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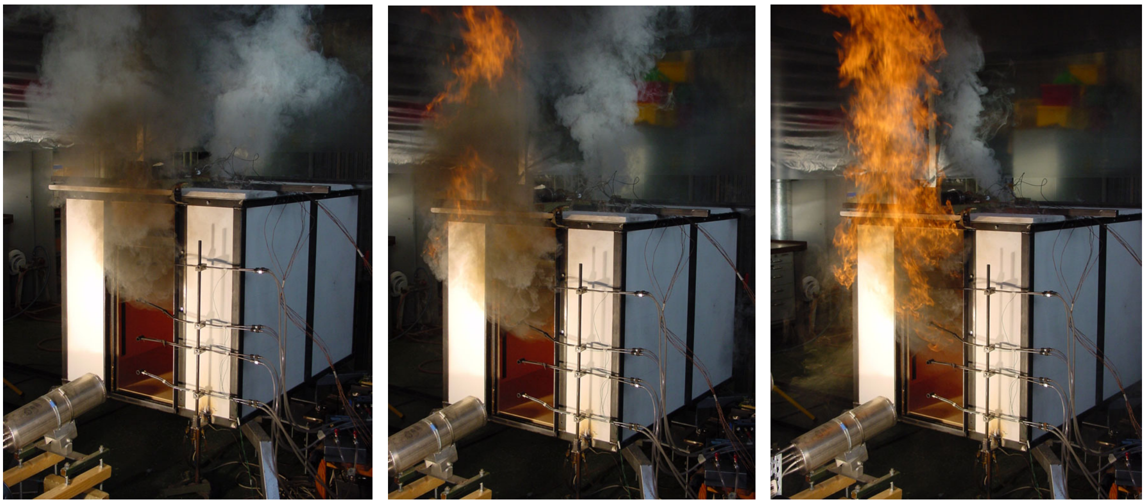
Technical report

Per Walmerdahl, Per Werling

Fire growth and spread – an experimental study in model-scale



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Report title

Fire growth and spread - an experimental study in model-scale

Abstract (not more than 200 words)

An experimental study in model-scale has been performed to investigate compartment fire growth and fire spread between compartments.

Initially a series of compartment fire growth tests were performed to study how different ignition sources will affect the time to flashover in a compartment with combustible linings. Further experiments were conducted to investigate both vertical and horisontal fire spread between compartments. Ventilation conditions were varied in order to resemble the situation onboard a ship or in an underground facility. A short evaluation of the compartment fire tests was done showing that flashover occurred at a relatively constant temperature of 650ºC and a level of incident heat radiation to the floor of about 17kW/m^2. The mass loss rate of the combustible linings was also close to constant at 22g/s. Fire spread between compartments does not at first sight subject itself to an easy characterisation using gas temperatures as criteria for definition. The ventilation conditions seemed to have a great impact on the results.

Future experimental studies should be aimed at further studying fire growth and spread between compartments and possibly making a comparative full-scale study. Comparisons between experimental data and CFD-model FDS and vulnerability assessment code AVAL are also of interest.

Keywords

Ignition, fire, fire growth, fire spread, flashover

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Brandtillväxt och -spridning - en experimentell studie i modellskala

Sammanfattning (högst 200 ord)
En experimentell studie i modellskala har genomförts i syfte att studera brandtillväxt i ett rum och brandspridning mellan rum.

Inledningsvis genomfördes en serie brandtillväxtförsök för att studera hur valet av antändningskälla styr tiden till övertändning i ett rum med brännbar ytbeklädnad. Vidare genomfördes försök i syfte att undersöka både vertikal och horisontell brandspridning mellan rum. Ventilationsförhållandena varierades för att efterlikna situationen ombord på ett fartyg eller i en undermarksanläggning. En enkel utvärdering av rumsbrandförsöken visade att övertändning inträffade vid en relativt konstant temperatur av 650ºC och en mot golvet infallande värmestrålning av ca. 17kW/m^2. Även förbränningshastigheten av den brännbara ytbeklädnaden var i det närmaste konstant och nära 22g/s. Brandspridning mellan rum verkar dock inte på ett enkelt sätt låta sig definieras i form av ett enkelt temperaturkriterium. De aktuella ventilationsförhållandena verkade spela en avgörande roll för slutresultatet.

Framtida experimentella studier bör inriktas på att vidare undersöka brandtillväxt i rum och brandspridning mellan rum och eventuellt genomföra en jämförande fullskalestudie. Jämförelser mellan experimentella data och beräkningar med CFD-modellen FDS och verkansvärderingsprogrammet AVAL är också av intresse.

Nyckelord
Antändning, brand, brandtillväxt, brandspridning, övertändning

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1 Introduction

1.1 Background

For a number of years, FOI has worked with the potential threat a fire and especially the subsequent smoke spread constitute to the survival of a building, military installation or ship. In the event of a fire, one crucial matter for survival is whether or not the fire is allowed to propagate and spread within and between compartments. Fires induced by weapons effects and similarly strong ignition sources can develop particularly fast and lead to an almost instantaneous flashover (FO) of a compartment accompanied by fast smoke spread to adjacent compartments. For example, a residual missile fuel fire onboard a warship can present a threat to the survival of the whole ship, something that became obvious during for example the Falklands War. It was proven that even though a weapon (e.g. a missile) does not detonate, the burning of residual fuel can be the cause of very violent fires. High levels of heat radiation will ignite combustibles and the fire spreads rapidly (Back *et al* 1999). Beside purely weapon-related scenarios, today there is also a need to develop knowledge to predict possible terrorist actions. In order to develop means of protection against similar actions, an understanding of this type of fires is essential. Furthermore, consideration of fire spread between compartments has not been addressed from a more applied viewpoint in experimental studies. This implies a need for well instrumented and documented experiments to be performed. Previous experiments have been focused mainly on fixed fire sources and studies of heat and smoke transport to adjacent and overhead compartments. One example of a two-room study is described in Nielsen (2000). These experiments only address the pre-flashover fire and not the actual growth and spread.

1.2 Purpose and objective

This study aims at summarising experimental results from two separate studies:

1. *Fire initiation and growth* using different ignition sources, and
2. *vertical and horizontal fire spread* between compartments.

Focus is on developing an understanding for the factors controlling ignition and early fire growth and how these depend on the type of ignition source and the experimental geometry. Of particular interest is also to locate possible “mechanisms” responsible for fire spread and how these can be used in the prediction and mitigation of these events. In the end, the study will give further insight to how fire development will depend on how the fire is initiated. This is an important matter when studying the level of protection in different installations and the evaluation of potential fire spread routes and times. Further more, the experimental data will serve as a basis for future comparison to CFD-models as well as vulnerability code AVAL.

1.3 Method

All tests are performed in a model-scale experimental set-up situated at the fire laboratory at Grindsjön Research Centre. A large number of measurements are done throughout the tests as well as video documentation of the more qualitative aspects of the fire growth and spread phenomena. Only a limited amount of data is discussed and presented in the report and for a more comprehensive presentation of experimental data the reader is referred to appendices.

1.4 Limitations

The study should be seen mainly as a summary of experimental data within the area of ignition as well as fire growth and spread. Experimental data are intimately associated with a specific test scenario and therefore caution should be used before applying results to conditions different from those described in the following.

2 Experimental set-up

In this chapter the model-scale experiments are outlined and a description of the measurements is given. First, the compartment fire tests are discussed after which the fire spread tests are outlined. Generally, the fire spread studies are aimed at evaluating a few "generic" cases and gather relevant quantitative and qualitative data from the tests.

2.1 Initiation and compartment fire growth

For the studies of fire growth and spread within a single compartment, the experimental set-up schematically illustrated in figure 2-1 was used. This set-up was used in test C1 to C7. More detailed information regarding experimental set-up, geometry and measurement location for the different tests is given in appendix A (figure A-1 and A-2).

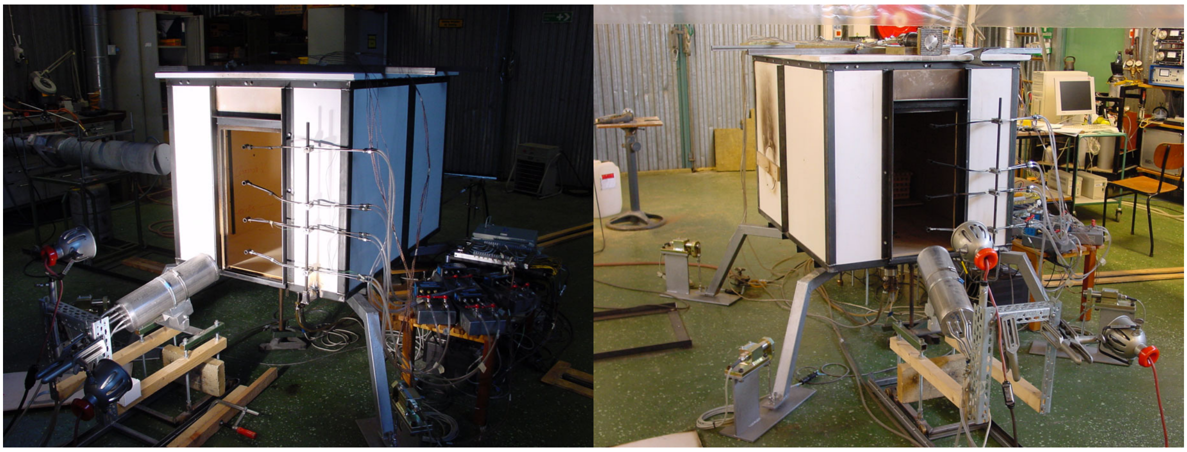

Figure 2-1 *Experimental rig for test C1-C7.*

Table 2-1 shows the different tests performed. Basically, a variety of ignition sources was used to represent different fuels, fire sizes and characteristics.

Test	C1	C2	C3	C4	C5	C6	C7
Ignition source	Methanol pool fire (17x17cm)	Heptane pool fire (17x17cm)	Hot combustion gases	Heptane pool fire (17x17cm)	Methanol pool fire (25x25cm)	Wood cribs (1.5x1.5x15 cm)	Propane burner
Mass loss rate [g/s] [1]	0.43 (see fig 2-2)	0.40 (see fig 2-2)	1.3	0.40 (see fig 2-2)	NA[2]	See fig 2-4	2.0
Fire size [kW] [3]	8.6	16.1	59.8	16.1	NA	NA	92
Full-scale fire size [kW] [4]	130	250	930	250	NA	NA	1434

Table 2-1 *Overview of ignition sources used for the compartment fire tests (NA=not available).*

As can be seen test 2 and 4 have identical conditions and this is an attempt to check reproducibility of the test results. More generally, the values given in table 2-1 represent average results from free-burning tests and can not be used as a precise definition of ignition source strength for enclosed burning.

[1] According to free-burning tests (see figure 2-2).
[2] Not measured in free-burning condition. An estimate can be done according to Karlsson *et al* (2000).
[3] According to equation (1).
[4] According to equation (2).

2.1.1 Ignition sources

As previously mentioned the ignition source was varied in the different tests. In most tests liquid fuel was used and in order to get an even burning rate circulating water was used to cool the fuel pans including the rims (Ingason *et al* 1999). The characteristics of the small free-burning pool fires are shown in figure 2-2.

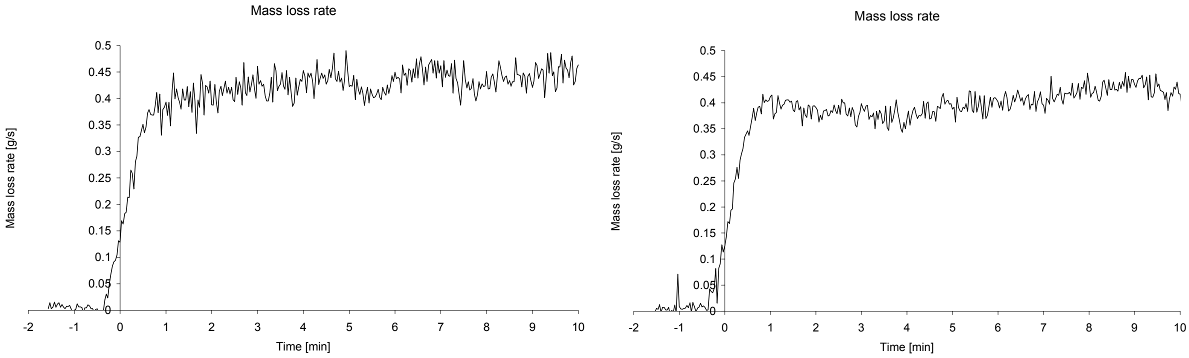

Figure 2-2 *Mass loss rate of the free-burning methanol (left) and heptane (right) pool fire.*

This approach generates a relatively constant mass burning rate of the fuel (0.43g/s and 0.40g/s for the methanol and heptane pool fire respectively). The fire size given in table 2.1 [kW] is calculated using the following relationship (Karlsson *et al*, 2000):

$$\dot{Q} = \dot{m} \cdot \Delta H_c \cdot \aleph \qquad (1)$$

In the above $\dot{m}$ is the mass loss rate [g/s], ΔH_c is the heat of combustion [kJ/kg] and $\aleph$ the combustion efficiency [-]. The mass loss rate is measured (free-burning) and the heat of combustion is set to 20, 44.6 and 46MJ/kg for methanol, heptane and propane respectively. The combustion efficiency is assumed 1.0 for methanol and propane and 0.9 for the small heptane fire. Corresponding full-scale fire sizes are determined from Heskestad (1974) and Emori *et al* (1983):

$$\dot{Q}_F = \dot{Q}_M \left(\frac{L_F}{L_M} \right)^{5/2} \qquad (2)$$

where $\dot{Q}_F$ and $\dot{Q}_M$ is the heat release rate in full- and model-scale respectively and L is the length scale, where L_F=3 and L_M=1.

Initially tests were done using small pool fires (methanol and heptane), which were allowed to burn throughout the test period. The fire source consisted of a square steel pan with an area of 0.029m^2 (side 0.17m). In the following test the effect of hot combustion gases on the ignition and early fire spread scenario was analysed. For this purpose a special arrangement was made and a schematic illustration is shown in figure 2-3.

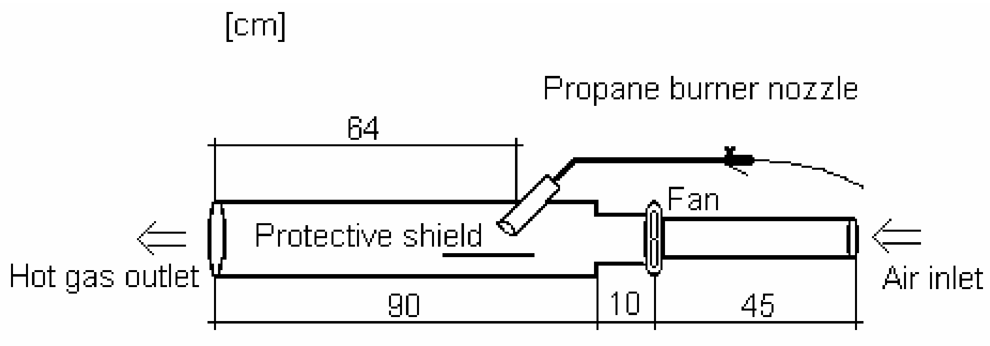

Figure 2-3 *Ignition device using hot combustion gases.*

Basically, a propane burner was used to generate the hot gases. A fan supplied air through the duct in addition to the air that went through the burner nozzle necessary for combustion of the propane. The external airflow generated by the fan helped controlling the flow and temperature of the hot gases. The air velocity through the pipe was about 1.0 m/s in "standby" mode and the temperature in the outlet was close to constant and 750ºC. The weight loss of the propane gas was measured by means of a separate scale described in chapter 2.1.2. No further measurement of the ventilation flow rate in the inflow duct was done during the tests.

Further, the wood cribs used in test C6 generated an ignition source increasing with time as illustrated in figure 2-4 (free-burning conditions).

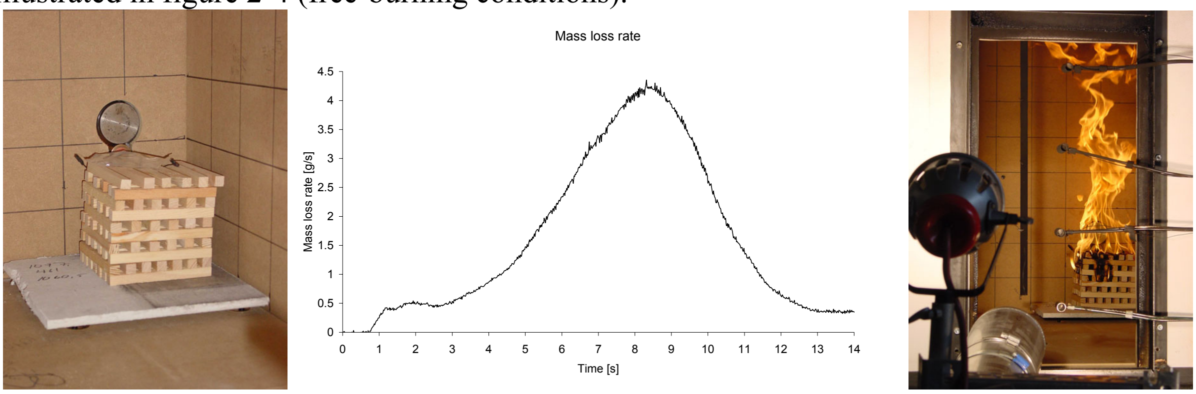

Figure 2-4 *Mass loss rate of the free-burning wood cribs as well as the actual wood crib layout during test C6.*

Finally, a test was done in order to qualitatively evaluate the fire development following the use of a strong ignition source. For this purpose the propane burner from test C3 was used. This was placed directly in the door opening aiming into the corner (above where the ignition source was placed in previous tests) and the flame extended and hit the corner wall about 40cm above the floor. In this case the mass loss rate was 2g/s and this corresponds to about 92kW.

2.1.2 Measurements

The experimental set-up used throughout the tests consists of a fire room with the dimensions 1.1x0.8x0.8m (LxWxH) representing a scale 1:3 model of a test container intended for full-scale studies.

An opening of 0.3x0.6m (WxH) is applied at one end of the model representing a door opening. The framework consists of steel with a lining of 20mm Promatect board for protecting the construction. In all tests (C1-C7) an inner lining of 12mm MDF (medium density fibre) board was applied to all surfaces (walls, ceiling and floor). The density for the board is 780kg/m^3 and the moist content is around 11% in all tests.

Several measurements were done during the tests. More comprehensive figures of the location of the measurement points described below are found in appendix A. Gas temperature is measured inside the fire room by means of two thermocouple trees (T-vert A and B) consisting of type K thermocouples with a wire diameter of 0.5mm. These are applied at heights 0.10, 0.25, 0.40, 0.55, 0.70 and 0.77m above the floor in the 0.8m high model. All thermocouples are mounted shielded from direct heat radiation from the ignition source in all tests. In order to document the incident heat radiation to the floor, one thermal heat radiation meter of the Gunners type (Gunners, 1967) was positioned according to figure A-1 in appendix A (Q1). In test C4-C6, another Gunners meter (Q2) was located on the side wall above the ignition source just above a total heat flux meter (THFM). In test 5 and 6, yet another Gunners meter (Q3) was located above the door opening to capture the level of heat radiation and give an indication to when a continuous flame ejects through the opening. In order to document air and gas flow velocities in and out of the compartment, bi-directional probes (McCaffrey *et al*, 1976) were positioned 0.10, 0.25, 0.40 and 0.55m above the floor (BD-vert). For every BD-probe a thermocouple of above type was attached for evaluating the gas temperature in each point (T-vert D). In order to evaluate the heat release rate (HRR) during the tests, the smoke and fire gases were collected in a hood (in total 6x4m wide) and analysed in the exhaust duct. The concentration of O_2, CO_2 and CO in the exhaust gases was evaluated as well as the temperature (type K thermocouple, 0.7mm) and flow velocity by means of above mentioned BD-probe. The HRR is then evaluated according to the simple relation given by equation (3) (Dahlberg 1992):

$$HRR = E \cdot \dot{m} \cdot (X^0_{O_2} - X_{O_2}) \tag{3}$$

In the above relation E is the amount of energy developed per consumed kilogram of oxygen [kJ/kg], $\dot{m}$ the mass flow in the exhaust duct [kg/s], $X^0_{O_2}$ is the mole fraction for O_2 in the ambient air [-] and X_{O_2} the mole fraction for O_2 in the flue gases [-]. The value for E is set to 13,100kJ/kg for all tests. Since only small amounts of CO and CO_2 was measured until flashover, it was deemed satisfactory to use relation (3) for evaluating the HRR. Alternatively, the relation given in for example Axelsson *et al* (2001) can be used.

The gases were sampled using an M&C Sampling System PSS and the content of O_2 was evaluated using an Analyser PMA 10 (0-30 vol%). The level of CO was analysed using a Maihak Finor (0-10 vol%) and a Maihak Unor 6N (0-1000 or 0-10000ppm) and CO_2 using a Maihak Finor (0-20 vol%). The gas velocity in the exhaust gas ventilation duct was evaluated by means of a pressure transducer 0-200Pa (type Furness Controls Ltd., Fco11 Micromanometer) and ±50Pa for the gas velocities in the door opening.

The mass loss rate could be evaluated since the model was placed on a “weighing floor” consisting of four load cells as seen in figure 2-1. These were of the type KIS-3 (Nobel Elektronik) each with a capacity of 100kg. The mass loss rate of the ignition source was measured using a separate scale. This consisted of three load cells (Nobel elektronik, load beam alpha) with a capacity of 10kg. Amplifiers used were Bofors B2F and Bofors BKI-4-D respectively.

