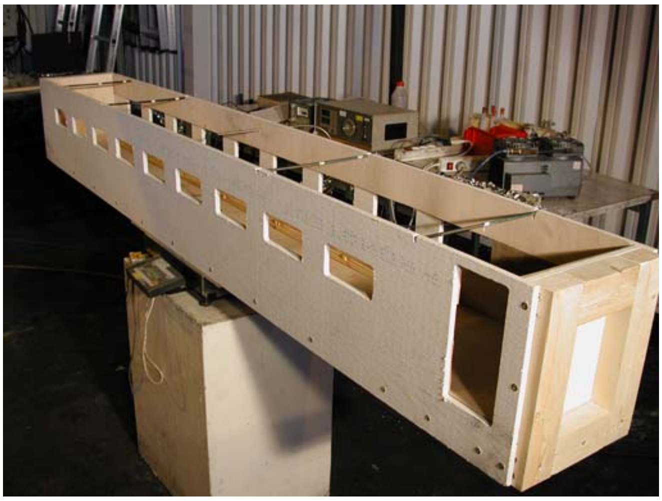

Figure 4 A photo of the test setup of the 1:10 scale model of a passenger railcar. The tests were performed at SP in February 2002.

Two wood cribs that were placed on the floor, simulating the seats on each side of the railcar. Each wood crib consists of three 1.8 m long wooden ribs (0,01 m x 0,01 m square cross-section) in two layers (total of six) and seven transverse 0.08 m long wooden ribs (with the same cross-sectional dimensions) placed in between the two layers. The arrangement of the cribs and geometrical dimensions of the model are shown in Figure 5.

The total weight of the wood cribs was about 1 kg and the moisture content was lower than 5 % since the cribs were dried in a furnace before each test. This corresponds to about 1 ton of fuel in large scale. Total weight of the plywood was about 5 – 5,5 kg and about 3 – 3,5 kg of the cardboard. This would correspond to a total mass of fuel of 3 – 5,5 ton. This is a reasonable value if compared to the fuel load in the intercity railcars tested in the EUREKA 499 test program. The energy content of the seats corresponds to about 12 MJ, which is about 12 GJ in a large scale assuming the same heat of combustion in both scales. The total heat content of the material used in each test (surface material and seats) was chosen to be in the range of a large scale railcar. Converted to large scale the fire load in the tests was about 60 GJ in the cardboard case and 95 GJ in the plywood case. In the EUREKA 499 test program the total heat content was 63 and 77 GJ, respectively for the intercity railcars (see tests 2 and 3 in Table 1). The ignition response of the interior surface material was also chosen to be varied. The difference in ignition time for these materials can be found in Tables 2 and 3. Note that the Plywood used in the tests was 3,5 mm and not 12 mm as in the Cone Calorimeter tests presented.

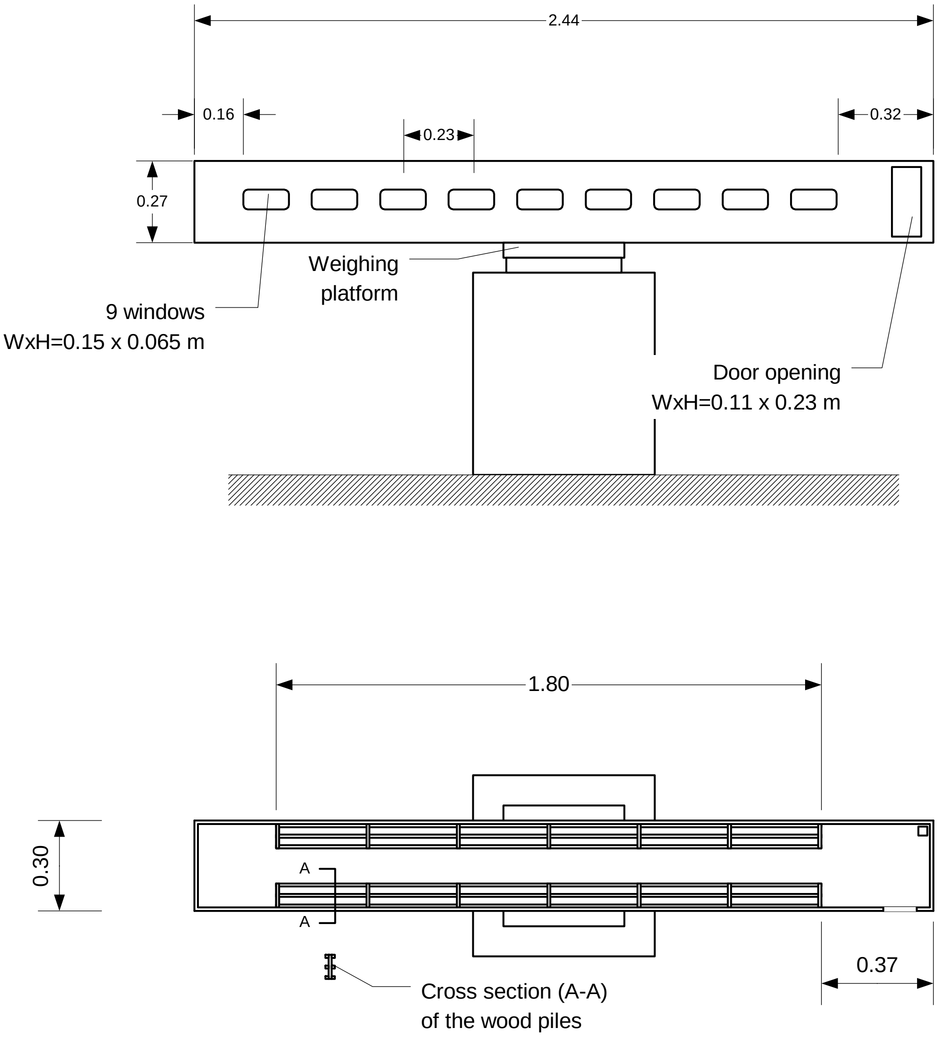

Figure 5 Geometrical dimensions of the 1:10 scale model of a passenger railcar. The upper drawing is a side view and the lower drawing is a birds-eye view.

An ignition source was located in the corner between the long side and the end of the railcar, opposite the opening for the door. The ignition source consisted of one 0,02 m x 0,02 m x 0,02 m fibreboard cube soaked in 15 mL heptane, placed adjacent to the wall material, as seen in Figure 6. The photo in Figure 6 is taken shortly after ignition.

Figure 6 The ignition source consisted of a fibreboard cube soaked in 15 mL heptane which was placed in the corner at floor level.

The interior surface material used, consisted of 3,5 mm thick plywood in the first two tests and double layers of 6,5 mm thick corrugated cardboard in the following three tests. The total thickness of the double layers of cardboard was 13 mm. The density of the plywood was calculated to be 623 kg/m^3 and the moisture measured to be 5 %. The density of the corrugated cardboard was calculated to be 126 kg/m^3 (measured the weight of a 0,1 m x 0,1 m piece of the 6,5 mm thick corrugated cardboard) and the moisture was less than 12 %. The floor, the end walls and the ceiling were fully covered with plywood and cardboard, respectively. For practical reasons, only the area above and below the windows was covered with combustible surface material resulting in a 0,065 m thick strip with no combustible material. This strip can be observed in Figure 7. The total surface area of combustible interior material was approximately 2,6 m^2.

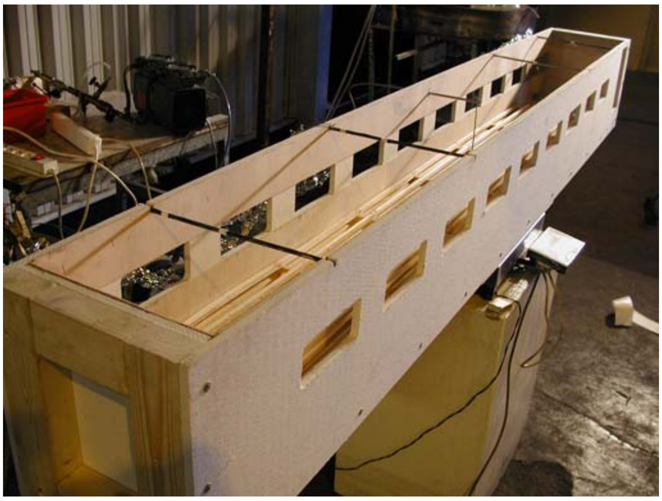

Figure 7 The figure shows how the plywood boards were mounted on the walls as well as the wood cribs along the floor. The model was placed on a weighing platform.

No Cone Calorimeter data is available for the surface material used here. However, corrugated cardboard of similar quality and thickness was tested in the cone calorimeter according to ISO 5660 by Lönnermark and Ingason [34]. The thickness of the corrugated cardboards tested in that case was 6 mm. Four tests were performed with an incident radiation of 50 kW/m^2. The average values from these four tests with 6 mm corrugated cardboard, are presented in Table 2.

Table 2 Results from the cone calorimeter tests for a 6 mm thick corrugated cardboard at 50 kW/m2 [34].

Parameter	**Average of 4 tests**
Time to ignition (s)	6
Max. rate of heat release (kW/m^2)	220
Average rate of heat release 3 min	120
Effective heat of combustion (MJ/kg)	16,3
Specific smoke production (m^2/kg)	14

There is no data available in the literature on 3,5 mm thick Plywood but such data is available on ordinary 12 mm thick Plywood (M23 in SBI RR) [35]. In Table 3, average values of 3 tests in a cone calorimeter at 50 kW/m^2 are given.

Table 3 Results from the cone calorimeter tests for a 12 mm thick ordinary Plywood board at 50 kW/m2 [35].

Parameter	**Average of 3 tests**
Time to ignition (s)	29
Max. rate of heat release (kW/m^2)	550
Average rate of heat release 3 min	134
Effective heat of combustion (MJ/kg)	11,6
Specific smoke production (m^2/kg)	62

4.2 Instrumentation

Various measurements were conducted during each test. The railcar model was placed on a weighing platform, which was connected to a data logging system recording the weight loss during the tests. During the test, the smoke and heat were collected into a calorimeter in order to determine the RHR from the fire. The ventilation in the hood was 10 000 m^3/h for all tests with the exception of test no.1, where the ventilation was 5000 m^3/h. The calorimeter was not able to collect all the smoke at the lower rate and after the first test the flow rate was increased from 5000 to 10 000 m^3/h. At this flow rate all the smoke gases released from the fire were collected.

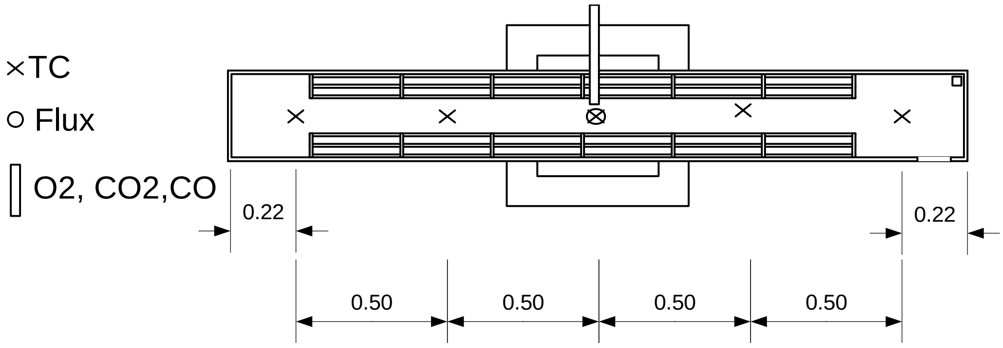

Figure 8 A birds-eye view of the layout of the instrumentation. The thermocouples (TC) were mounted 0,24 m above floor level. In the centre there was a heat flux meter at the floor level, a gas sampling tube and an array of thermocouples.

The temperature was measured with 0,25 mm type K thermocouples (TC) in the centre of the railcar and at 5 different levels from the floor: 0,03m (TC5), 0,08m (TC4), 0,135m (TC3), 0,19m (TC2), and 0,24m (TC1). An additional four TCs were located at level 0,24 m evenly distributed along the ceiling, TC6-TC9,. An exhaust pipe for gas sampling (O_2, CO_2, CO) was placed in the centre at level 0,24 m from the floor. Observe that the highest value that could be measured with the CO_2 device was 10 % and 3 % for the CO device. This is reflected in the plotted data in Appendix A as a straight horizontal line.

At floor level in the centre of the railcar, a water cooled heat flux meter of type Schmidt-Boelter, with a calibrated measuring range up to 20 kW/m^2, was placed to record the total heat flux towards to measuring probe at the floor level.

4.3 Test procedure

In total five tests were performed with different start and test conditions. In principal two parameters were varied between the tests. Two different interior surface materials were used at the ceiling, the floor and at the walls. During the tests different numbers of windows were opened, see table 4. These windows were opened when the fire visually started to decelerate, which means that they were not opened at a predetermined time.

The data logging system was started 2 minutes before ignition of the ignition source. The data was recorded every second. The time information given in the presentation of the results is related to ignition time at 00:00 (min:s). The development of the fire was registered visually (Appendix A) and, in tests 2 and test 5, the windows were opened during the test.