Throughout all tests, measurements were logged every second by means of Schlumberger SI35951C IMP dataloggers and collected using the measurement system Impview. All instruments were started two minutes before test start to assure stability and functionality (see for example diagram in figure 2-2).

2.1.3 Observations

A number of observations are made during the tests. Examples are time to ignition of the combustible linings and flashover of the compartment. In order to minimise observer effects and problems relating to interpretation of when different phenomena arise video recordings are made during all tests. First, the experimental set-up is recorded in an overview manner by means of a digital video camera. Second, a purpose built water-cooled and insulated camera is used in order to document the events within the compartment. This camera is of the superdynamic CCD type (Panasonic WV-CP464) and the casing is shown in figure 2-5.

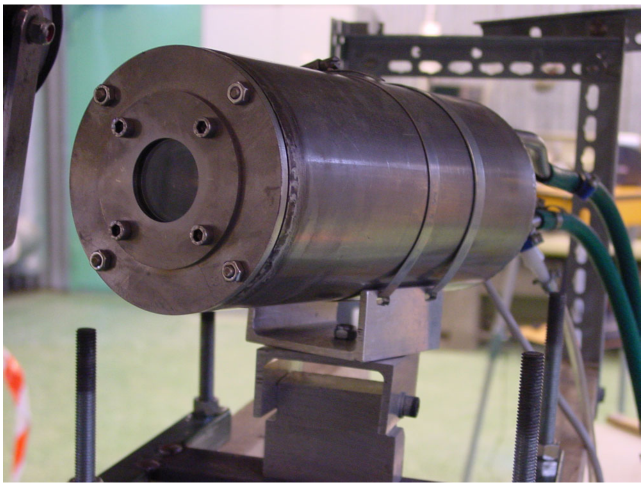

Figure 2-5 *Superdynamic camera for close-up flashover studies.*

2.2 Vertical fire spread

Underground facilities and ships to some extent share the problem that fire breakout is likely to reach under-ventilated conditions as a result of that the fire is only ventilated from above (illustrated in figure 2-6). These conditions represent the case in which the door opening to the fire room is closed. This presents a very different fire situation compared to the more "conventional" building fire, where openings in the façade give other ventilation conditions. In this former case, fire size is primarily governed by the available air supply rate through the ventilation opening, through which both fresh air enters the compartment and combustion gases exits. For the case of a ceiling opening, only a limited number of experimental studies have been performed. As the fire grows, burning will become oscillatory (Kerrison *et al*, 1998) and the burning rate will vary over time. How this will affect if and when fire spread will occur does not seem to have been investigated experimentally earlier.

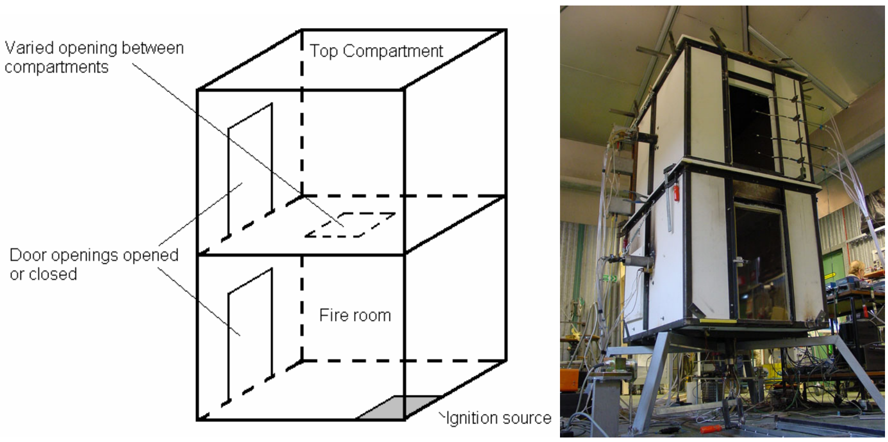

Figure 2-6 *Illustration of the experimental geometry to study vertical fire spread between compartments.*

Another specific case is if the fire is well ventilated and consideration is given to fire spread to an overhead compartment, which is closed. Finally, consideration will be given to spread of fire to an overhead compartment if both compartments are well ventilated. Table 2-2 gives a summary of the five tests performed.

Test	V1	V2	V3	V4	V5
Door opening fire room [m^2]	-	-	-	0.3x0.6	0.3x0.6
Door opening top compartment [m^2]	0.3x0.6	0.3x0.6	0.3x0.6	0.3x0.6	-
Opening between compartments [m^2]	0.5x0.5	0.4x0.4	0.3x0.3	0.3x0.3	0.3x0.3

Table 2-2 *Summary of vertical fire spread tests.*

The main aim was to study three different ventilation conditions according to previous descriptions. The ignition source was a heptane pool fire (17x17cm in a water-cooled container) in all tests and the position of the source was in the corner of the bottom compartment. Generally, the only parameter that was varied during the tests was the ventilation conditions. A combustible lining consisting of 12mm MDF-board was applied to the walls (except for the wall with the door opening) in the fire compartment in all tests. In the top compartment only one side wall was lined with MDF-board in order to make the determination of when fire spreads easier.

2.2.1 Measurements

Similar measurements as for the compartment fire growth tests were done and this is illustrated in figure A-3 to A-5 of appendix A. The main part of the measurements are done in a corresponding way as described in chapter 2.1.2. However, a few added measurements are done according to the following. Heat radiation is measured on two additional locations, namely in the middle of the side wall in both compartments (Q2 and Q3). In the fire compartment a total heat flux meter (THFM1) is placed underneath the heat radiation meter Q2. Further more, optical density (OD) meters are located on three levels in the top compartment. This measurement equipment consists of smoke extinction meters over a path length of 0.8m, which is also the depth of the compartment. The device itself consists of a lamp, a lens, windows and a photocell. The lamp is of halogen type and the lens aligns the beam to a parallel, which the photocell then measures the reduced intensity of. The windows protect the interior of the meter from heat and smoke. Air is also forced through the meter to prevent the deposition of soot on the windows during the tests. The optical density per path length (OD) is defined by:

$$OD = \frac{1}{L} \cdot \log_{10}\left(\frac{I_0}{I}\right) = \frac{1}{L} \cdot \log_{10}\left(\frac{100}{T}\right) \qquad (2)$$

where the initial light intensity of I_0 is reduced to a value of I over the path length L, resulting in T percent transmission. The unit for OD is [m^{-1}]. An oxygen meter (of previously described type) is added and located in the fire compartment to measure the oxygen concentration (O2). Finally, the pressure rise in the fire room is measured (P).

2.2.2 Observations

An important factor in this test series is the determination of when fire spread occurs. A similar approach as that described in section 2.1.3 was used in order to document important aspects for post-test evaluation.

2.3 Horizontal fire spread

Another possibility for fire to spread is from the fire room to the adjacent compartment as a consequence of convective heat transfer or flame through a door or hatch opening. This case represents the more “conventional” building fire case. Despite this fact no well documented experimental studies could be found except for cases with a fixed fire size (Nielsen 2000). In figure 2-7 the experimental set-up is schematically illustrated.

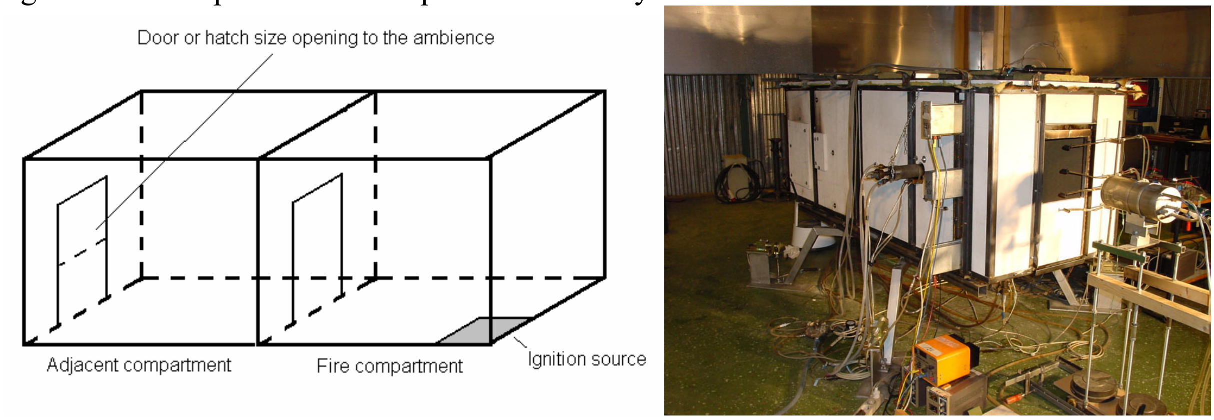

Figure 2-7 *Illustration of the experimental geometry to study horisontal fire spread between compartments.*

Only two tests were performed and these were focused on studying the effect of different ventilation conditions. Table 2-3 summarises the conditions for these.

Test	**1**	**2**
Opening between compartments [m^2]	0.3x0.6	0.3x0.6
Opening to the ambiance [m^2]	0.3x0.6	0.3x0.3

Table 2-3 *Summary of horisontal fire spread tests.*

The ignition source used was the same as during the previously described vertical test series.

2.3.1 Measurements

To a large extent instrumentation of the fire room coincides with that previously described. Changes and additions are given in figure A-6 to A-8 of appendix A.

2.3.2 Observations

Previously described camera equipment was used in a similar manner to document the qualitative aspects of the tests.

3 Results

This section aims at summarising experimental data. The following will give a presentation and overview of some results from the experimental study concerning both compartment fire growth and fire spread between compartments. All measurement data (for test C1-C7, V1-V5 and H1-H2) except for the gas analysis results from CO and CO_2 measurements and the pressure rise in the fire room is presented in appendix B. Generally, these values were low during all test periods. Further, the oxygen concentration in the fire room during the fire spread tests failed in test V1-V2 and V4-V5. Also, the heat radiation measurements for test V1-V5 and H1-H2 are not presented here. Further analysis of the data is required along with a consideration to calibration procedures. Finally, no observations are given for test V3, since the fire did not spread from the fire compartment.

3.1 Initiation and compartment fire spread

The first series of tests described is the compartment fire tests and these were performed in 2002 and beginning of 2003. In the following a brief overview of some of the more relevant test results is given. The short evaluation of measurement data is focused on conditions at the time of flashover. Further measurement data is given in figure B-1 to B-45 of appendix B.

3.1.1 Time to flashover

A first distinction between the different tests performed can be done using the time to flashover. Flashover is here defined as a continuous flame emerging through the opening and is determined visually from video recordings and in some cases with the aid of measurement data from the heat radiation meter positioned above the door opening. A flashover sequence from test C6 is illustrated in figure 3-1.

Figure 3-1 *Flashover sequence from test C6.*

The actual time to flashover for the different tests is given in table 3-1. As can be observed, the heptane ignition source generates the fastest developing fire.

	Test C1	**Test C2**	**Test C3**	**Test C4**	**Test C5**	**Test C6**	**Test C7**
Time to flashover [min:sec]	10:00	03:30	08:45	03:05	07:40	05:30	01:00

Table 3-1 *Time to flashover for test C1-C7.*

3.1.2 Gas temperature

The reaching of a critical gas temperature is sometimes used as a criterion for flashover. For a majority of applications the value 600ºC is often used. In figure 3-2 the temperature development (3cm below the ceiling in the middle of the fire room) for the compartment tests are summarised as a rough comparison.

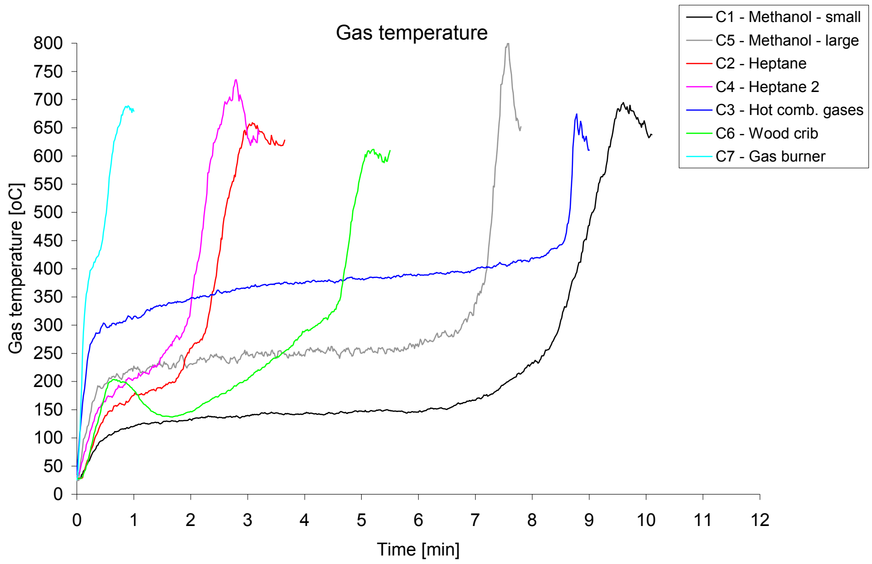

Figure 3-2 *Gas temperature 3cm below the ceiling in test C1-C7.*

As can be observed the gas temperature development in the fire compartment varies greatly between the different tests due to ignition source and strength. However, if the temperature at the time of flashover (for definition see section 3.1.1) is evaluated the average value becomes 645ºC (variation between 603-711ºC).

This value can be compared to the temperature in the door opening as shown in figure 3-3. This temperature varies between 510 and 718ºC (with an average of 655ºC) at the time flashover is observed.

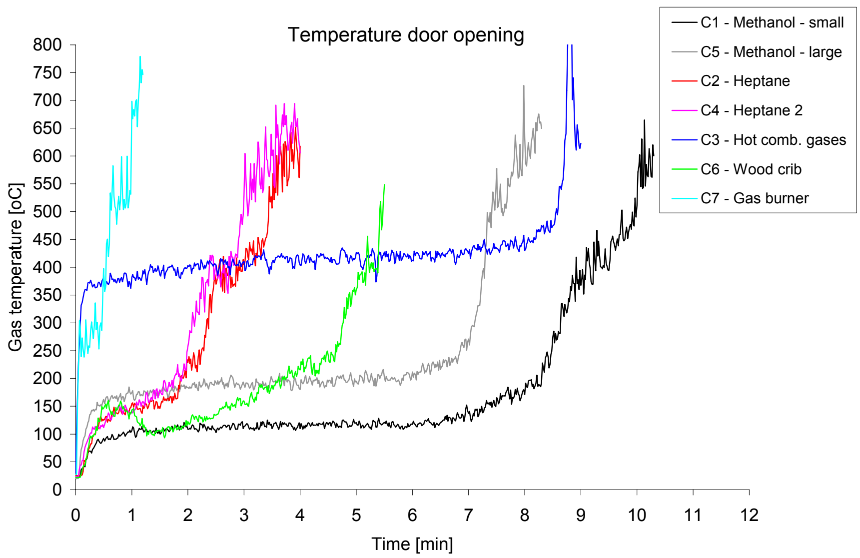

Figure 3-3 *Temperature in the door opening 5cm below the soffit.*

3.1.3 Gas velocity in door opening

The gas velocities in the door opening give an indication to the vent flow situation close to and at the time of flashover. Figure 3-4 shows the gas velocity 5cm below the soffit at the time of flashover for the different tests. For all tests except C3 and C7 (where a gas burner is used and the fire can not be assumed to be dominated by natural convection) the gas velocity at the time of flashover assumes a close to constant value. The average value is 3.2m/s with a variation between 3.1 and 3.5m/s.

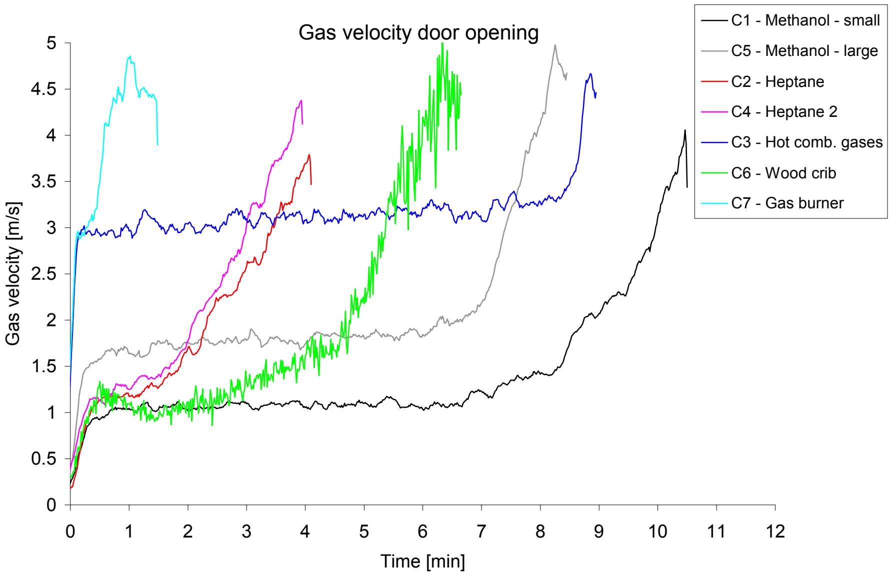

Figure 3-4 *Gas velocity (5cm below the soffit) in the door opening during test C1-C7.*

3.1.4 Heat radiation

Another way to define flashover in a compartment is to use heat radiation to the floor. A value frequently used for this is 20kW/m^2. A summary of the radiative heat transfer to the floor is given in figure 3-5.

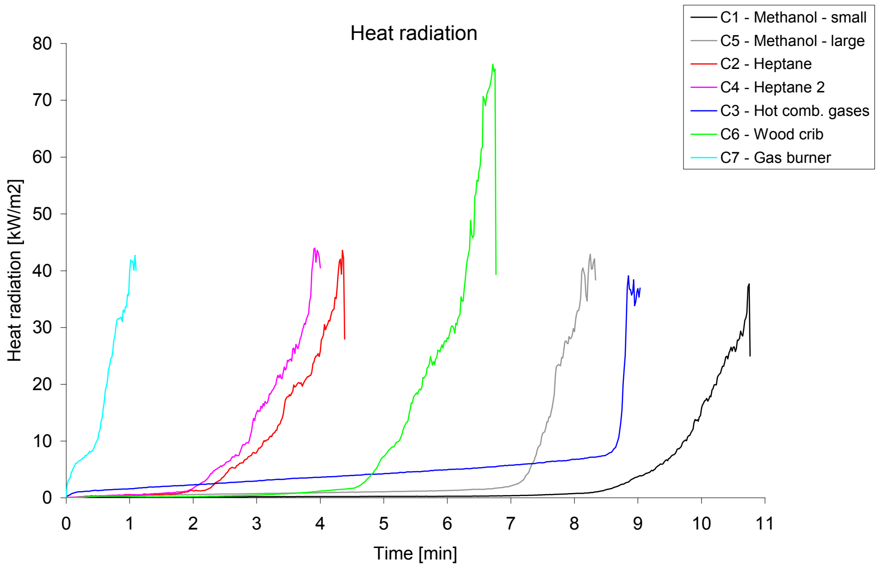

Figure 3-5 *Heat radiation to the floor for test C1-C7.*

Flashover occurs at a level of close to 17kW/m^2 (average of test C1-C6) in all tests with a variation between 16 and 18kW/m^2.

3.1.5 Heat release rate

The HRR for the different tests is given in figure 3-6 for all tests but test C7.

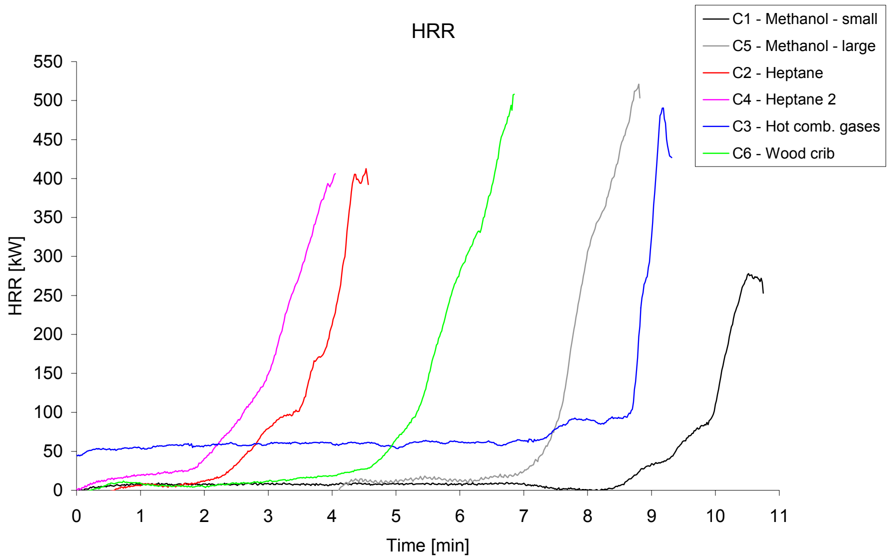

Figure 3-6 *HRR for tests C1-C6.*

The average value for the HRR at the time of flashover (for test C1-C6) is 132kW and the value varies between 110 and 153kW.

3.1.6 Mass loss rate

As described earlier, mass loss rate for both the ignition source and the combustible linings was measured separately.

A summary of these latter results is given in figure 3-7 (except for test C7). An average value for the mass loss rate of the combustible linings at the time of flashover is 22g/s with a variation between 19 and 27g/s.