Table 4 Summary of test conditions

Start- and test conditions

Test no. →	1	2	3	4	5
Inside surface material	3.5 mm plywood	3.5 mm plywood	2 layers of 6.5 mm corrugated cardboard	2 layers of 6.5 mm corrugated cardboard	2 layers of 6.5 mm corrugated cardboard
Total weight of wall material (kg)	NR	5,3	NR	3,44	3,08
Total weight of wood cribs (kg)	1,12	NR	NR	0,97	0,91
Ambient temperature (ºC)	18	19	17	19	20
Windows at ignition	All opened	All closed	All opened	All opened	All closed
Door at ignition	Open	Open	Open	Open	Open
Sequence of opening of windows (min:s)		Time 5:17 –> 4 x 2 window opened Time 9:12 –> 5 x 2 window opened			Time 2:06 –> 4 x 2 window opened Time 4:35 –> 5 x 2 window opened
Flow rate in the calorimeter hood (m^3/h)	5000	10000	10000	10000	10000
Comments	Smoke leakage in the hood			Repetition of test 3	

NR – Not Registred

5 Test Results

The results from the tests are summarised in Table 5 and visual observations during each test are presented in Appendix A. All the measured data is presented in diagrams in Appendix B.

In Figure 9, a sequence of photos taken from test 4, is shown. The first picture shows when the flames start to emerge from the door opening and the first window. This occurred 30 seconds after the ignition. The flames impinge on the ceiling and spread towards the other end of the model compartment. Due to the incident radiation from the hot flames at the ceiling it starts to burn, followed by the floor and wall material. The flames begin to emerge from the first pair of windows when the fire spread on the floor was established. Finally the entire compartment was filled with flames and the fire reached its peak RHR. After about 3 minutes from ignition the entire compartment was flashed over. As can be seen in Table 5, the measured peak RHR occurred after 3,9 minutes. All the combustible material inside the model compartment was ignited and the fire became ventilation controlled.

Table 5 Summary of the test results of the model scale tests of a railcar compartment fire.

Test results – Model scale

Test no. →	1	2	3	4	5
Inside surface material	plywood	plywood	corrugated cardboard	corrugated cardboard	corrugated cardboard
Windows at ignition	all open	all closed	all open	all open	all closed
Peak RHR (kW)	148	136,5	142,8	147,6	113,2
Time to reach peak RHR (min)	6,5	11,1	3,8	3,9	6,5
Total energy released (kJ)	97828	96735	62359	62081	57451
Total mass consumed according to weight measurements (kg)	9,58	NA	4,8	4,2 (4,41)*	4,5 (3,99)*
Peak ceiling temp (ºC)	914	921	871	942	962
Peak radiation (kW/m^2)	74,2	71,2	63,4	68,1	63,7
Oxygen level at peak RHR (%)	0	0	0	0	0

Results converted to large scale

Peak RHR (MW) Eqn (4)	46,8	43,2	45,2	46,7	35,8
Time to reach peak RHR (min) according to Eqn (5)	20,6	35,1	12	12,3	20,6
Total energy released (GJ) Eqn (6) assuming same ΔH_c in both scales	97,8	96,7	62,4	62,1	57,5
Total mass consumed (kg) according to Eqn (7)	9580	NA	4800	4410	3990

NA – Not Available
* see Table 4

t= 0:38 min:s

t=1:00 min:s

t=1:03 min:s

t=1:05 min:s

t=1:28 min:s

t=1:51 min:s

t=2:14 min:s

t=2:25 min:s

t=2:44 min:s

t=3:01 min:s

Figure 9 The fire development in test 4 with corrugated cardboard.

6 Discussion of results

The tests show that the openings (windows) play a major role in the development of the fire and that the type of surface interior material influences the initial fire growth rate. Once the initial fire had been established and started to spread along the railcar (flames out of the first windows) the slopes of the RHR became quite similar. The peak RHR was about the same when all the windows were open at the point of ignition, independent of interior surface materials used. In Figure 10, a comparison is shown for test 3 and test 4 with two layers of 6,5 mm thick corrugated cardboard and one test with 3.5 mm plywood (test 1). Test 4 was a repetition of test 3 which can be seen in the results shown in Figure 10. The two curves overlap each other very well. The fire development was much faster with the low density material (cardboard) compared to high density material (plywood). This agrees well with the results of the Cone Calorimeter tests for corresponding materials (Table 2 and 3) concerning ignition times, although one should remember that the Plywood test in the Cone Calorimeter presented in Table 3 was 12 mm thick and not 3,5 mm thick as was used in the tests.

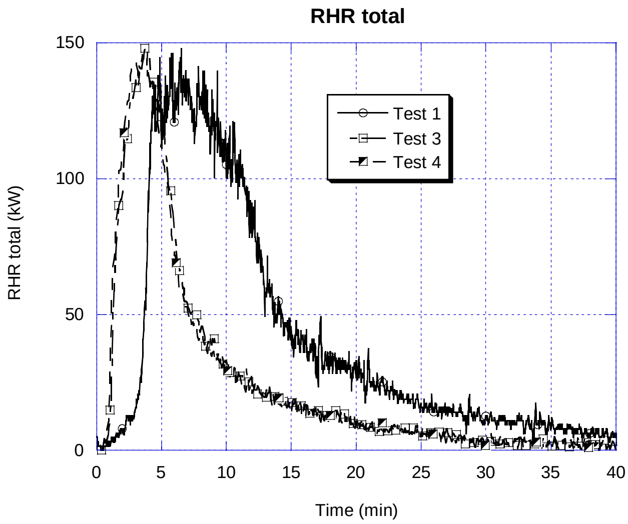

Figure 10 The measured RHR for tests with open windows and a door at ignition.

The average value of the 3 minute RHR Cone Calorimeter values for plywood and corrugated cardboard is 127 kW/m^2 (i.e., (120+134)/2=127 kW/m^2).If we multiply this value with the total fuel surface area, 2,6 m^2, we obtain 330 kWs, which is considerably higher than the average value of 146,6 kW measured for the three tests. The reason for this discrepancy is related to the ventilation control of the fire. The oxygen levels at the ceiling become depleted to zero in all the tests (Table 5), which shows that the fire was ventilation controlled when the peak RHR occurred.

Estimates using equation (2) show that the theoretical peak RHR value is equal to 85,3 kW using a ventilation factor of $A_0\sqrt{h_0}$ = 0,0447 m$^{5/2}$. When all windows are open at ignition, the peak RHR is on average 72 % (146,6 kW/85,3 kW= 1,72) higher than the value obtained according to equation (2). This means that 42 % of the total fuel vaporised within the coach (assuming that all the oxygen in the entrained air is consumed within the coach), is burned outside the openings. Bullen and Thomas [29] have showed that the amount of excess fuel burning outside the openings is mainly dependent on the fuel surface area and the ventilation factor $A_0\sqrt{h_0}$. Thus, assuming that this factor is relatively constant for this type of geometry (an intercity railcar) the peak RHR according to equation (3) can be multiplied by a factor of η =1,72. This requires that all the windows have shattered at the time of peak RHR and that a burn out of the fuel inside the compartment has not started.

The average peak RHR in the model scale (146,6 kW) corresponds to a RHR in large scale of 46,4 MWs (equation 4). This is considerably higher than the peak RHR that were obtained in the EUREKA 499 tests with the Intercity trains. From Table 1 we can see that the peak RHR were 13 MW and 19 MW, respectively. The reason for these low values can be related to the fact that the test was carried out with the windows closed at ignition.

In the following, a description is given of the RHR development when windows were opened in a sequence. After the ignition, the first 4 windows on each side were not opened until the fire visually started to decelerate. During this period, the only ventilation was through the door opening. In Figure 12 we can see that peak RHR during this period was not more than 11 kW for test 5 (i.e. η =0,61) and not more than 6 kW for test 2 (η =0,33). Equation (2) yields peak RHR equal to 18 kWs ($A_0\sqrt{h_0}$ =0,0121 $m^{5/2}$). As can be observed in Figure 12, after the 4 windows where opened, the fire started to grow again. The fire reached a new peak RHR value in both tests and started to decelerate again before the rest of the windows were opened on both sides. During this period, the peak RHR was about 60 kW in test 5 (η =1,25) and 70 kW in test 2 (η =1,45). The peak RHR according to equation (2) is 48,1 kW ($A_0\sqrt{h_0}$ =0,0321 $m^{5/2}$). When the last 5 windows on each side were opened (all windows open) the fire started to grow again and reach a new peak value at 136,5 kW in test 2 (η =1,6) and 113,2 kW in test 5 (η =1,33). The peak value in test 5 is quite close to the calculated value using equation (3) (η =1,72), whereas the peak RHR is much lower in test 5. The reason is simply that the fuel (interior surface material made of corrugated cardboards) in test 5 started to burn out before the fire reached to the other end of the model compartment. This value is slightly higher than was obtained in the measurements. The results obtained indicate that η increases as the fuel surface area and $A_0\sqrt{h_0}$ increases. These results are therefore in line with what Bullen and Thomas [29] obtained in their study.

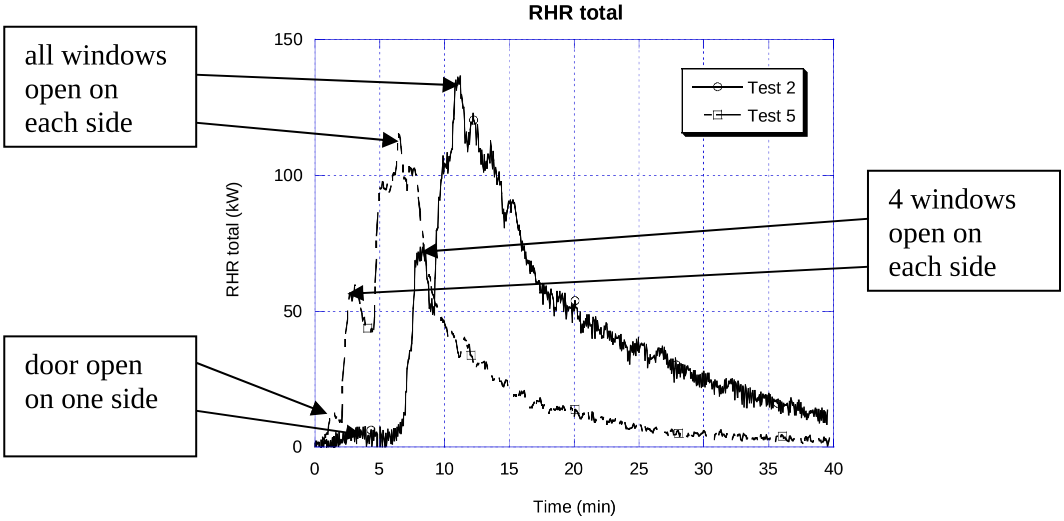

Figure 11 The RHR for tests with closed windows and a open door at ignition.

It is clear from the data presented here that the fire development is controlled to a great extend by the ventilation (openings). Even if the interior material is flammable the fire will not grow to higher RHR values than the ventilation allows. Therefore, the fire size will be dependent on the railcar body integrity and whether the windows and doors are intact. It will also depend on the amount of combustible material inside the railcar compartment. The burn out time of the fuel has certain importance (for the value of the peak RHR) in the case when the windows do not fall out or shatter easily due to heat radiation (as was probably the case in the EUREKA tests presented in Table 1). The results show that the fire development can be reconstructed by regarding the opening times of every individual door or window. This type of procedure has already been performed by Lattimer and Beyler [11] with good results. The opening geometry, the flammability and the thermal response of the interior material and the total fuel mass determine the peak RHR and the time to reach it. Conclusively, an important parameter to consider here is the interaction of heat radiation and the tendency of the windows to shatter.

The peak RHR that was measured in the tests when all windows had been opened was found to vary between 113 kW (36 MW in large scale) and 148 kW (47 MW in large scale). The reason for a lower peak RHR of 113 kW is the effect of burn out of the fuel occurring when windows where opened in a sequence. In the case when all windows were open at ignition the peak RHR varied only between 143 to 148 kW. Two type of interior fuel surface material were tested: one which was easy to ignite (cardboard), and one which was thermally more inert (plywood). The time to reach a peak value was 3,9 minutes (12 min in large scale) with cardboard and 6,5 minutes (20 min in large scale) with plywood. If the windows had been kept closed all the time but one door opened the peak RHR would not have been higher than 11 kW (3,5 MW). With only four windows and the door open the peak RHR was only 60 kW (19 MW) and 70 kW (22 MW), respectively.

In the tests the maximum ceiling temperature inside the railcar was found to be in the range of 871 – 962 ºC. The corresponding maximum incident heat radiation towards the floor level was measured to be in the range of 63 kW/m^2 – 74 kW/m^2. In all the tests the oxygen concentrations at ceiling level was reduced to zero within 2 – 5 minutes and the CO_2 and CO measurements hit the limits of their measuring ranges, i.e. 10 % and 3 %, respectively.