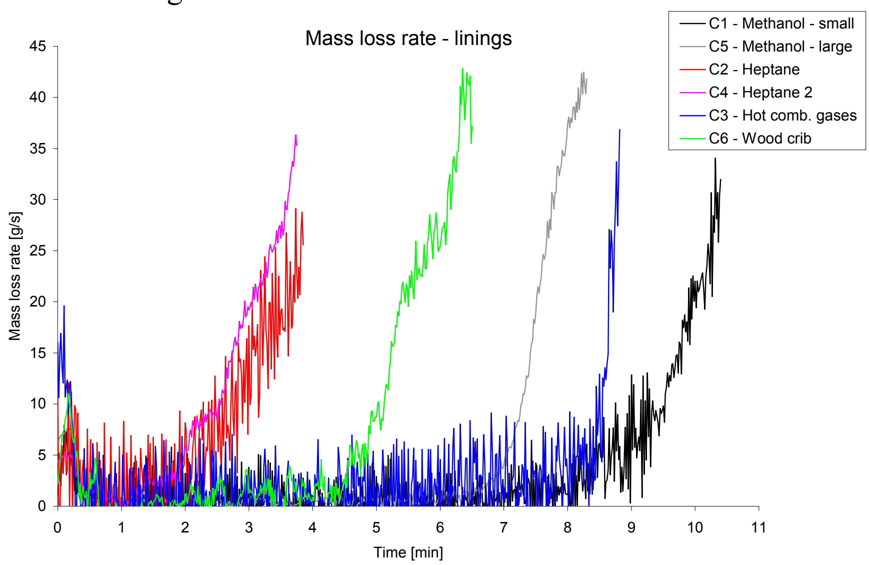

Figure 3-7 *Mass loss rate of the combustible linings for test C1-C6.*

3.2 *Vertical fire spread between compartments*

In the following only a limited amount of data from the vertical fire spread tests is presented and compared. For a more comprehensive presentation of data and observations, the reader is referred to appendix B and figure B-46 to B-93.

3.2.1 Time to fire spread

A first distinction between the different tests is if and when fire spreads between the two compartments. A summary of results is given in table 3-2.

	Test V1	**Test V2**	**Test V3**	**Test V4**	**Test V5**
Time to fire spread [min:sec]	10:15	25:15	No spread, fire self extinct	05:00	No spread before FO of fire comp.

Table 3-2 *Time to fire spread from the fire compartment to the above compartment.*

As can be seen spread of fire is only achieved for a minimum ceiling vent size in the top vented compartment case (test V1 and V2 but not V3). Also, spread is rapid for a well-ventilated case (test V4) and finally no spread is seen for the case where the top compartment is sealed except for the opening from the fire compartment.

3.2.2 Gas temperature

Sometimes gas temperature is used as a rough criterion for defining when ignition in a compartment occurs. For that purpose it is of interest to study the temperature in the top compartment (3cm below the ceiling) and comparing the different tests. A comparison of test V1-V5 is illustrated in figure 3-8.

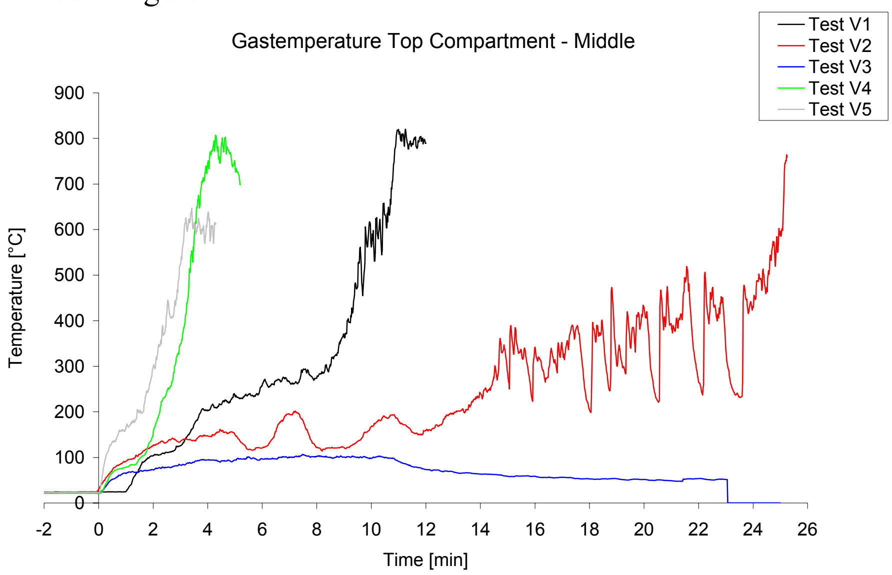

Figure 3-8 *Temperature in the top compartment for test V1-V5.*

The temperature at the time of ignition of the combustible lining in the top compartment is 640ºC for test V1 and 600ºC for test V2 (pronounced oscillatory burning). In test V4, the temperature in the top compartment reached 750ºC before actual fire spread is observed. However, in test V4 a more pronounced "chimney effect" is seen where air entrainment is mainly seen in the lower opening and ejection of combustion gases throughout the upper opening via the opening between compartments. In test V5 no ignition occurs during the test period and this is probably due to a lowered concentration of oxygen in the compartment.

3.3 Horisontal fire spread between compartments

In the following, only the times to fire spread between compartments and the gas temperature in the adjacent compartment is presented. Other measurement data and observations are given in appendix B and figure B-94 to B-113.

3.3.1 Time to fire spread

As for the horisontal fire tests, a first evaluation and comparison of the different tests can be done by compiling the times to ignition according to table 3-3.

Test	H1	H2
Time to fire spread [min:sec]	08:25	No spread before lining material in fire room collapses after 14 min

Table 3-3 *Time to fire spread from the fire compartment to the adjacent compartment.*

As can be seen the more well-ventilated case (test H1) generates a spread of the fire, whereas the case with only a hatch size opening to provide air is not sufficient to sustain fire spread for this particular set-up.

3.3.2 Gas temperature

The gas temperature in the adjacent room (into which the fire is to spread) for the different tests is illustrated in figure 3-9. For test H1 fire spread occurs when the temperature in the ceiling of the adjacent room reaches 565ºC.

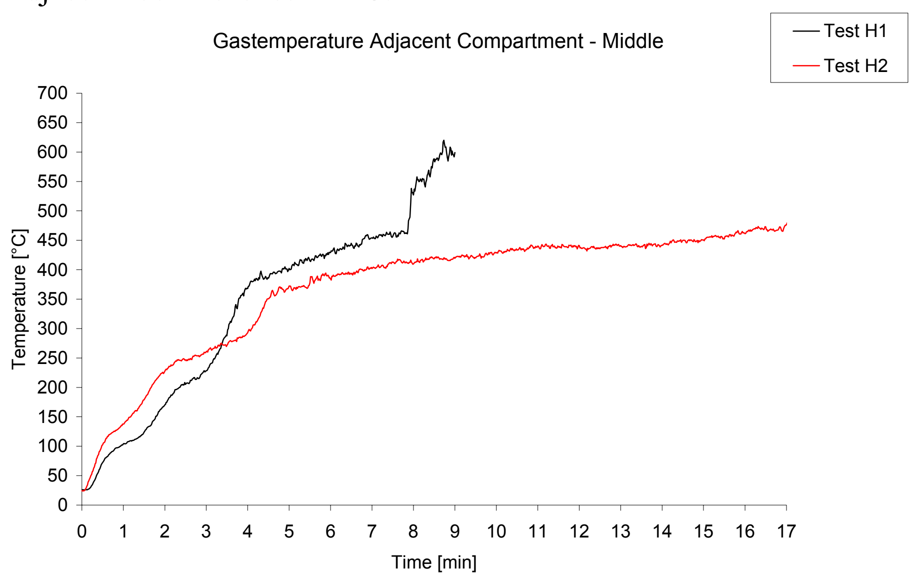

Figure 3-9 *Gas temperature in the adjacent compartment.*

4 Summary and conclusions

An experimental study has been performed in order to investigate fire growth within, and spread between, compartments. Main focus has been on developing a better understanding for the fire growth and spread phenomena in order to better predict and mitigate these events. The tests were performed in a model-scale experimental set-up and within the report most experimental data are presented in appendices. No far-reaching conclusions can be drawn from these introductory tests performed. However, it would seem that the fire growth phase is intimately coupled to the type of ignition source used. A more powerful and/or radiant heat source generates a more quickly developing fire in the tests performed. No deeper analysis of the experimental data is done within the report, but some parameters have been evaluated at the time of flashover and compared to see if these can be considered constant. For example, the gas temperature in the ceiling showed to fluctuate between 600-700ºC with an average of 645ºC. The corresponding average value for the gases exiting the opening just below the soffit was 655ºC. This indicates that flashover is likely to occur at the time the gas temperature in the upper gas layer reaches 650ºC. This complies quite well with the assumption in for example the AVAL fire model that flashover occurs at a fixed temperature.

Further, the average value for the heat radiation to the flow at the time of flashover was 17kW/m^2 in the compartment fire tests. This can be compared to 20kW/m^2, a level of heat radiation often used to define flashover conditions. The average value for the HRR at the time of flashover was 132kW and the mass loss rate of the combustible linings was 22g/s. These two latter parameters fluctuated around the average value a little more than the above mentioned. This is probably due to the fact that these values are calculated and averaged over a period of time around the time of flashover.

As for the vertical and horisontal fire spread tests only very little can be concluded at this point. The gas temperature in the overhead and adjacent compartments at the time of fire spread seems to vary quite a lot from the limited amount of tests performed. This indicates that a better ignition criterion might be needed in the description of fire spread in prediction tools such as AVAL. The reaching of a critical level of heat radiation might constitute a more accurate description of the fire spread phenomena. In order to evaluate some of the heat radiation results from the vertical and horisontal tests, an investigation of how best to calibrate heat radiation meters for a certain scenario is needed.

A possibility for future studies is to further investigate fire spread phenomena between compartments using different ventilation conditions and ignition sources. Finally, making one or two full-scale experiments of similar experimental set-up would be of great interest for validation of model-scale assumptions. Comparison of experimental data to CFD-model FDS and vulnerability code AVAL would also be of interest.

5 References

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Appendix A. Experimental set-up

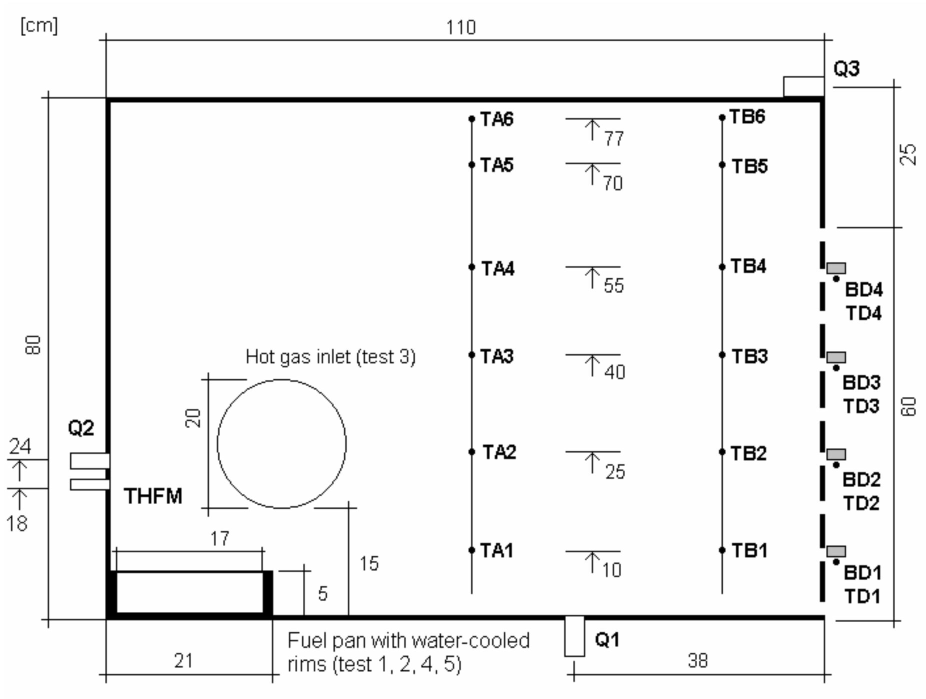

Figure A-1 *Side view of experimental set-up for compartment fire growth tests.*

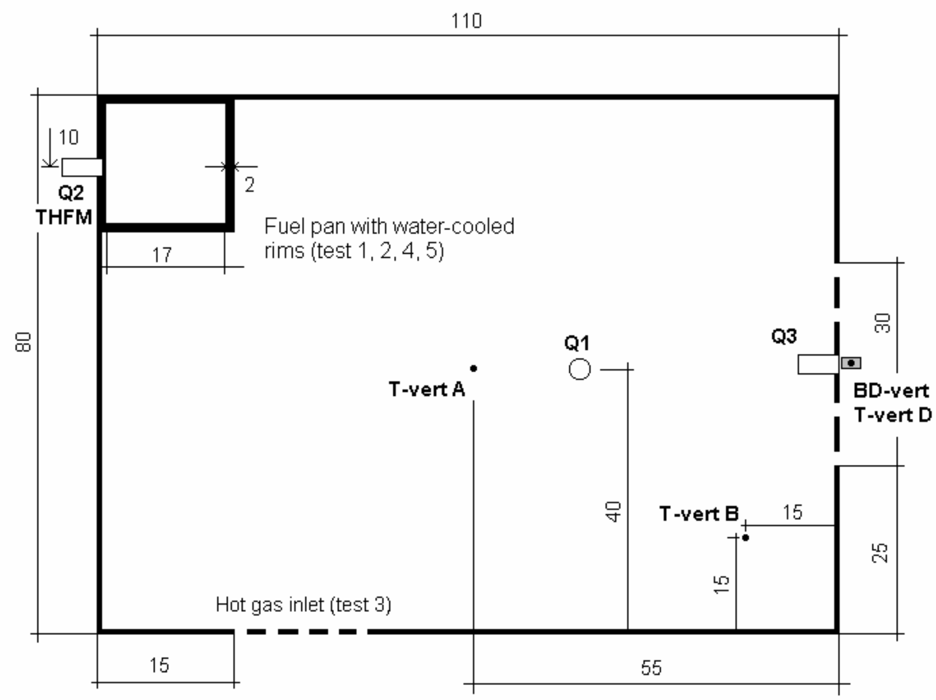

Figure A-2 *Top view of experimental set-up for compartment fire growth tests.*

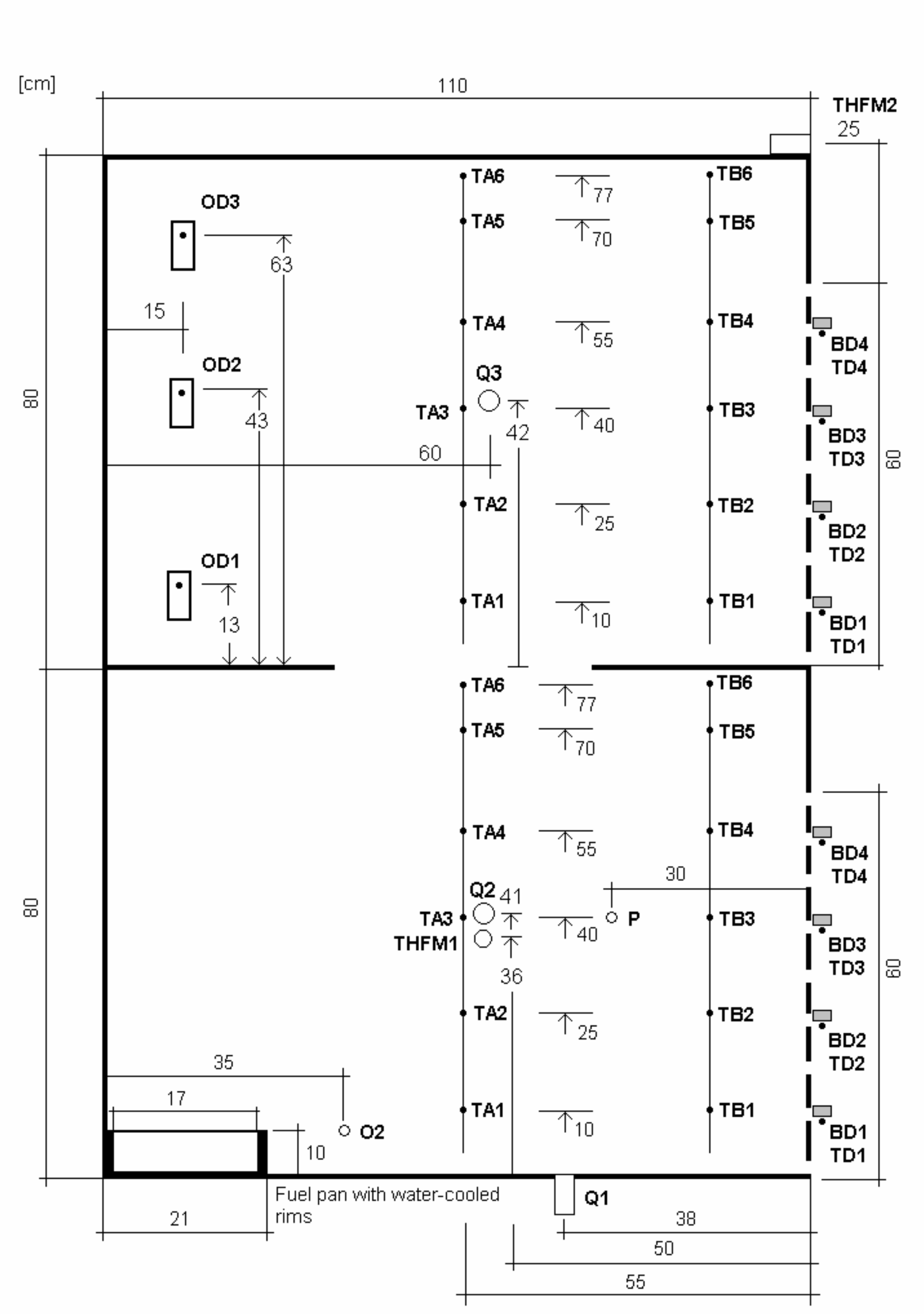

Figure A-3 *Side view of experimental set-up for vertical fire spread tests.*

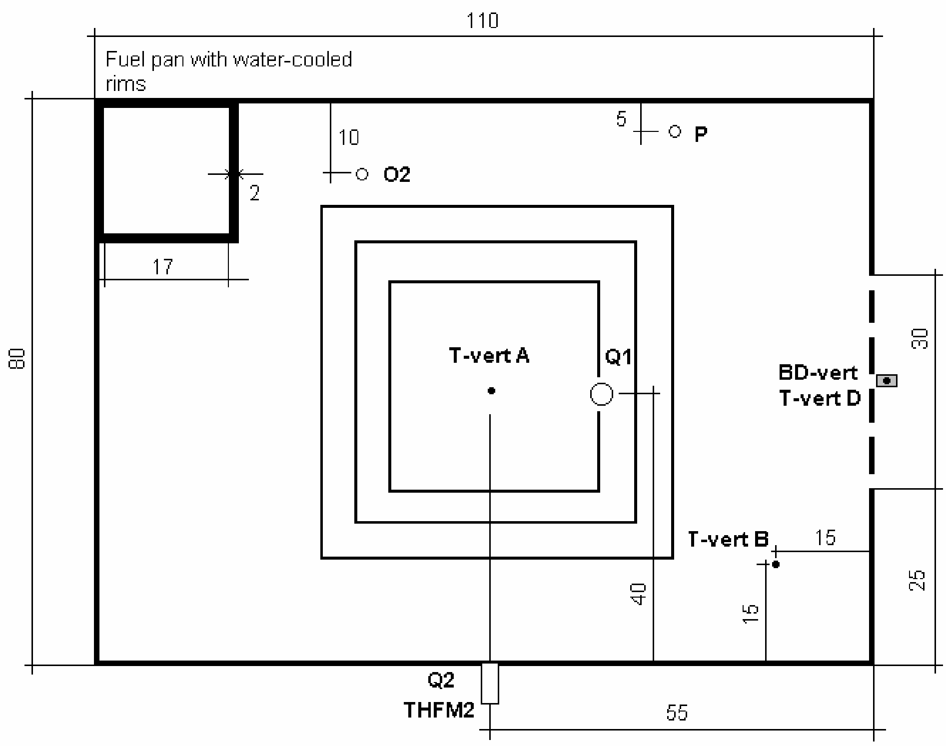

Figure A-4 *Top view of experimental set-up for the fire compartment in the vertical fire spread tests.*

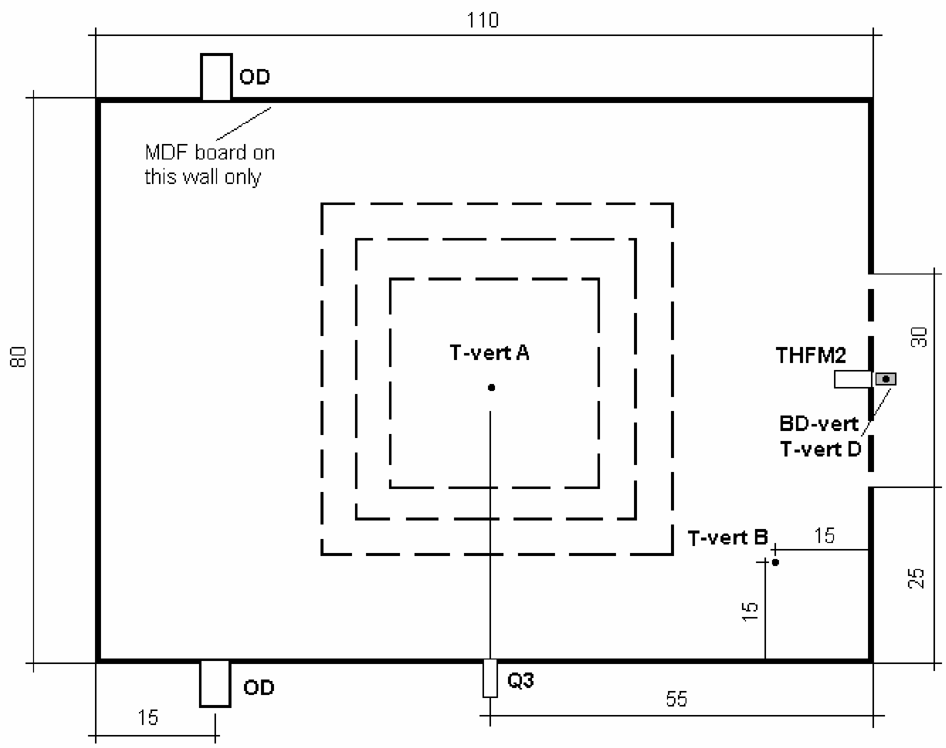

Figure A-5 *Top view of experimental set-up for the top compartment in the vertical fire spread tests.*