7 Conclusions

A series of test were performed in a model of a typical passenger train compartment (railcar). The tests were carried out in a scale of 1:10. The parameters varied include: the number of windows that were opened, the fuel loads and the type of interior surface material. A complete correspondence between large scale and model scale is not possible to obtain due to lack of scaling of turbulence intensity, thermal response of interior materials and radiation effects. The tests presented, however, do give a realistic picture of the principals of fire development in railcars. A more realistic time scale of the fire development can only be obtained by large scale testing.

The most important parameters for the development of the fire, provided that the interior surface material exhibits sufficient flammability, is the body type of the railcar and the quality and mounting of the windows. As long as the windows or doors do not break or fall out (and there are no other large openings) and/or the fire does not burn through the ceiling, the fire is expected to develop relatively slowly. The fire may even decelerate and finally self extinguish due to low oxygen levels if no or very small openings are created. This will occur even if the interior material is relatively flammable. On the other hand, when the windows break, the fire can spread and increase in intensity very quickly. Therefore, the peak RHR will depend to a large extent on the body structure and the ventilation through the openings. This, of course, assumes that the interior material has a certain level of flammability and energy in order to support fire spread within the railcar. The surface interior material was found to influence the initial rate of fire growth and the fire duration. The burn out time of the fuel has certain importance in the case when the windows do not fall out or shatter easily. In summary: the ventilation, the flammability and the thermal response of the interior material and the total fuel mass determine the peak RHR and the time to reach it.

The fire development can be reconstructed by assuming opening times of every individual door or window and by considering the burn out time of the fuel. The amount of excess fuel burning outside the railcar compartment will be dependent on the ventilation factor and the fuel surface area related to the openings. An important parameter when considering the fire development is the interaction of heat radiation and the tendency of the windows to shatter. In a tunnel fire this interaction may be enhanced by flames leaping along the tunnel ceiling.

One interesting aspect for future research is what would happen if two doors where open? This was not tested here but one would expect that it would have a certain importance on the potential for a fire to development inside the railcar.

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Appendix A Observations during tests

Test no. 1 All windows open, plywood

Time (min:s)	Event, observations
-02:00	Start of data logging system
00:00	Ignition
01:43	Flames out from the door opening
02:45	Smoke from all windows
03:03	Smoke layer in the roof at the upper edge of the windows
03:36	Flames out from window
04:03	Flash over
04:29	Wood seat ignited
09:00	Complete flash over.

Test no. 2 All windows closed at ignition, plywood

Time (min:s)	Event, observations
-02:00	Start of data logging system
00:00	Ignition
02:00	Flames out from the door opening
02:30	Flames towards the second window
03:00	Smoke layer half enclosure
04:30	The fire have decreased in the corner
05:17	The four windows nearest the door was opened
06:00	The fire have decreasing
06:37	A piece of tape was removed, could maybe affect the fire
06:53	Flames from door opening and the first window
07:14	Flash over in two windows, the floor is burning
08:21	Woodpile is burning
09:12	Remaining windows was opened
10:45	Flash over in seven windows
11:00	Flash over in eight windows
12:15	Flash over in nine windows
12:30	Complete flash over
13:20	Flames evenly distributed in all windows

Test no. 3 All windows open at ignition, 13 mm corrigated cardboard

Time (min:s)	Event, observations
-02:00	Start of data logging system
00:00	Ignition
00:15	Ignition at the ceiling
00:34	Flames out from the door opening
00:45	Flames in the ceiling towards the third window
01:08	Ignition at the floor
01:25	Woodpile is burning
01:35	Flames out from three windows, the floor is burning
01:45	Flash over half the compartment
02:03	Flames out from five windows, the floor is burning
02:31	Flames out from seven windows, the floor is burning
02:45	Flames out all windows
02:56	Complete flash over
03:06	Fire decreasing at the door opening
03:26	The entire compartment flahshover
04:50	No fire at door opening up to first window

Test no. 4 All windows open at ignition, 13 mm corrigated cardboard. Repetition of test no. 3

Time (min:s)	Event, observations
-02:00	Start of data logging system
00:00	Ignition
00:10	Ignition in the ceiling
00:25	Flames in the ceiling towards the second windows
00:29	Flames out from the door opening
00:49	Flames in the ceiling towards the third window
00:56	Ignition at the floor
01:06	Flames out from three windows, the floor is burning. Woodpile is burning
01:25	Flames out from five windows
01:42	Flames out from six windows
01:50	Flames out from seven windows, floor and wood pile burning towards sixth window
02:12	Flames out from eight windows
02:32	Flames out from nine windows, the entire floor is burning
02:44	Complete flash over
03:40	Fire decreasing at the door opening
04:03	Laminar flames out of the windows
04:42	Slightly more flames out of the front side

Test no. 5 All windows closed at ignition, 13 mm corrigated cardboard

Time (min:s)	Event, observations
-02:00	Start of data logging system
00:00	Ignition
00:18	Flames out from the door opening, flames in the ceiling
01:15	Ignition in the floor
02:06	The four windows nearest the door was opened
04:03	Flames out from all opened windows
04:35	Remaining windows was opened, only fire towards fourth window
05:14	No fire at the door opening