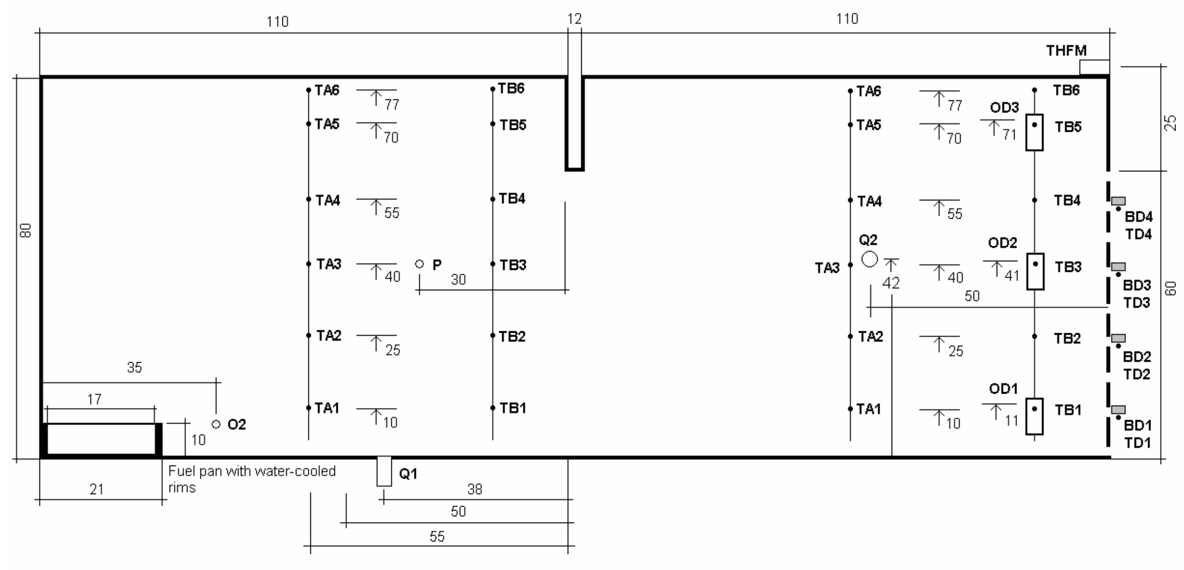

Figure A-6 *Side view of experimental set-up for the horisontal fire spread test H1.*

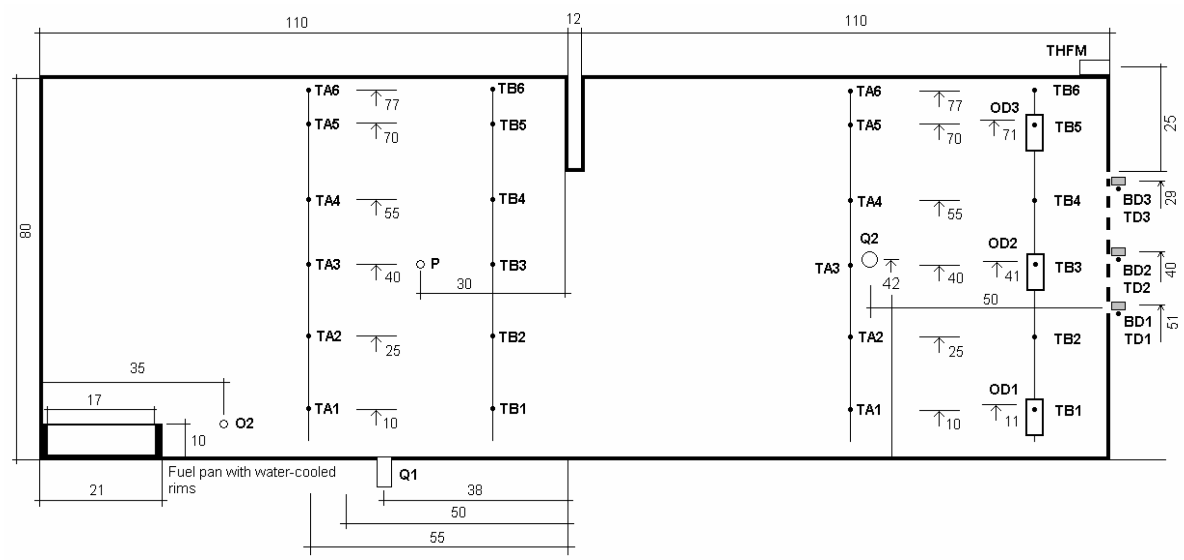

Figure A-7 *Side view of experimental set-up for the horisontal fire spread test H2.*

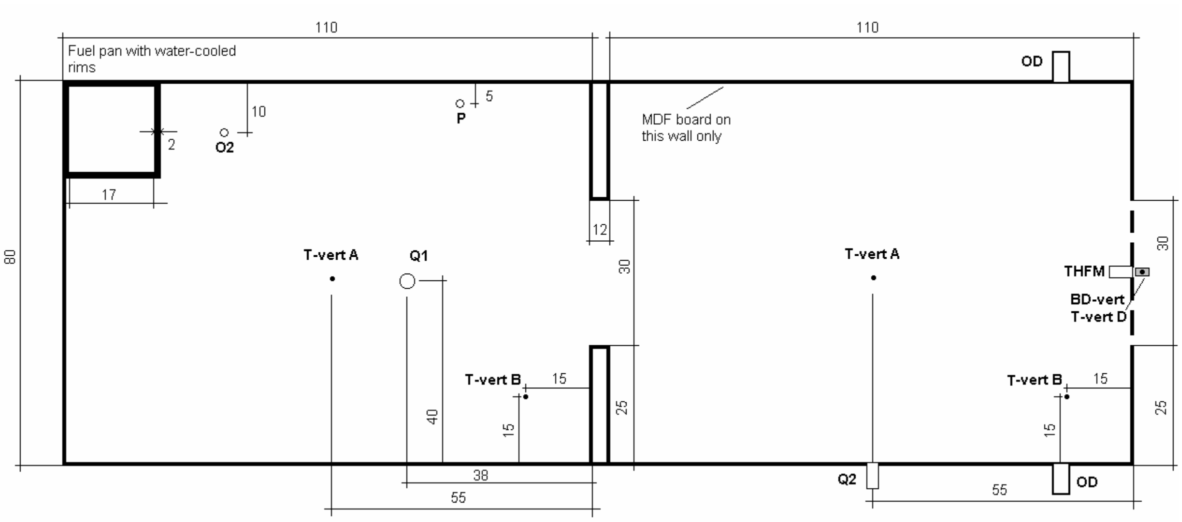

Figure A-8 *Top view of experimental set-up for the horisontal fire spread tests.*

Appendix B. Experimental data and observations

Time [min:sec]	**Event/observation**
00:00	Test start
02:45	Walls above steel pan start pyrolysing
06:30	Walls above steel pan ignite
07:30	Flames reach the ceiling
10:00	Flashover
10:30	Test terminated

Table B-1 *Main events during test C1 with a methanol pool fire.*

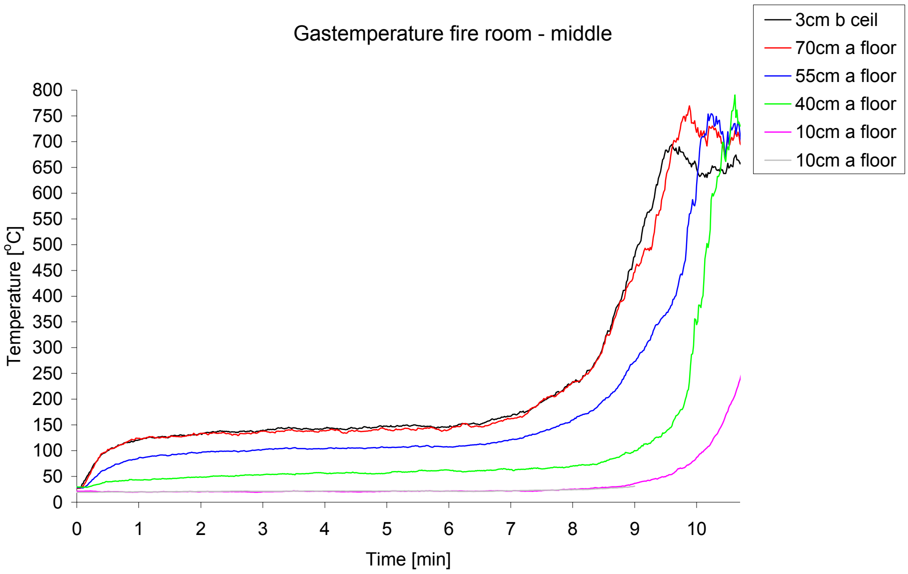

Figure B-1 *Gastemperature in the middle of the fire compartment for test C1.*

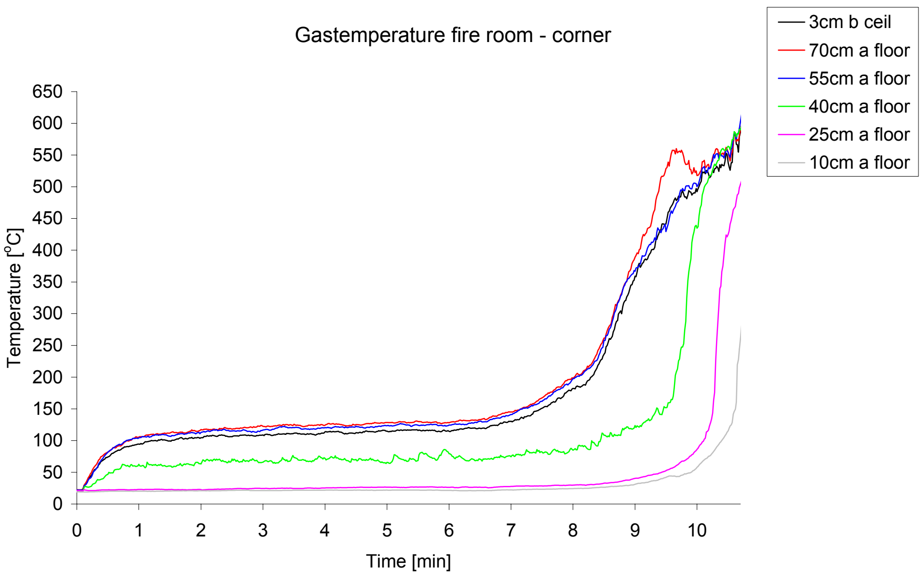

Figure B-2 *Gastemperature in the corner of the fire compartment for test C1.*

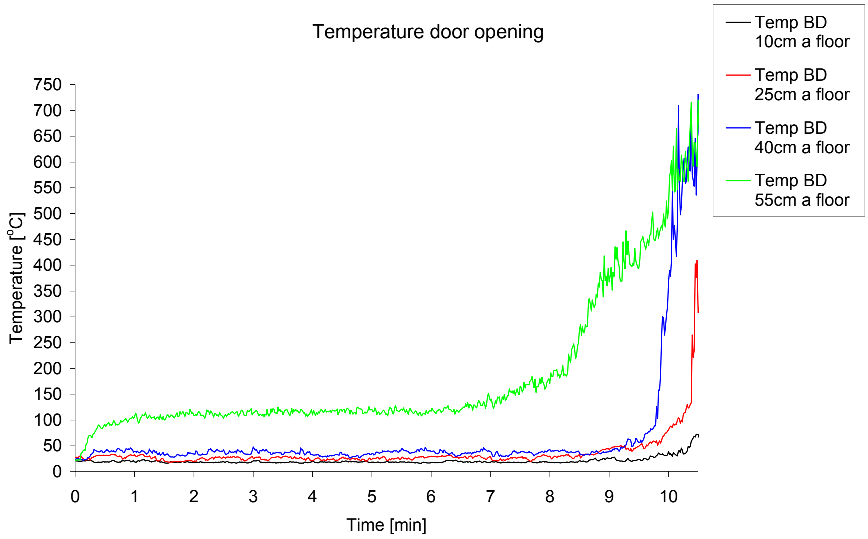

Figure B-3 *Gastemperature in the door opening for test C1.*

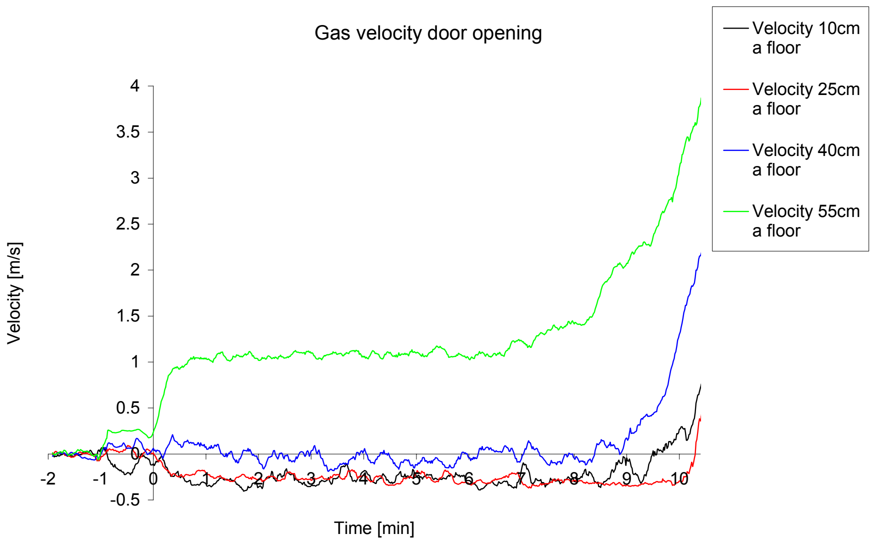

Figure B-4 *Gas velocity in the door opening for test C1.*

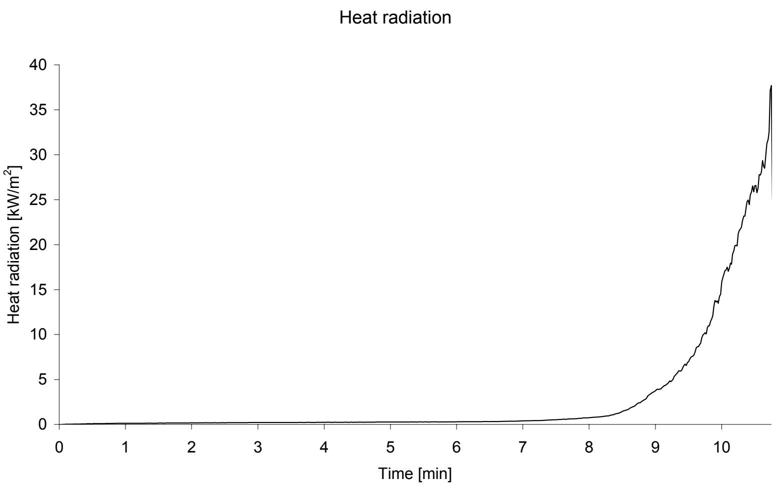

Figure B-5 *Heat radiation to the floor for test C1.*

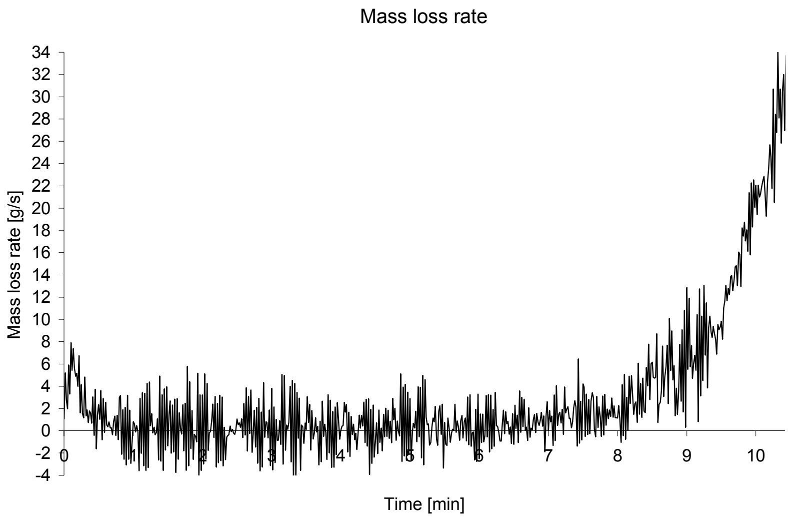

Figure B-6 *Mass loss rate of the linings for test C1.*

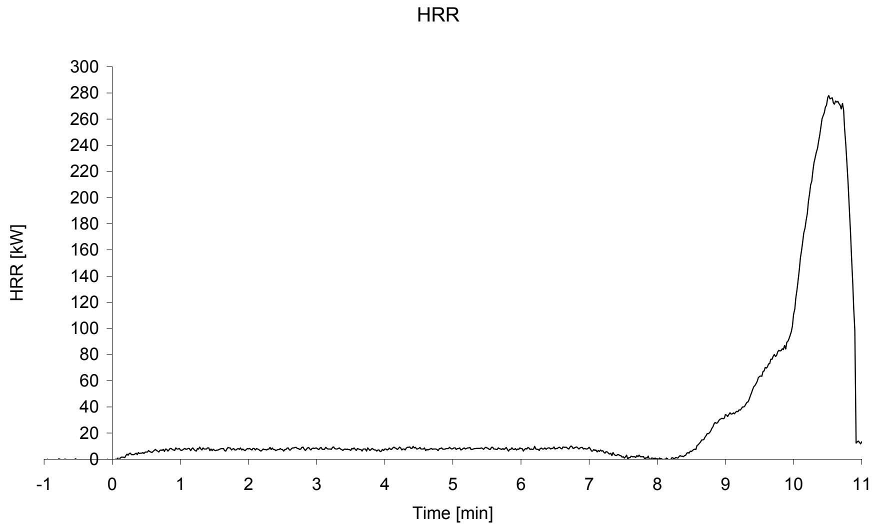

Figure B-7 *Heat release rate for test C1.*

Time [min:sec]	**Event/observation**
00:00	Test start
00:30	Walls above steel pan start pyrolysing and ignite
01:30	Flames reach the ceiling
03:30	Flashover
04:00	Test terminated

Table B-2 *Main events during test C2 with a heptane fire.*

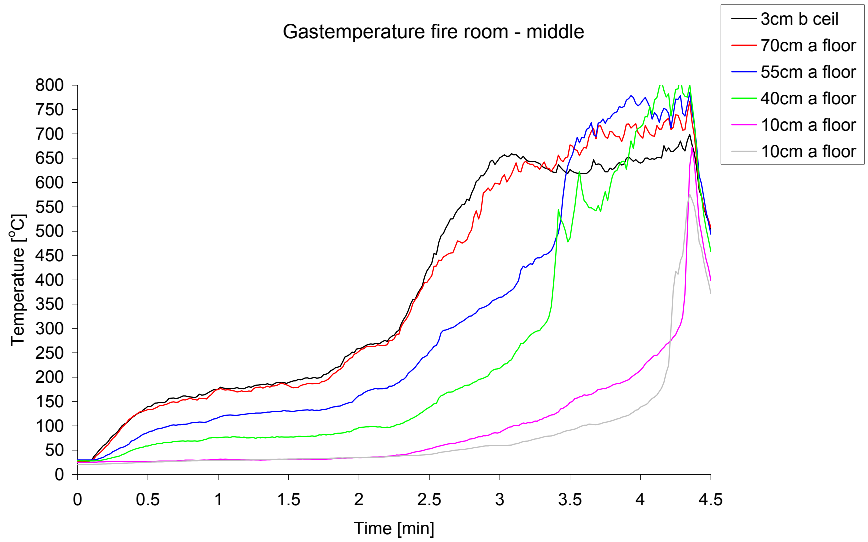

Figure B-8 *Gastemperature in the middle of the fire compartment for test C2.*

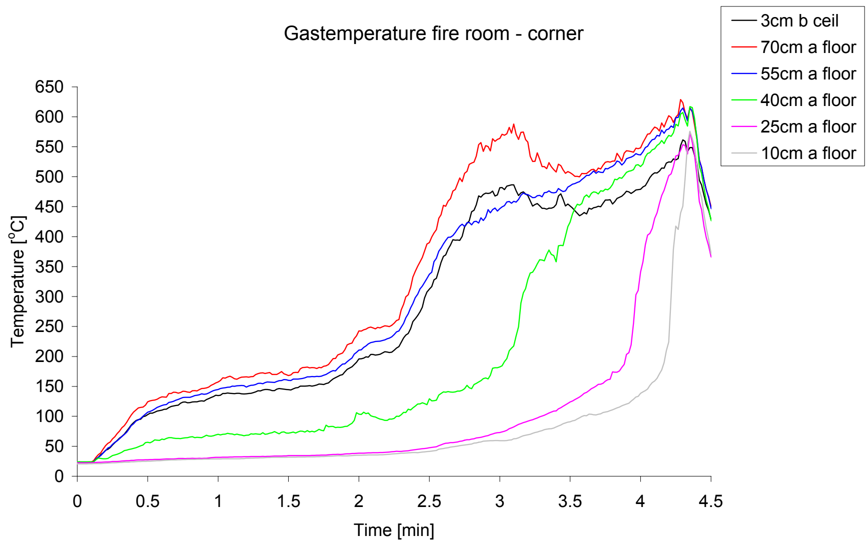

Figure B-9 *Gastemperature in the corner of the fire compartment for test C2.*

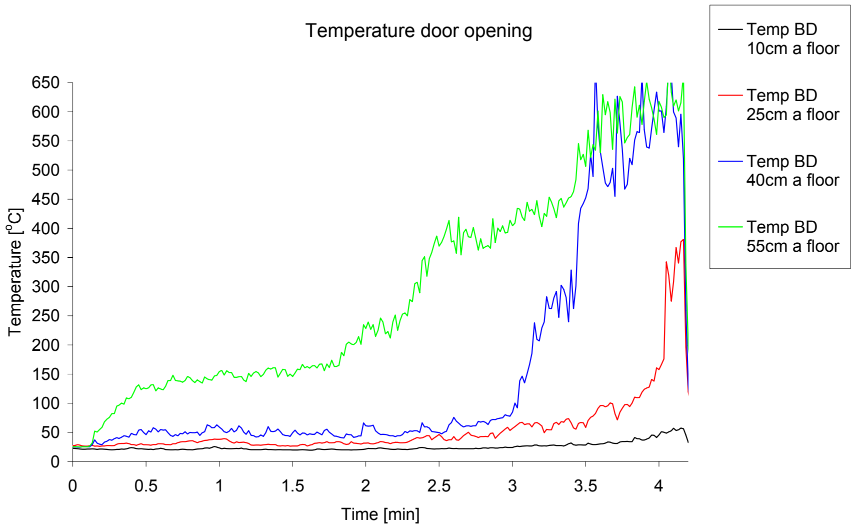

Figure B-10 *Gastemperature in the door opening for test C2.*

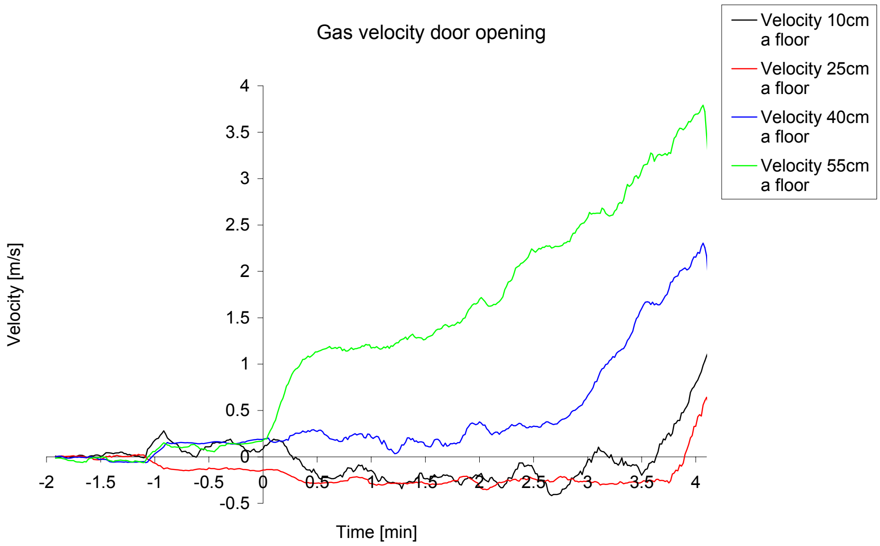

Figure B-11 *Gas velocity in the door opening for test C2.*

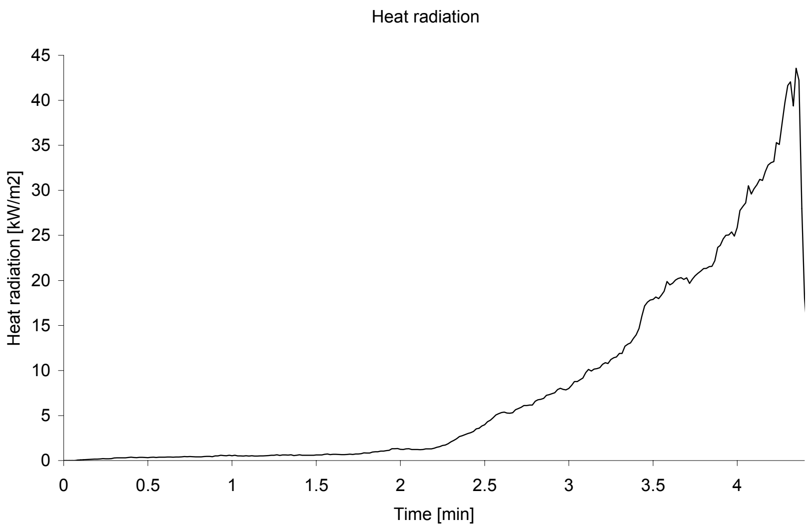

Figure B-12 *Heat radiation to the floor for test C2.*

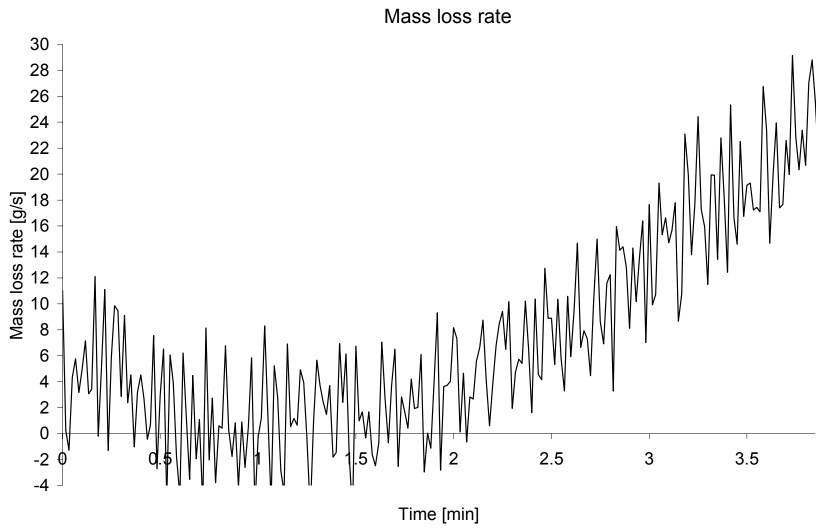

Figure B-13 *Mass loss rate of the linings for test C2.*

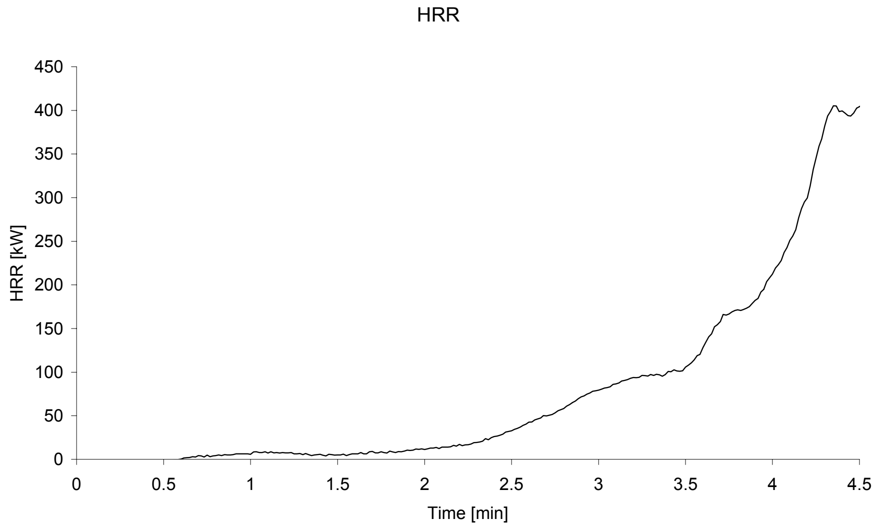

Figure B-14 *Heat release rate for test C2.*

Time [min:sec]	Event/observation
00:00	Test start
05:00	Walls opposite inflow start pyrolysing
08:35	Spontaneous ignition and first visible flame
08:45	Flashover
09:00	Test terminated

Table B-3 *Main events during test C3 using hot combustion gases.*

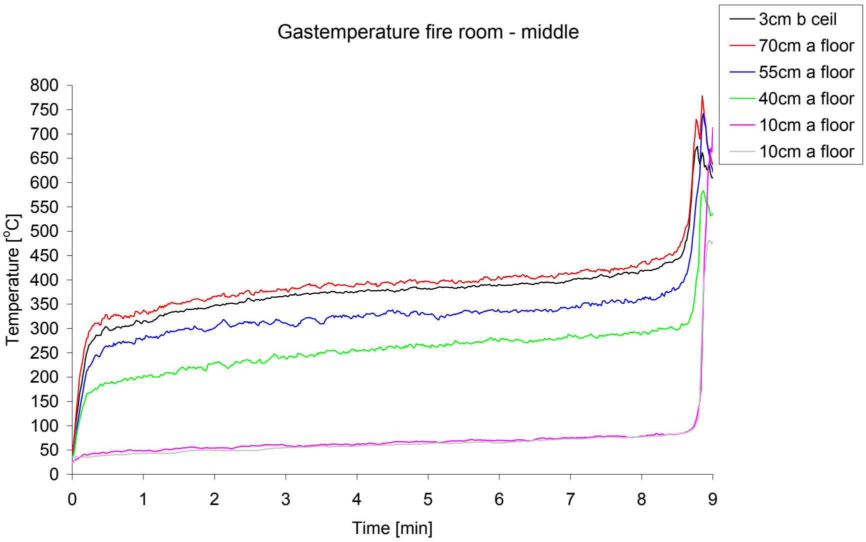

Figure B-15 *Gastemperature in the middle of the fire compartment for test C3.*

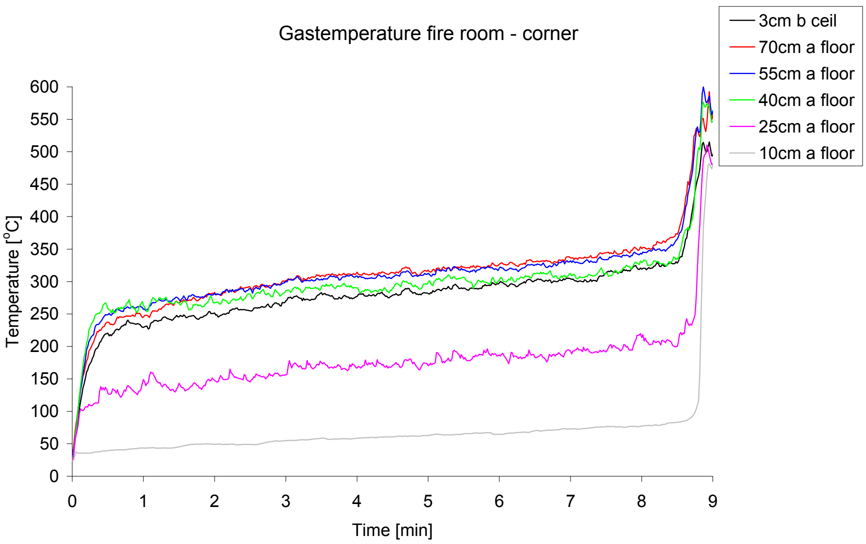

Figure B-16 *Gastemperature in the corner of the fire compartment for test C3.*

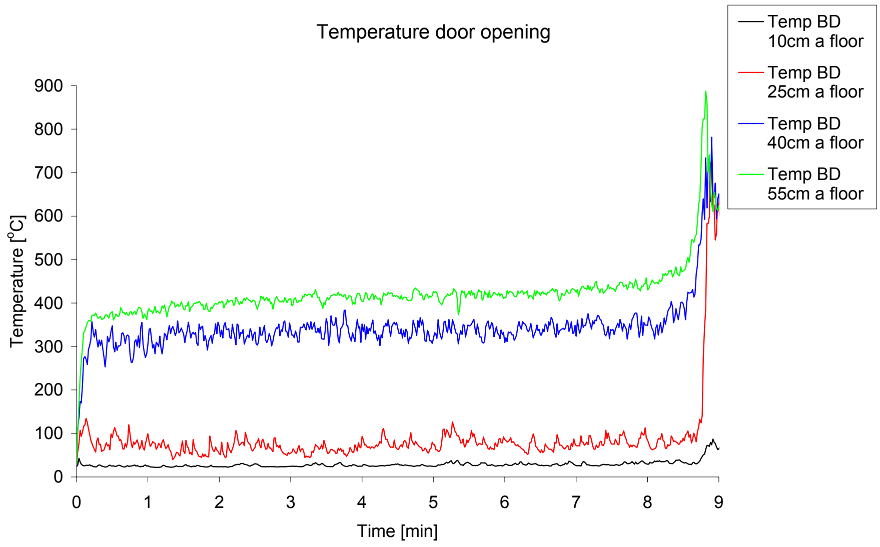

Figure B-17 *Gastemperature in the door opening for test C3.*

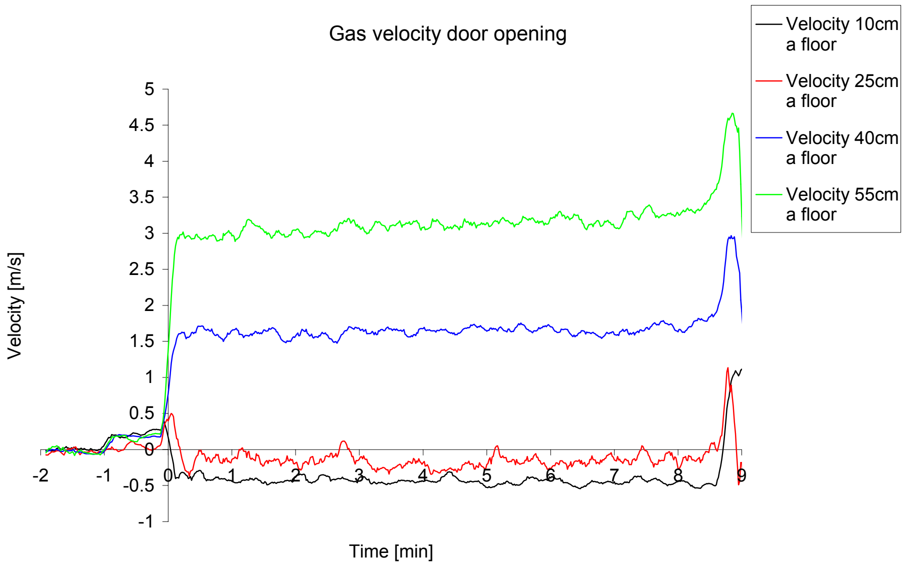

Figure B-18 *Gas velocity in the door opening for test C3.*

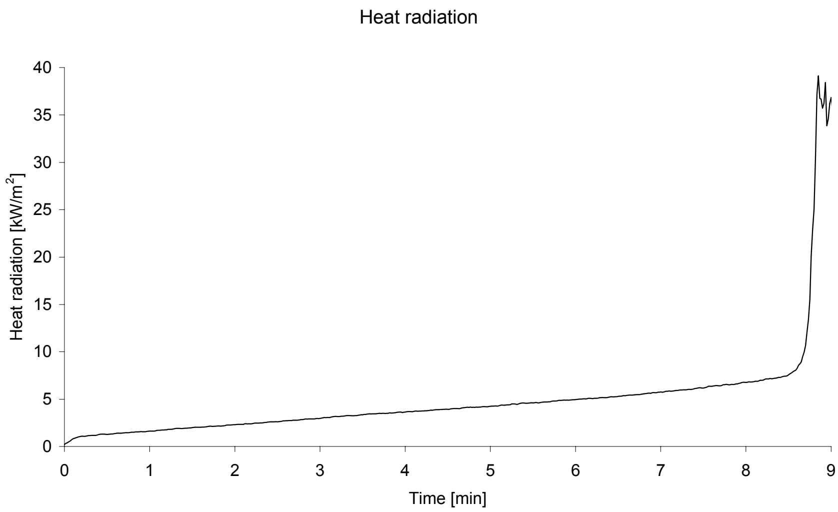

Figure B-19 *Heat radiation to the floor for test C3.*

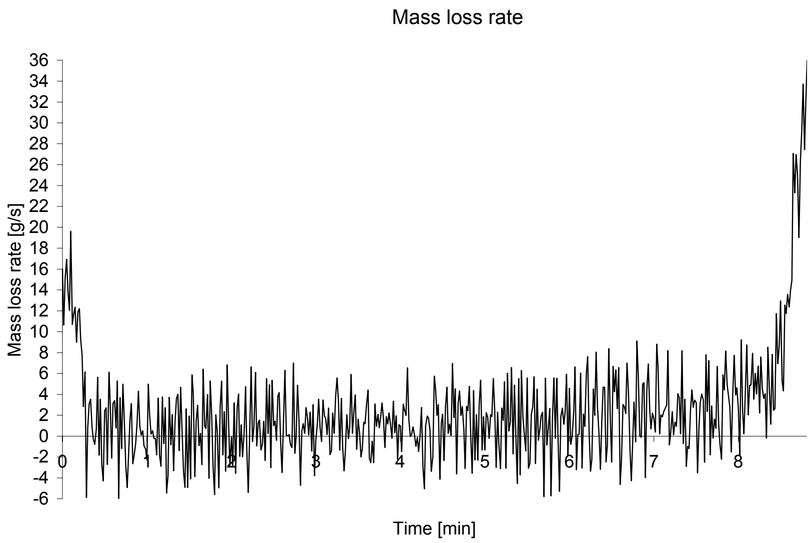

Figure B-20 *Mass loss rate of the linings for test C3.*

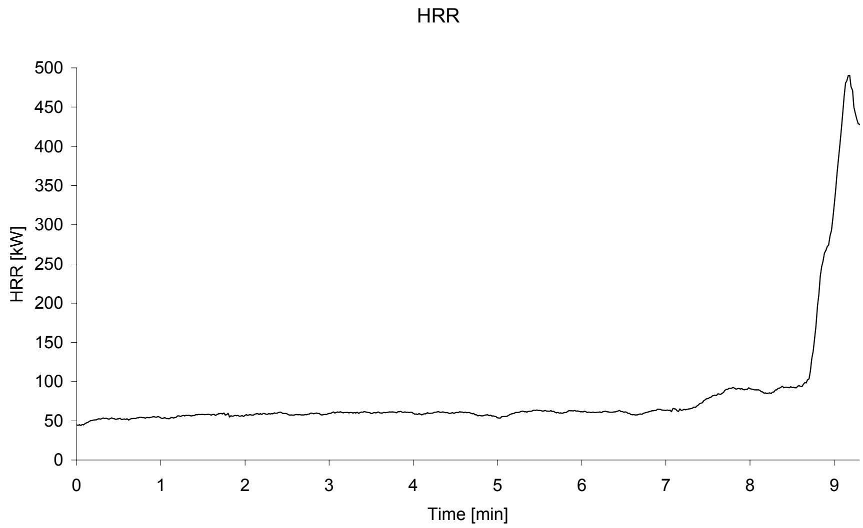

Figure B-21 *Heat release rate for test C3.*

Time [min:sec]	Event/observation
00:00	Test start
00:15	Flame (continuous) height 35cm
00:45	Surface darkens above fuel pan
01:20	Flame height 45cm
01:45	Flame height 50cm
01:50	Ignition of MDF board above burner
02:00	Flame reaches the ceiling
02:40	Combustion in lower part of smoke layer
03:00	First flame emerges through opening
03:10	Floor pyrolysis starts
03:15	Flashover
03:55	Floor ignition
04:00	Test is terminated