Appendix B Test results

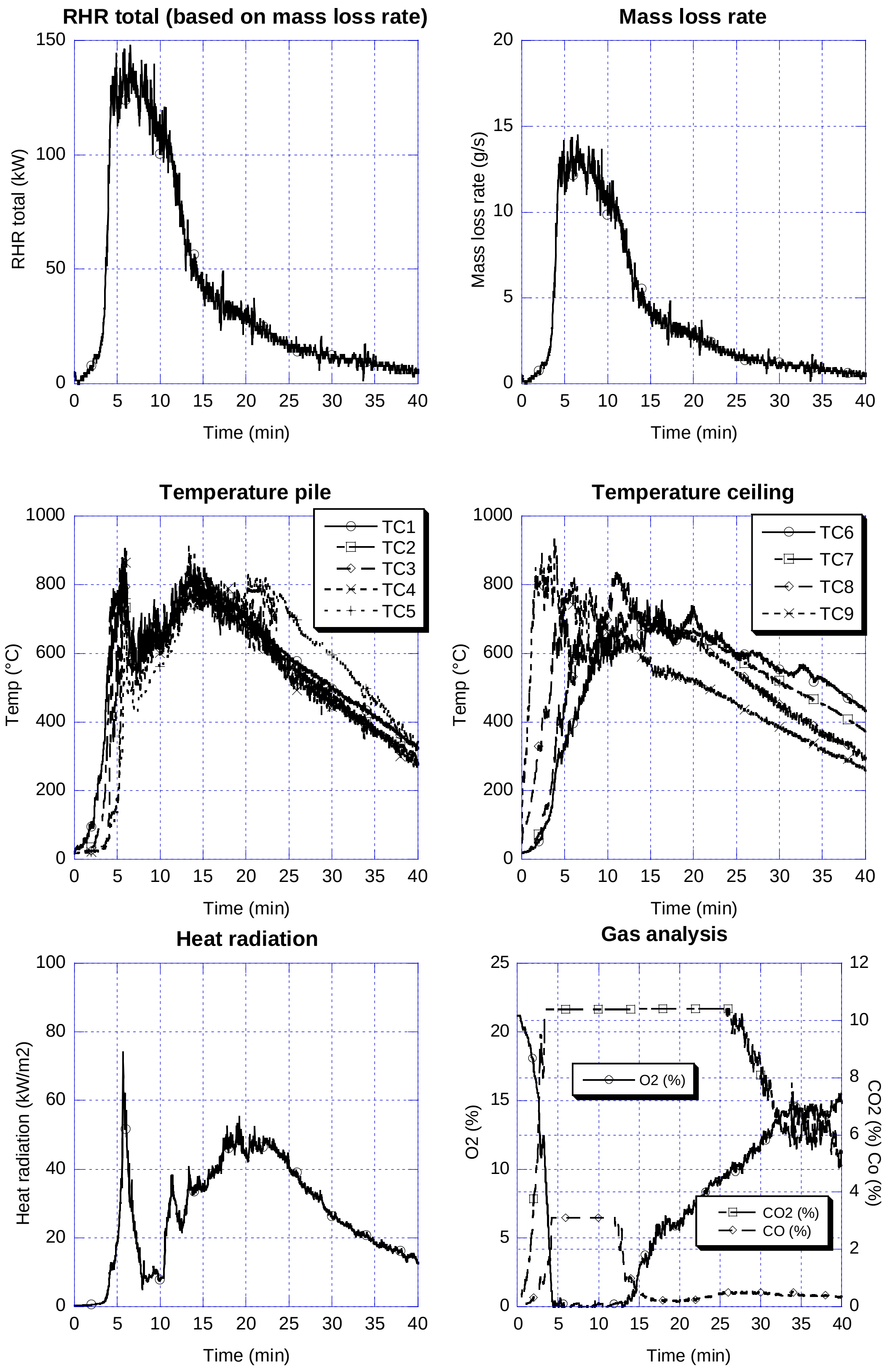

Figure B1 The test results from test 1 using 3.5 mm plywood on the walls and ceiling.

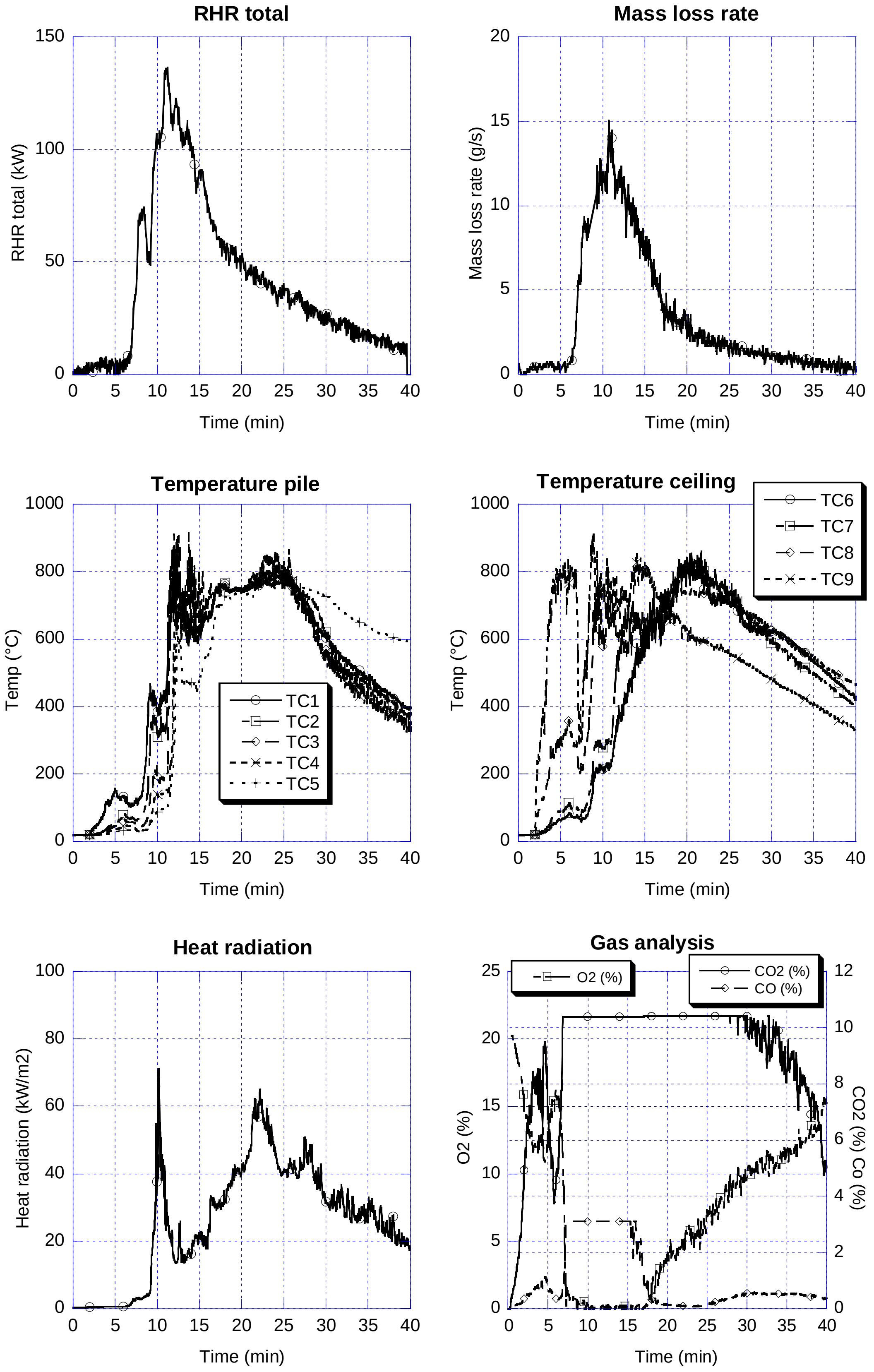

Figure B2 The test results from test 2 using 3.5 mm plywood on the walls and ceiling. All windows closed at ignition. The first eight windows opened at 5:17 min:s and the last ten windows opened at 9:12 min:s .

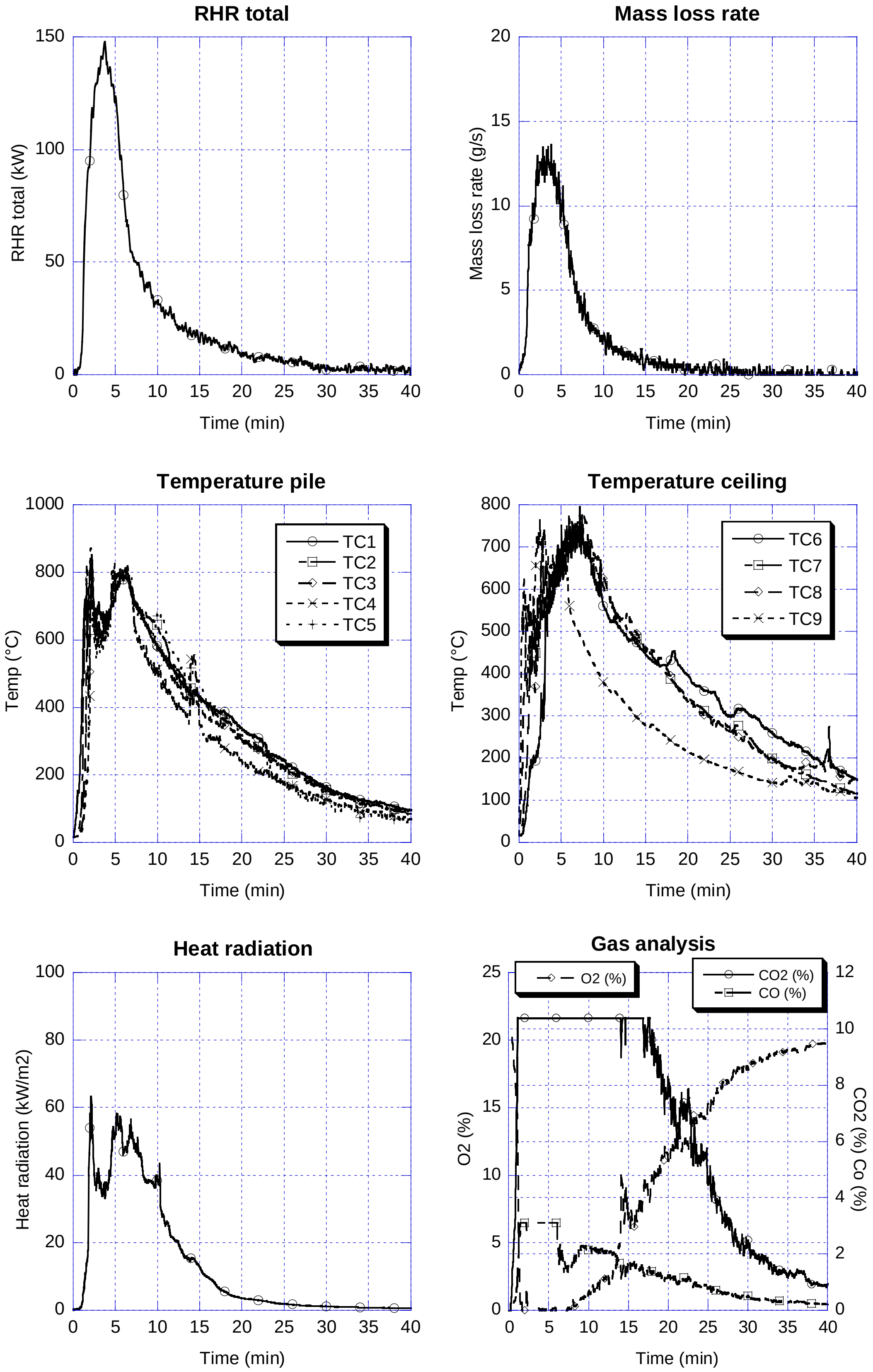

Figure B3 The test results from test 3 using 13 mm corrugated cardboard on the walls and ceiling. All windows open at ignition.