Table B-4 *Main events during test C4 using a heptane pool fire.*

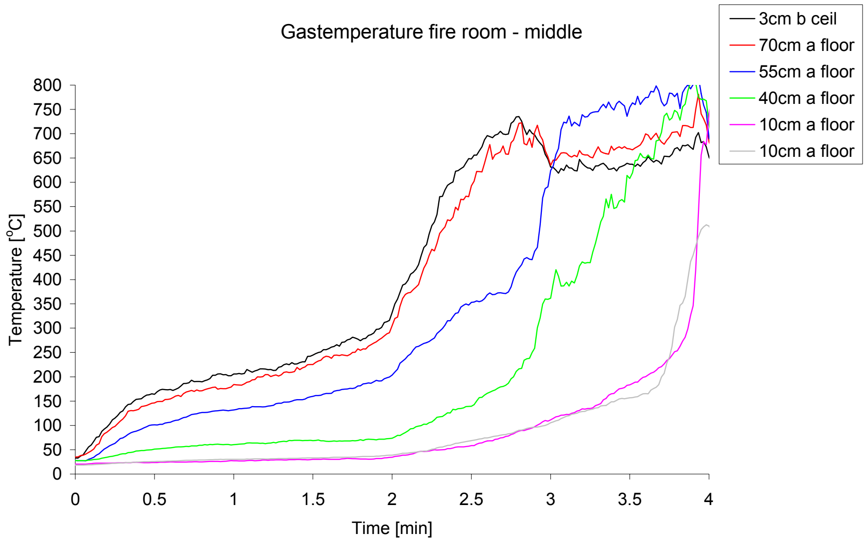

Figure B-22 *Gastemperature in the middle of the fire compartment for test C4.*

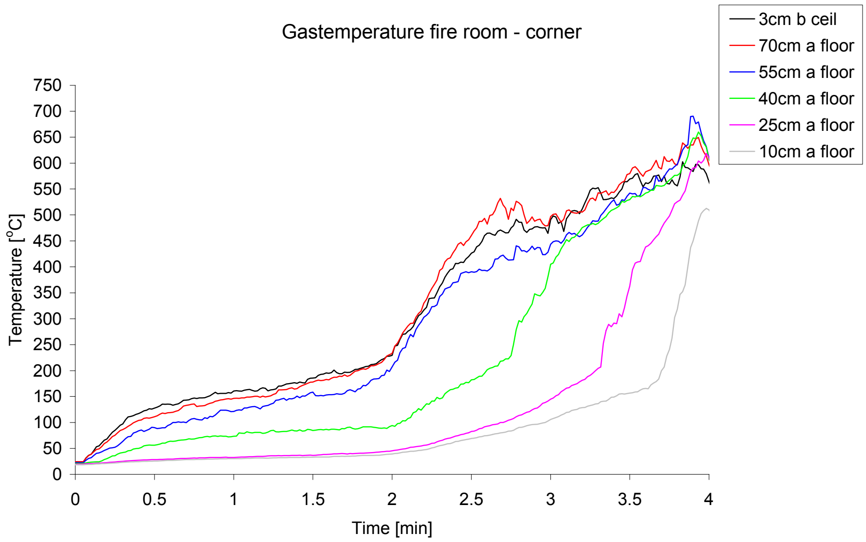

Figure B-23 *Gastemperature in the corner of the fire compartment for test C4.*

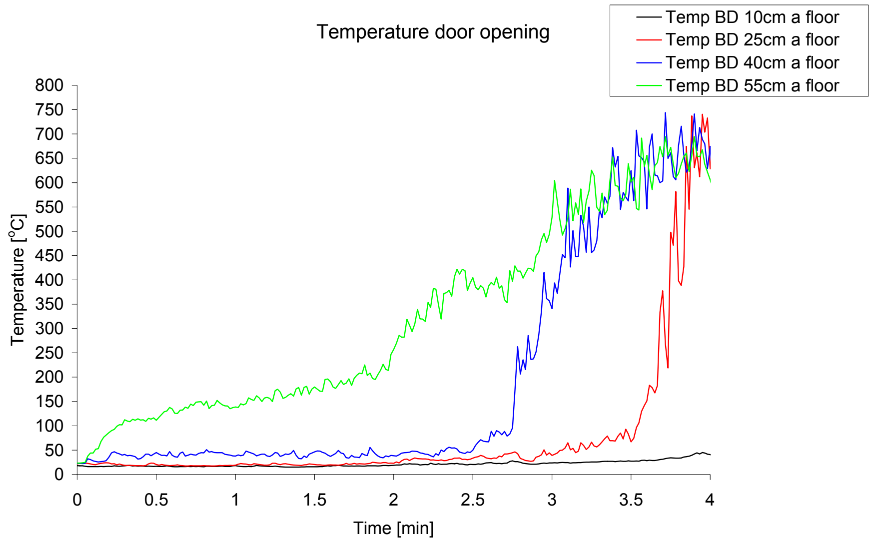

Figure B-24 *Gastemperature in the door opening for test C4.*

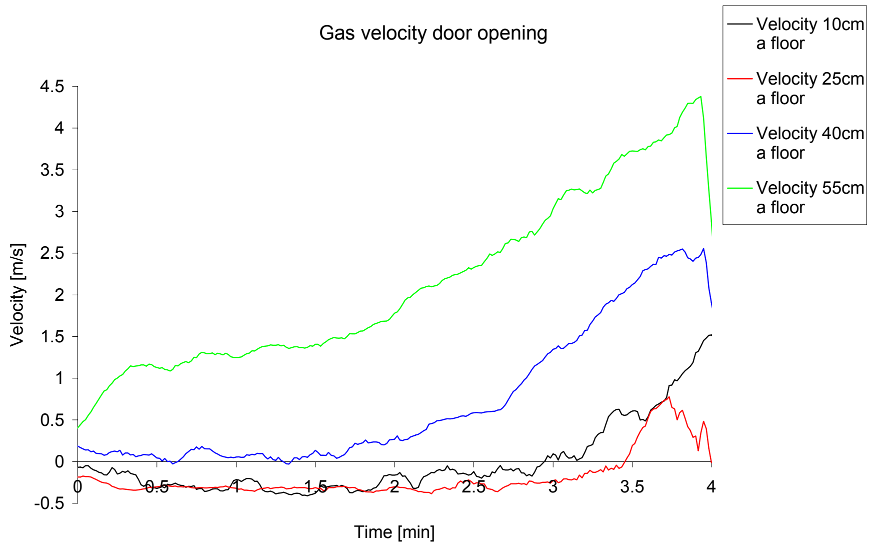

Figure B-25 *Gas velocity in the door opening for test C4.*

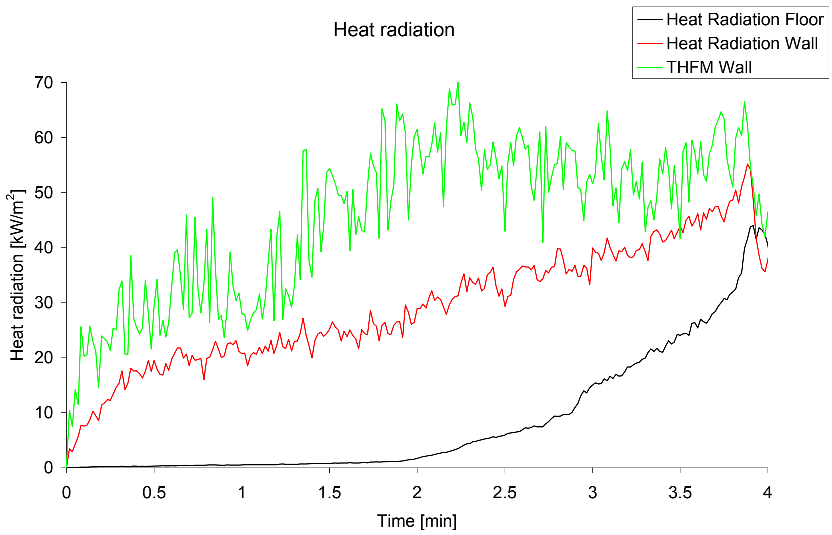

Figure B-26 *Heat radiation for test C4.*

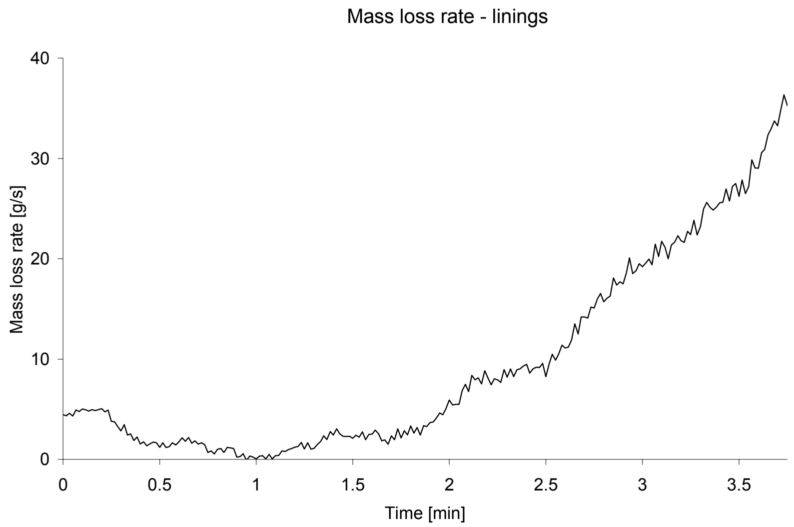

Figure B-27 *Mass loss rate of the linings for test C4.*

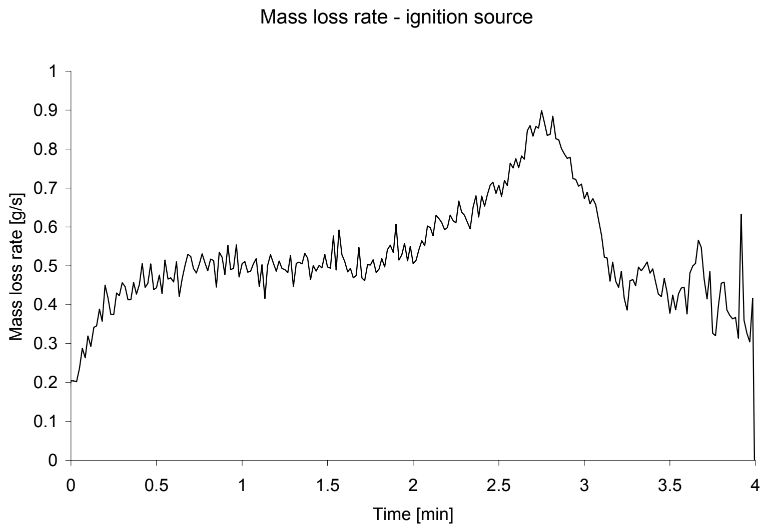

Figure B-28 *Mass loss rate of the ignition source for test C4.*

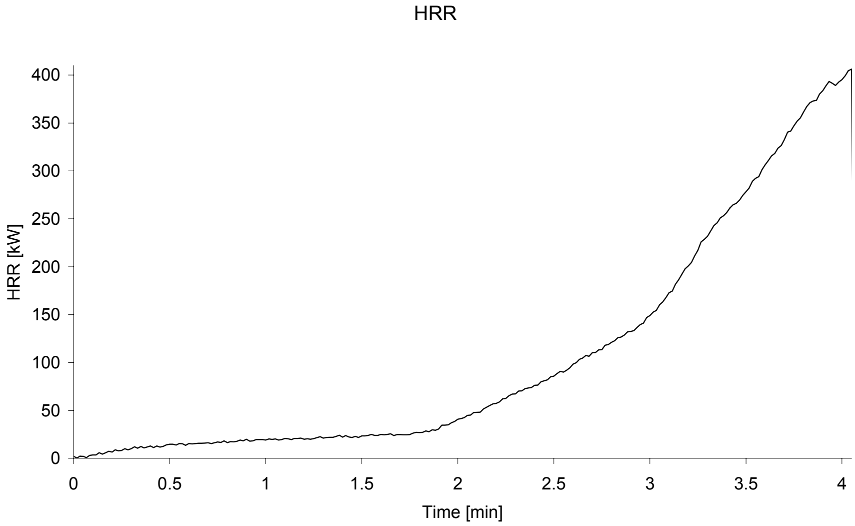

Figure B-29 *Heat release rate for test C4.*

Time [min:sec]	Event/observation
00:00	Test start
00:15	Flame (continuous) height 20cm
02:45	Surface starts to darken above fuel pan
06:05	Ignition of MDF above burner
06:10	Flame height 40cm
07:00	Flame reaches ceiling
07:20	Ceiling flame reaches opposite wall (0.8m)
07:30	Combustion in lower part of smoke layer
07:40	First flame emerges through opening followed by flashover
07:45	Floor pyrolysis starts
08:30	Test is terminated

Table B-5 *Main events during test C5 using a methanol pool fire.*

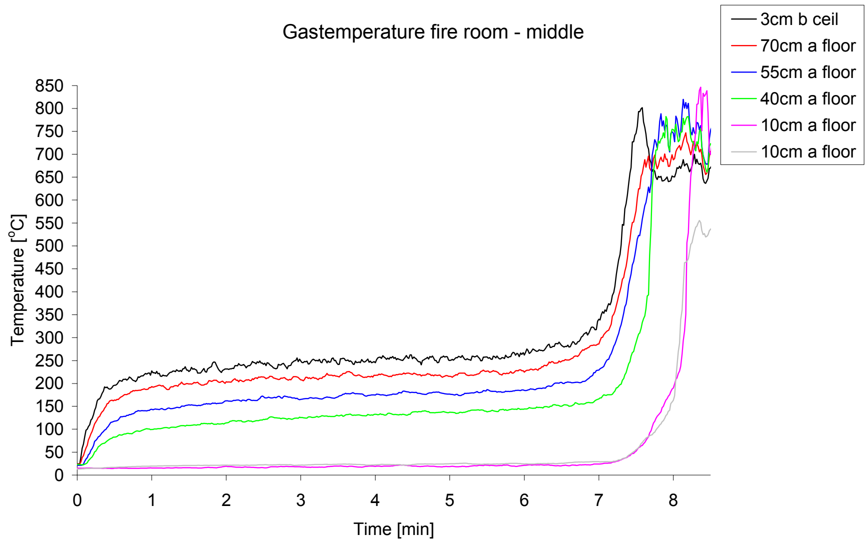

Figure B-30 *Gastemperature in the middle of the fire compartment for test C5.*

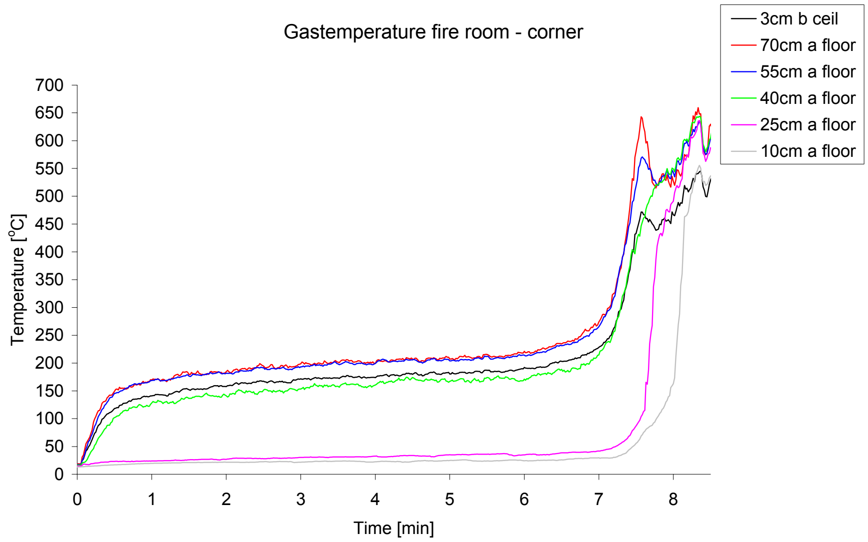

Figure B-31 *Gastemperature in the corner of the fire compartment for test C5.*

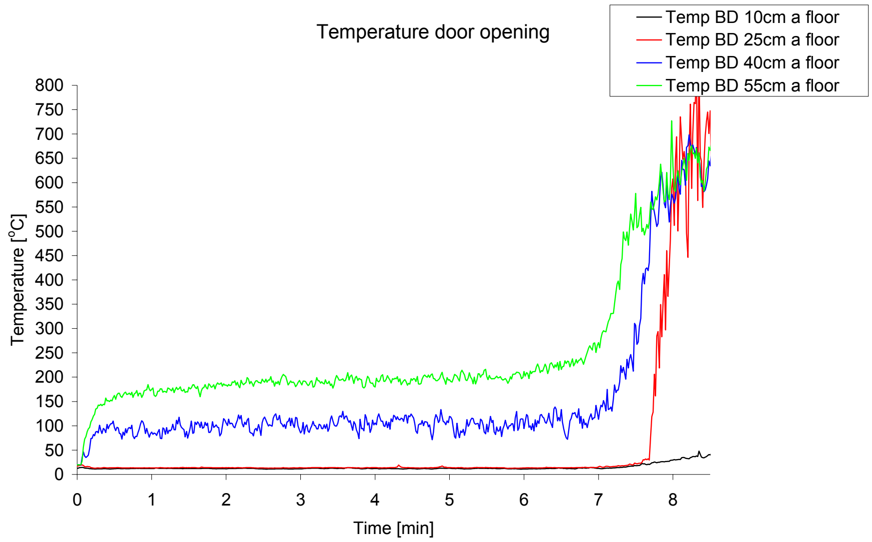

Figure B-32 *Gastemperature in the door opening for test C5.*

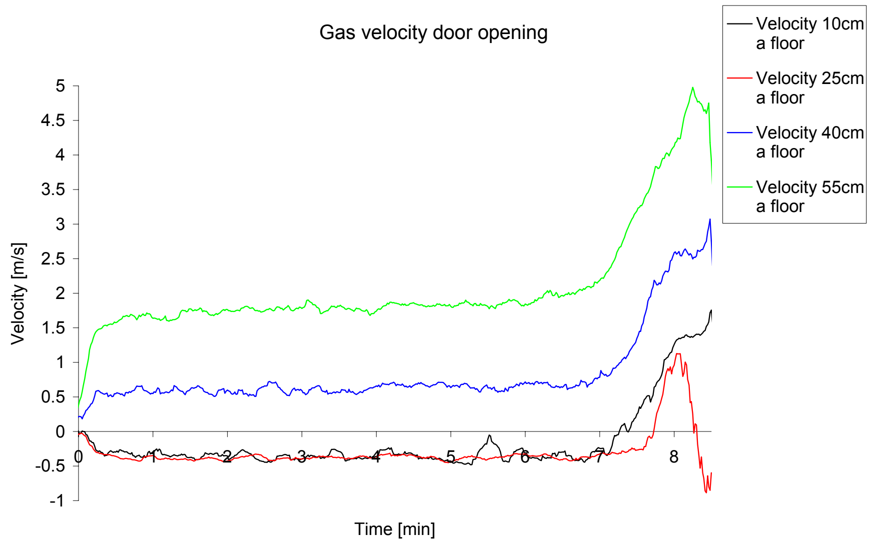

Figure B-33 *Gas velocity in the door opening for test C5.*

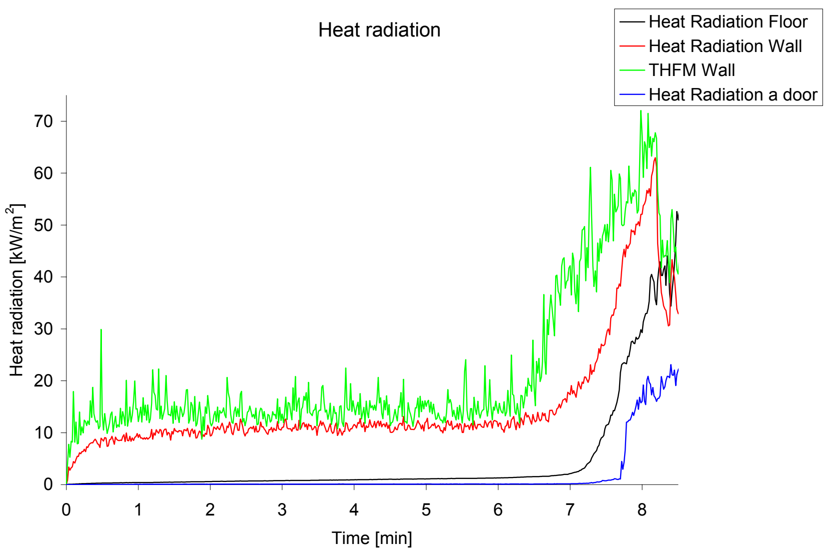

Figure B-34 *Heat radiation for test C5.*

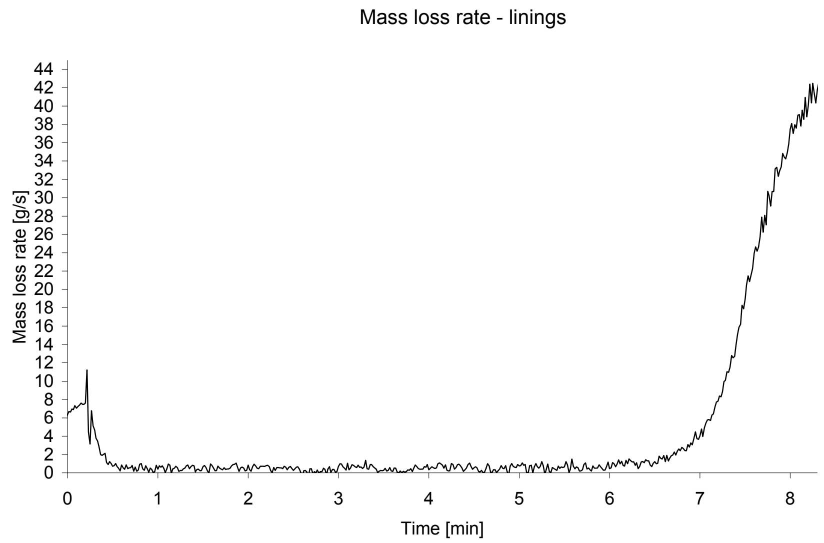

Figure B-35 *Mass loss rate of the linings for test C5.*

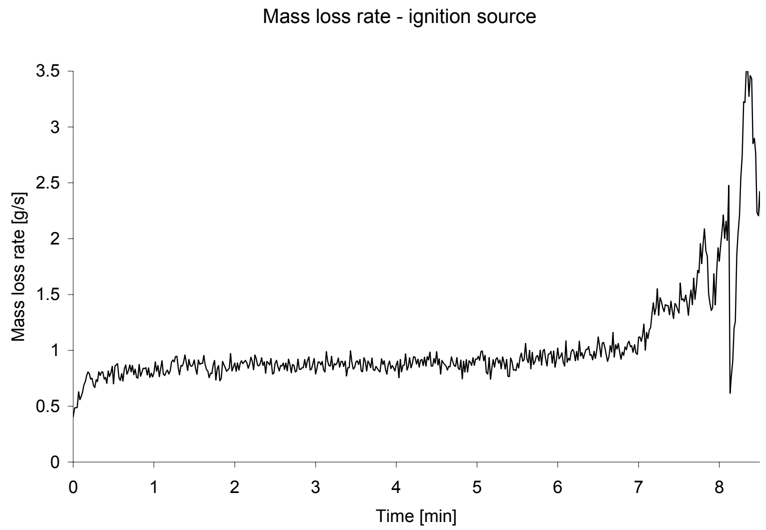

Figure B-36 *Mass loss rate for the ignition source for test C5.*

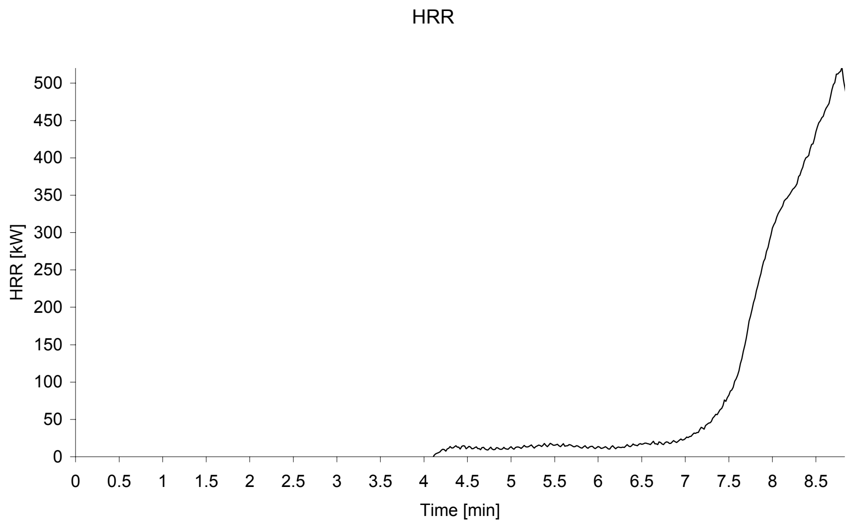

Figure B-37 *Heat release rate for test C5 (the oxygen measurement failed the first 4 minutes).*

Time [min:sec]	Event/observation
00:00	Test start
01:20	Visible flame
01:35	Flame (continuous) height 40cm
02:05	Flame (continuous) height 60cm
03:10	Flame (continuous) reach the ceiling
03:50	Surface darkens in ceiling above fire and walls close to ceiling
04:05	Pyrolysis of the ceiling begins
04:40	Ignition of MDF board in ceiling
04:50	Ceiling flame reaches opposite wall (0.8m)
05:10	Combustion in lower part of smoke layer
05:30	First flame emerges through opening followed by flashover
05:30	Floor pyrolysis starts
06:20	Floor ignites
06:40	Test terminated

Table B-6 *Main events during test C6 using a wood crib fire.*

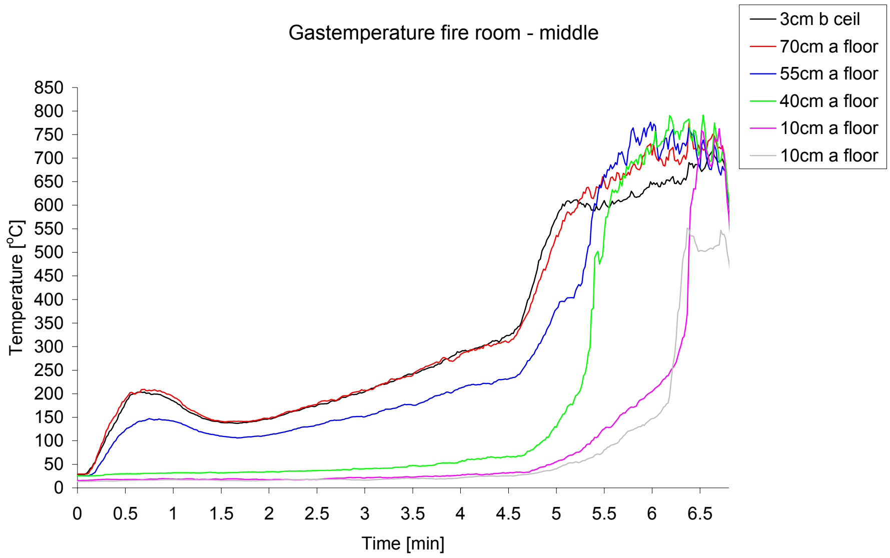

Figure B-38 *Gastemperature in the middle of the fire compartment for test C6.*

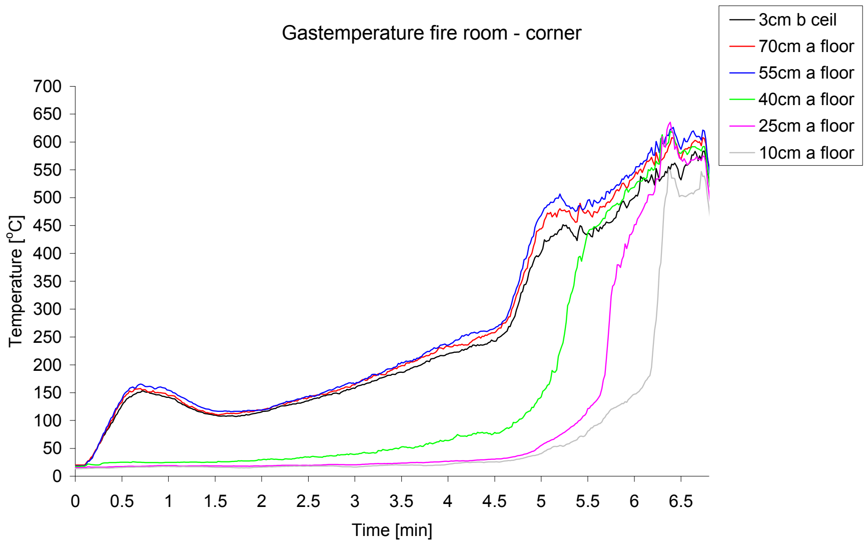

Figure B-39 *Gastemperature in the corner of the fire compartment for test C6.*

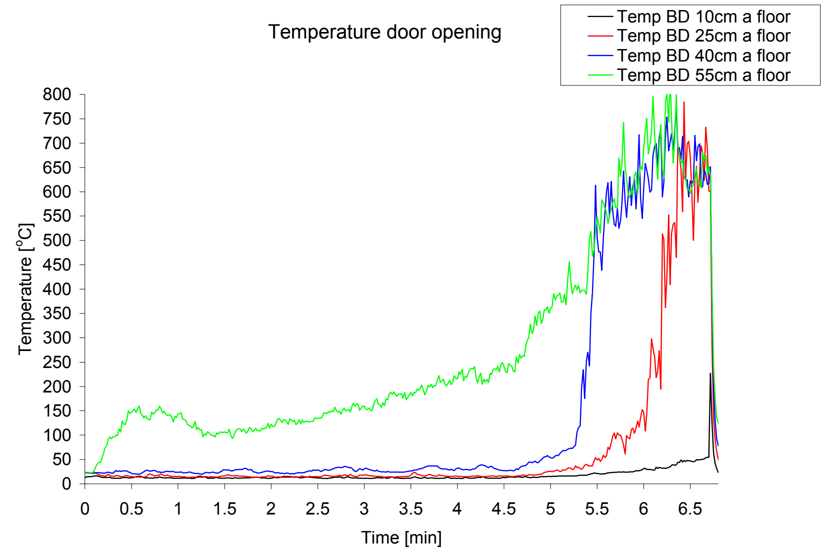

Figure B-40 *Gastemperature in the door opening for test C6.*

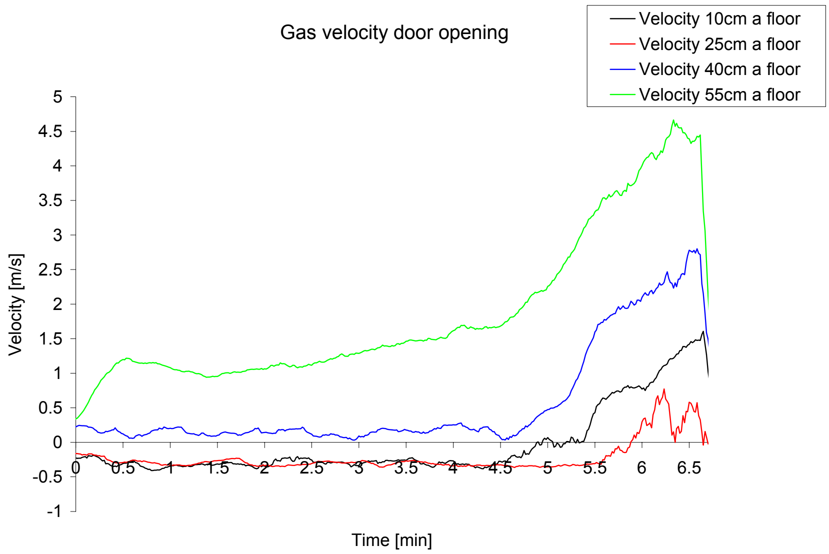

Figure B-41 *Gas velocity in the door opening for test C6.*

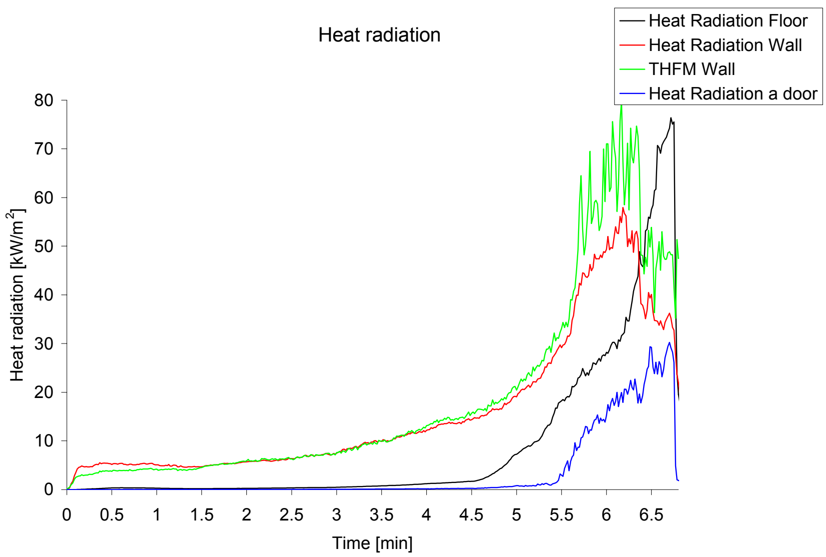

Figure B-42 *Heat radiation for test C6.*

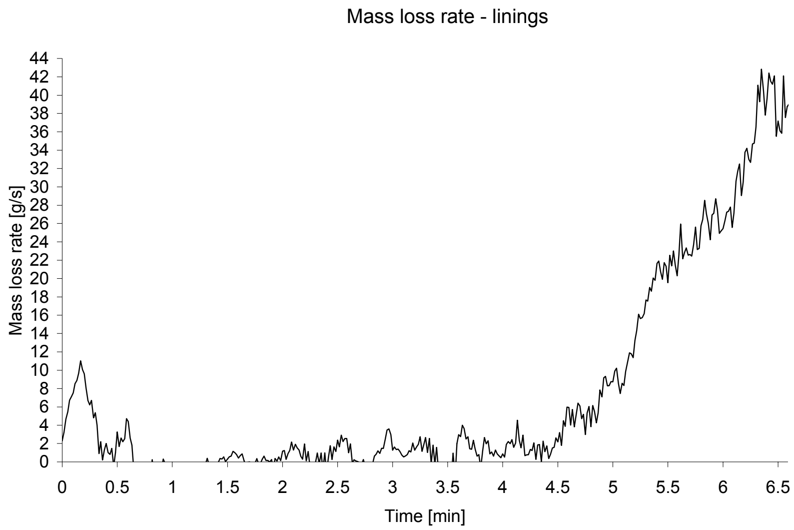

Figure B-43 *Mass loss rate of the linings for test C6.*

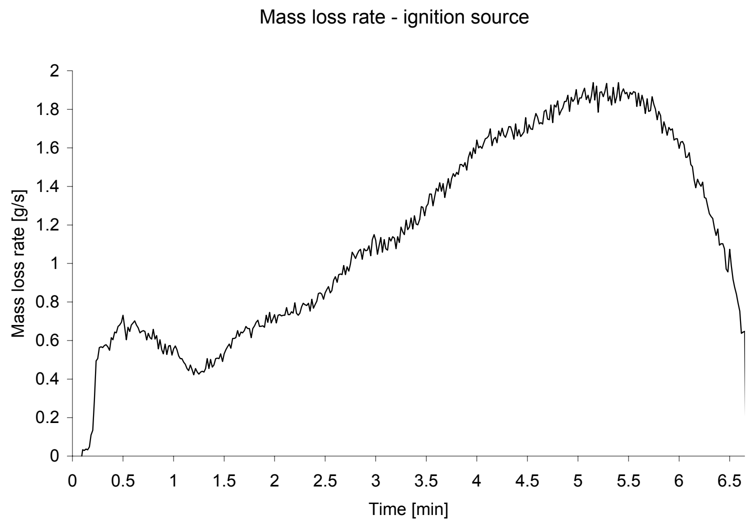

Figure B-44 *Mass loss rate for the ignition source for test C6.*

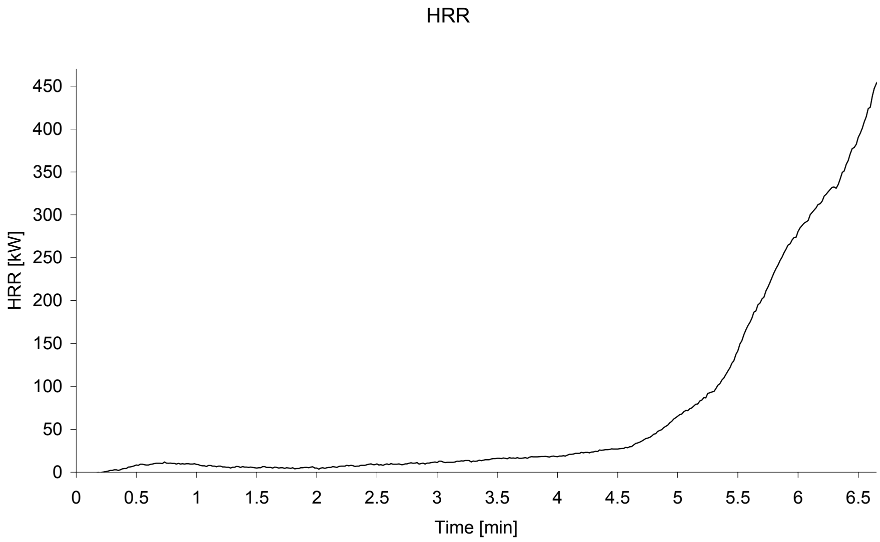

Figure B-45 *Heat release rate for test C6.*

Time [min:sec]	Event/observation
00:00	Test start
02:20	Flames reach the ceiling (continously) of the fire compartment
03:30	First flame enters the upper compartment
08:00	Continuous flame through the opening between compartments
08:30	Fire becomes underventilated and no flame through to the upper compartment
09:00	Combustion becomes oscillary
09:50	Wall pyrolysis in the upper compartment starts
10:15	Fire spread to the upper compartment is observed

Table B-7 *Main events during test V1.*

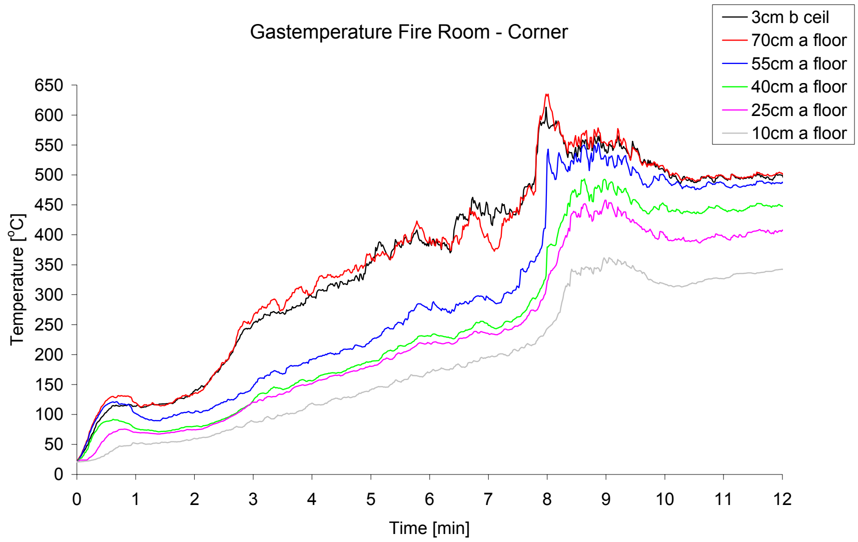

Figure B-46 *Gastemperature in the corner of the fire compartment for test V1.*

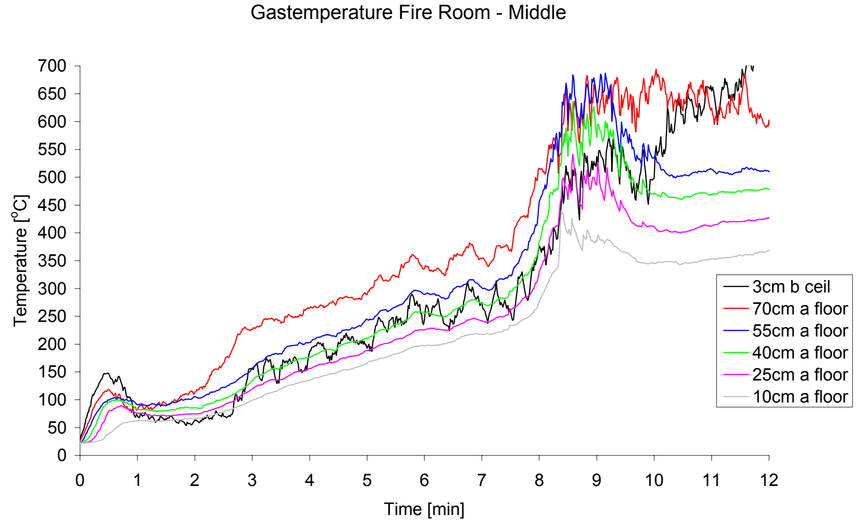

Figure B-47 *Gastemperature in the middle of the fire compartment for test V1.*

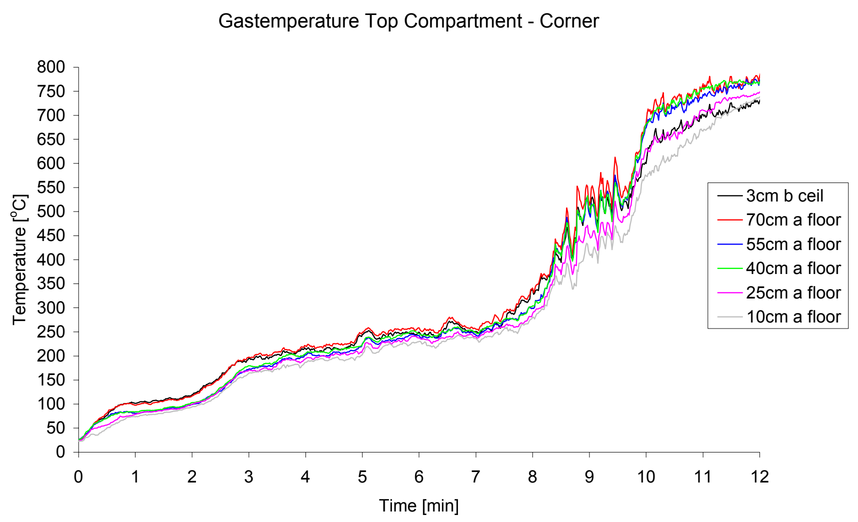

Figure B-48 *Gastemperature in the corner of the top compartment for test V1.*

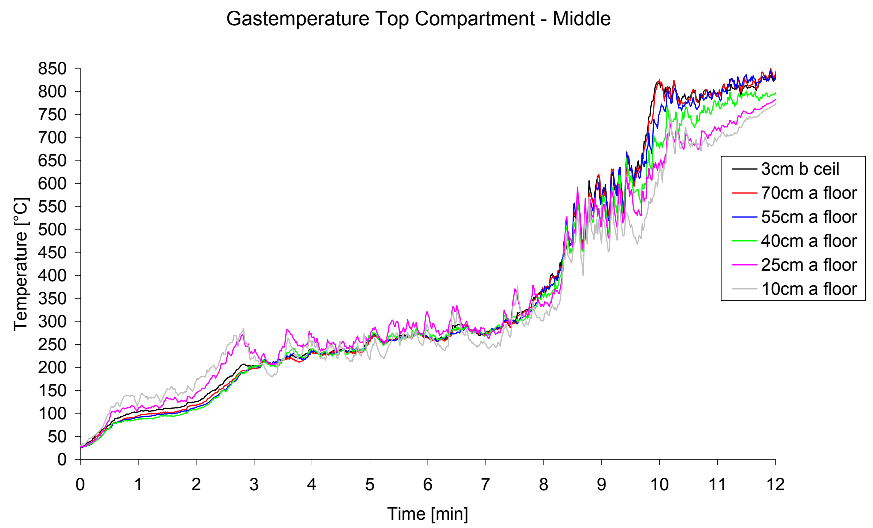

Figure B-49 *Gastemperature in the middle of the top compartment for test V1.*

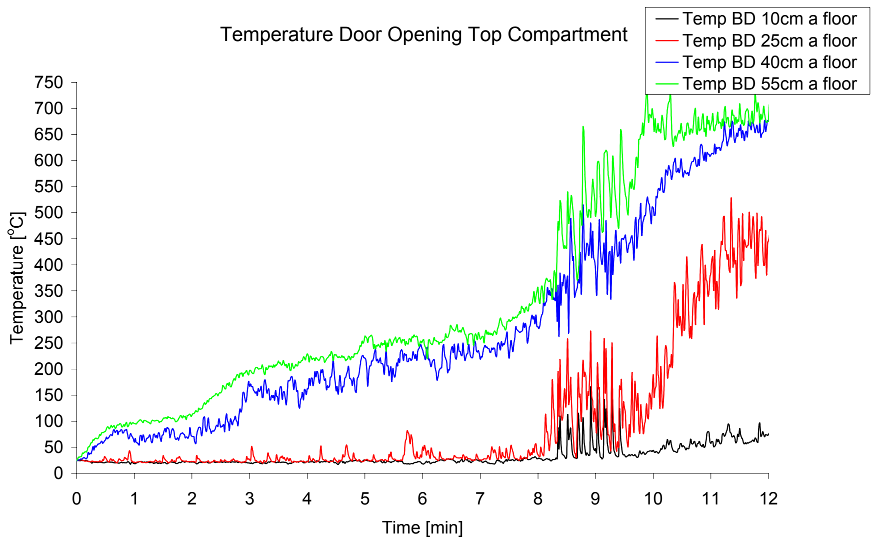

Figure B-50 *Gastemperature in the door opening of the top compartment for test V1.*