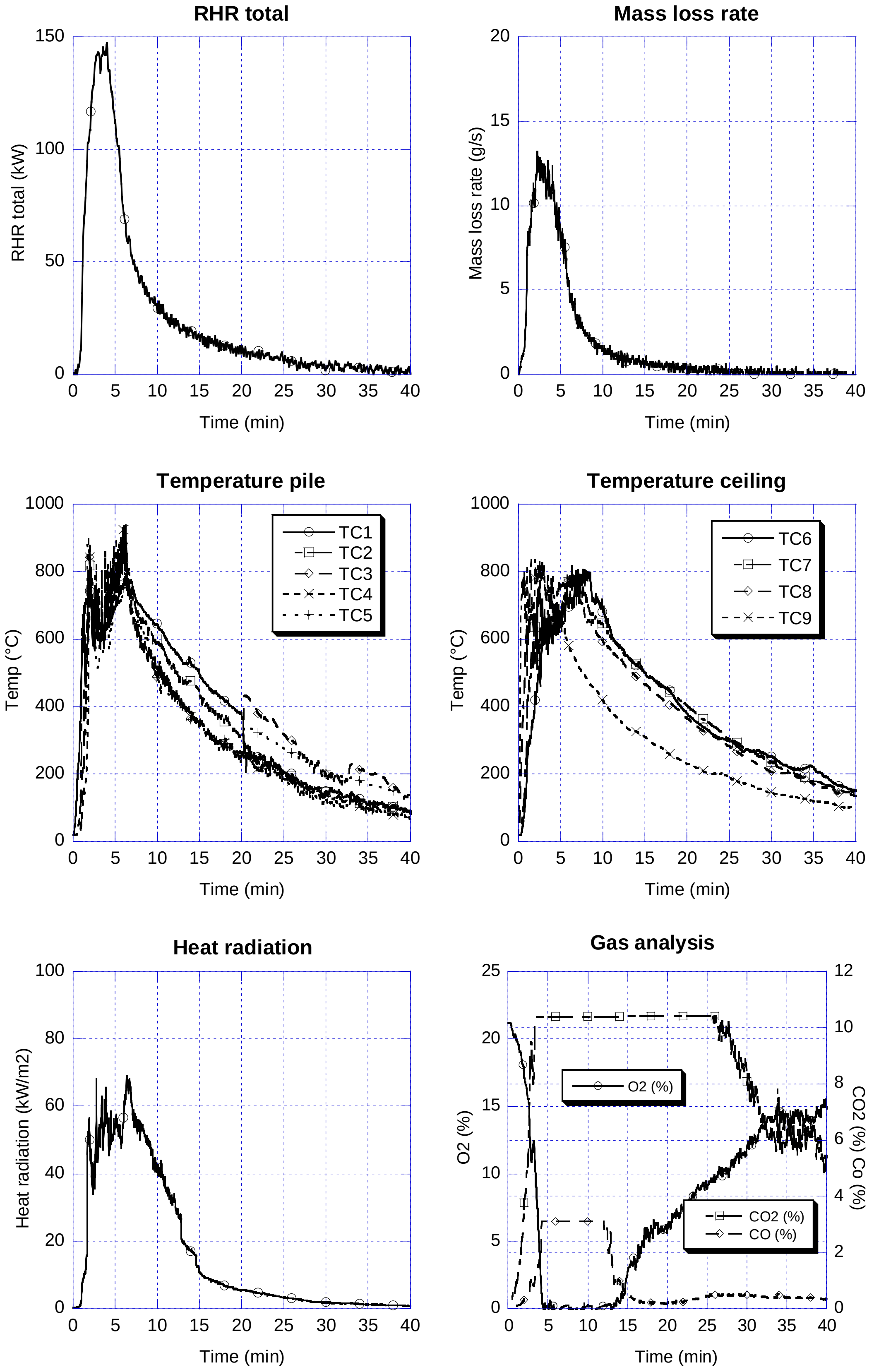

Figure B4 The test results from test 4 using 13 mm corrugated cardboard on the walls and ceiling. All windows open at ignition.

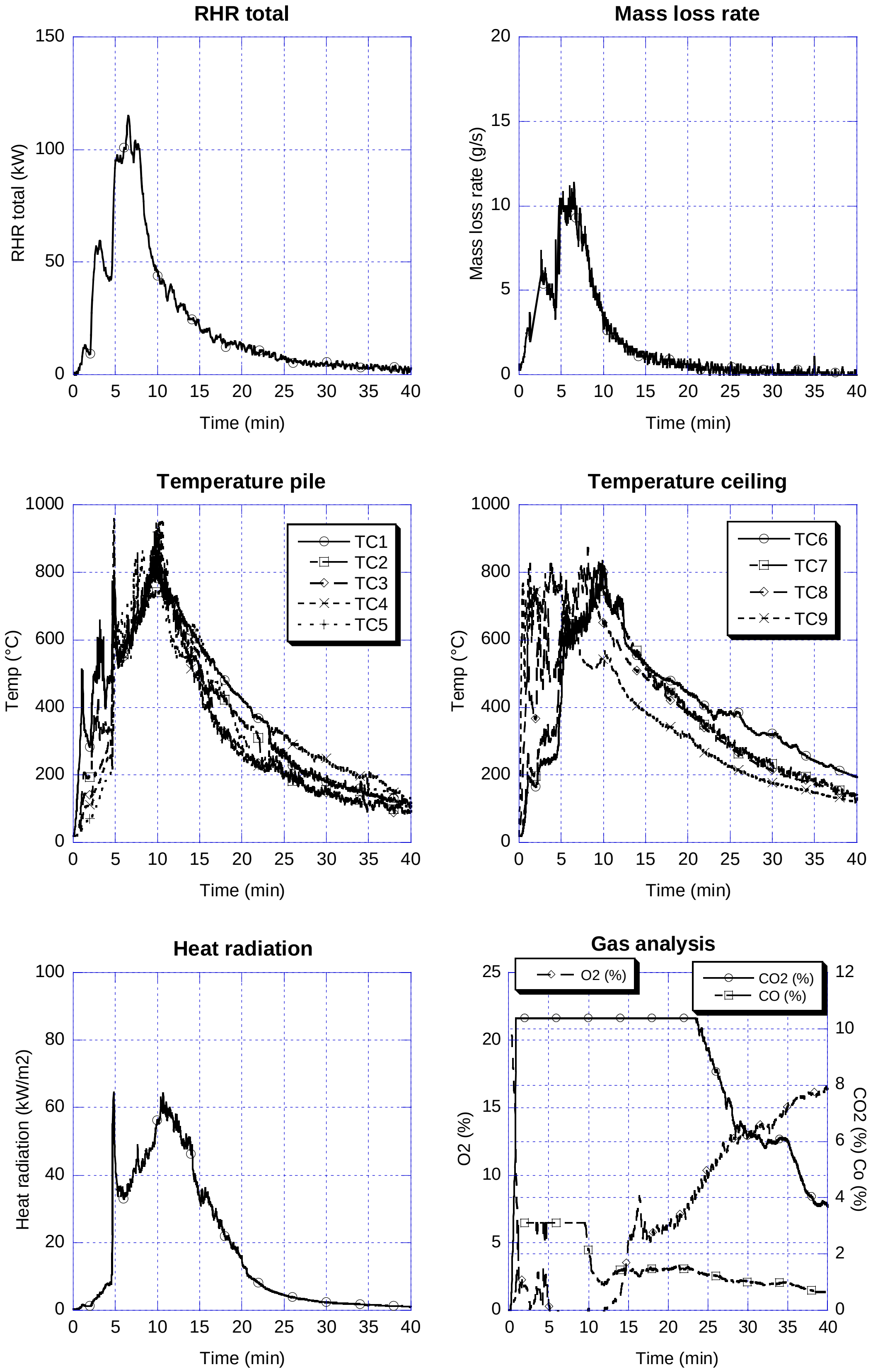

Figure B5 The test results from test 5 using 13 mm corrugated cardboard on the walls and ceiling. All windows closed at ignition. First eight windows opened at 2:06 min:s and the final ten opened at 4:35 min:s.

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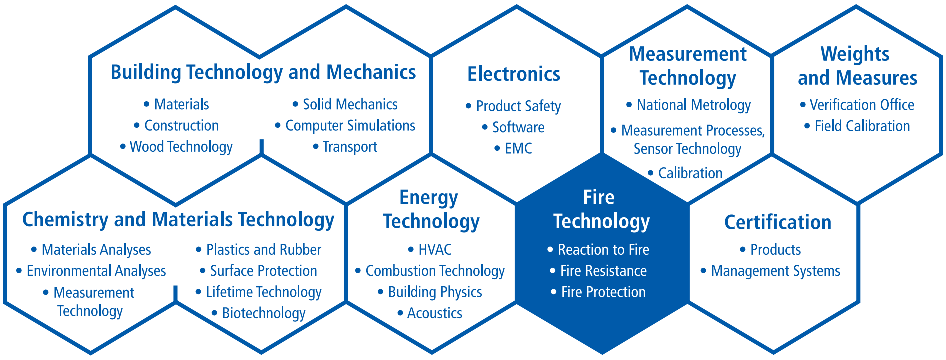

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