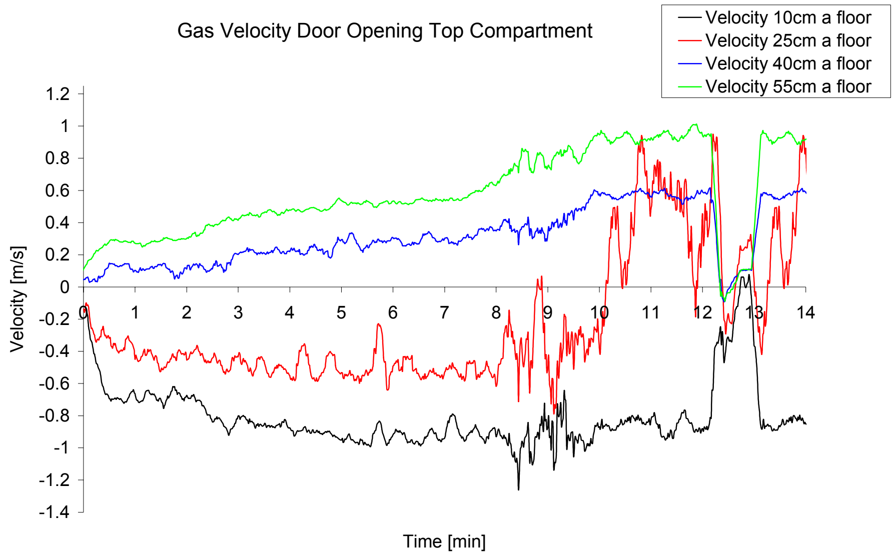

Figure B-51 *Gas velocity in the door opening of the top compartment for test V1.*

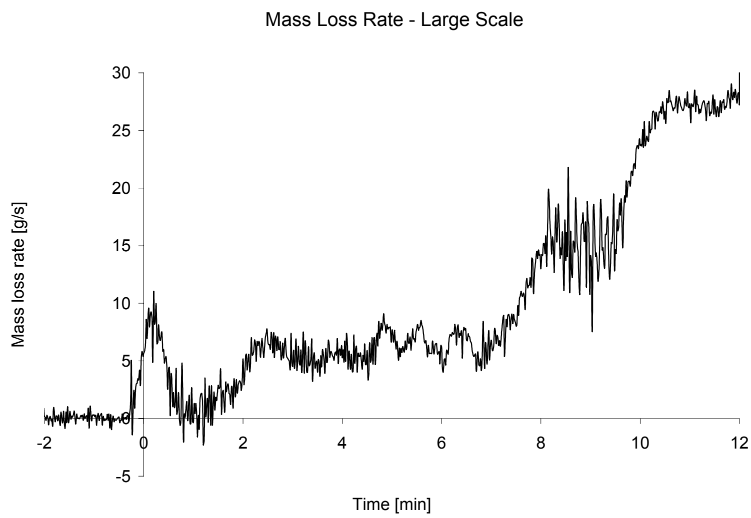

Figure B-52 *Mass loss rate of the linings for test V1.*

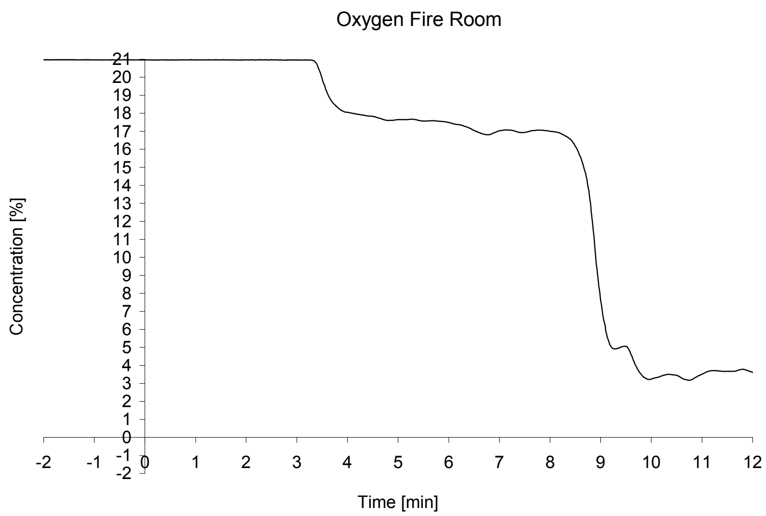

Figure B-53 *Oxygen concentration in the fire room for test V1.*

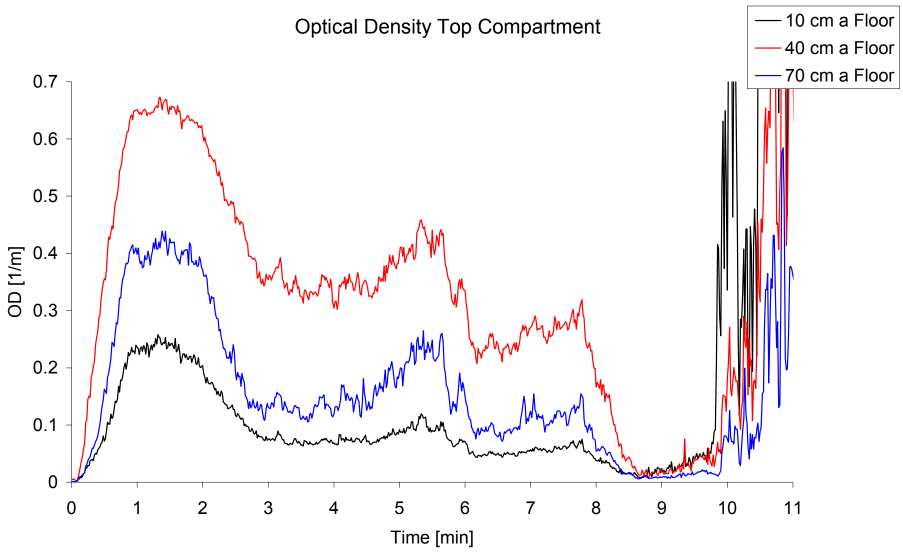

Figure B-54 *Optical density in the top compartment for test V1.*

Time [min:sec]	Event/observation
00:00	Fire start
01:15	Flames reach the ceiling (continously)
05:20	Fire intensity reduced due to underventilation, combustion becomes oscillatory, i.e. the combustion follows a cycle of reduced intensity combined with a increased rate of pyrolysis followed by the evolution of a fire ball and a period of increased burning rate.
25:15	Fire spread to the upper compartment is observed after which the test is terminated

Table B-8 *Main events during test V2.*

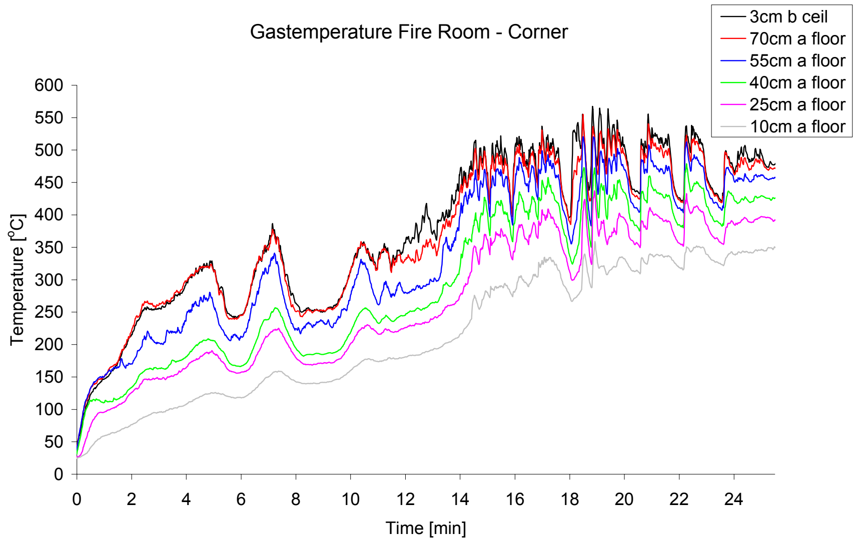

Figure B-55 *Gastemperature in the corner of the fire compartment for test V2.*

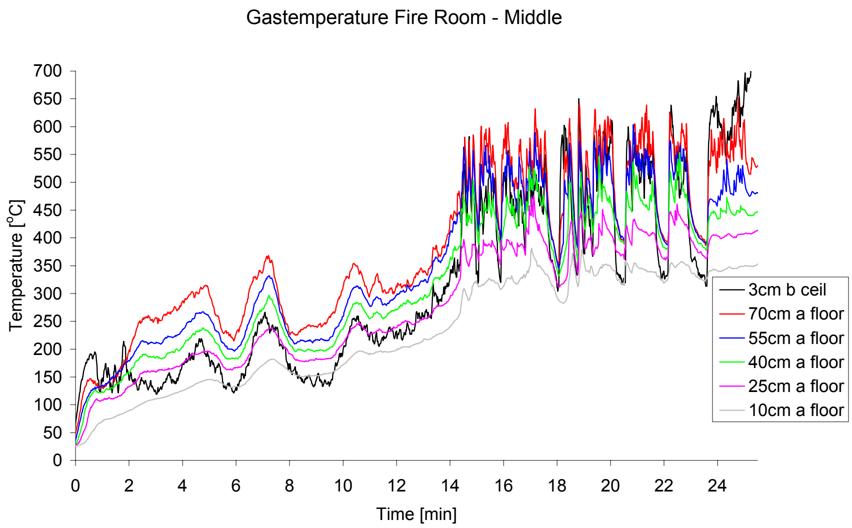

Figure B-56 *Gastemperature in the middle of the fire compartment for test V2-vertical.*

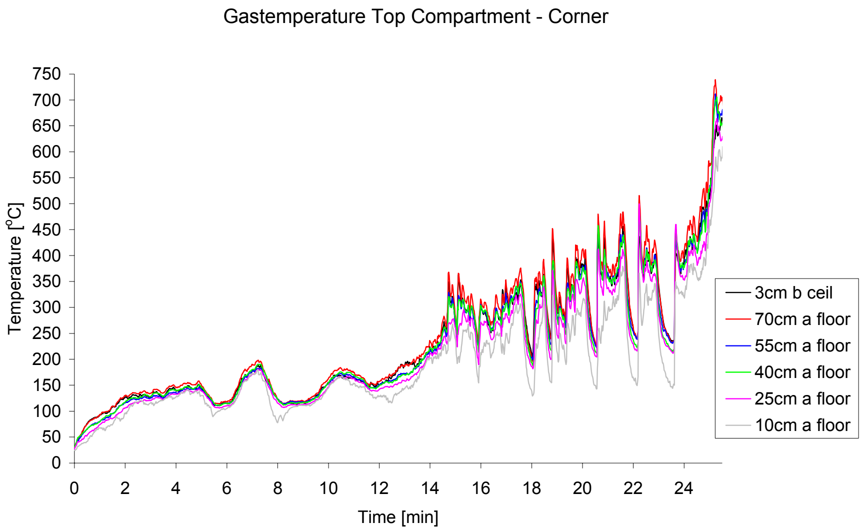

Figure B-57 *Gastemperature in the corner of the top compartment for test V2.*

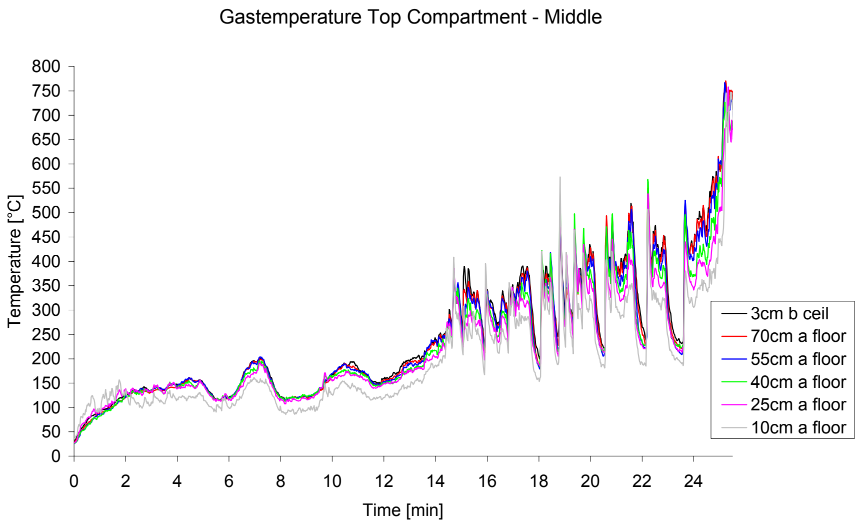

Figure B-58 *Gastemperature in the middle of the top compartment for test V2.*

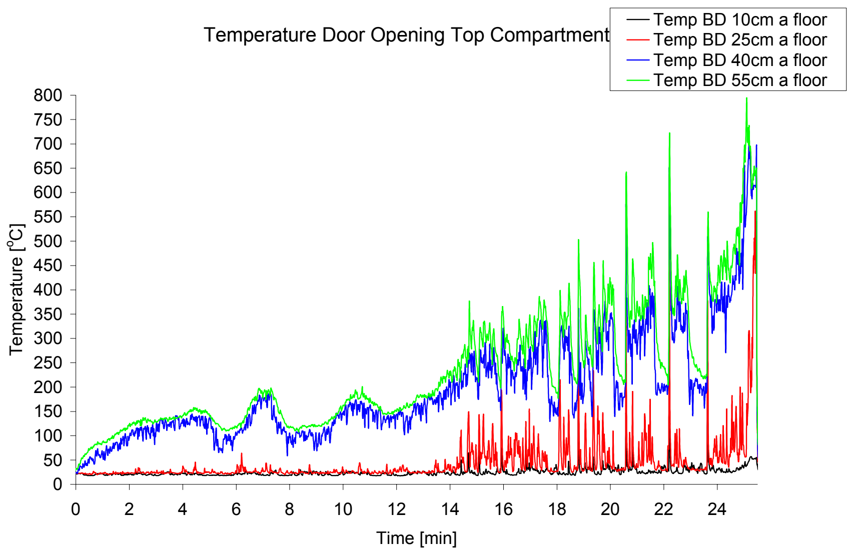

Figure B-59 *Gastemperature in the door opening of the top compartment for test V2.*

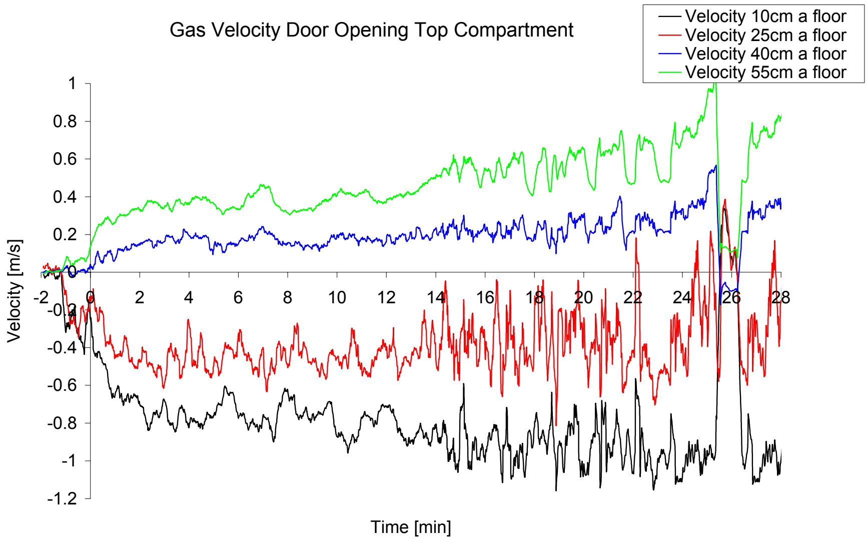

Figure B-60 *Gas velocity in the door opening of the top compartment for test V2.*

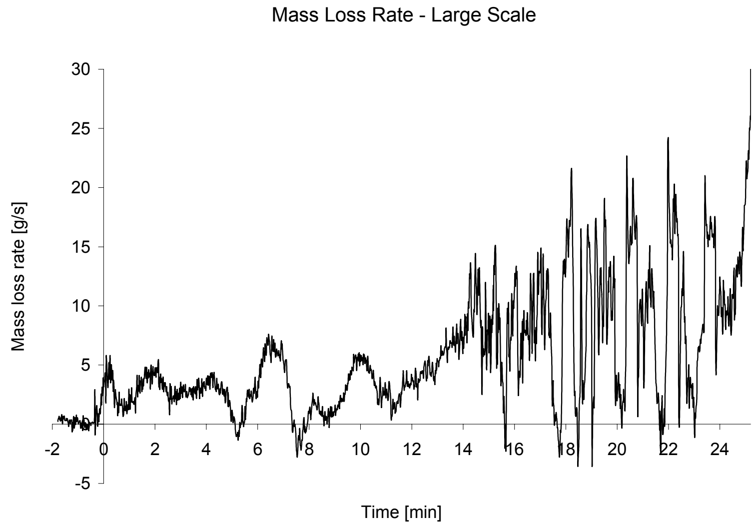

Figure B-61 *Mass loss rate of the linings for test V2.*

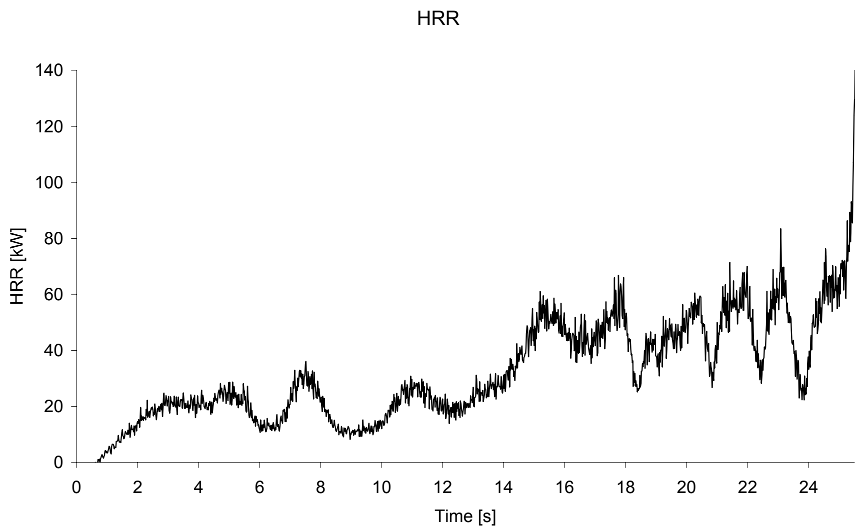

Figure B-62 *Heat release rate for test V2.*

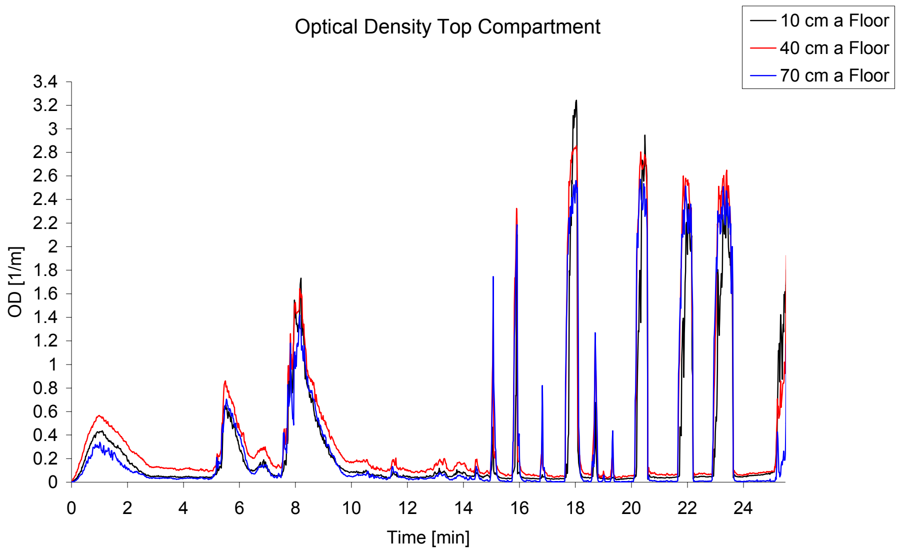

Figure B-63 *Optical density for the top compartment for test V2.*

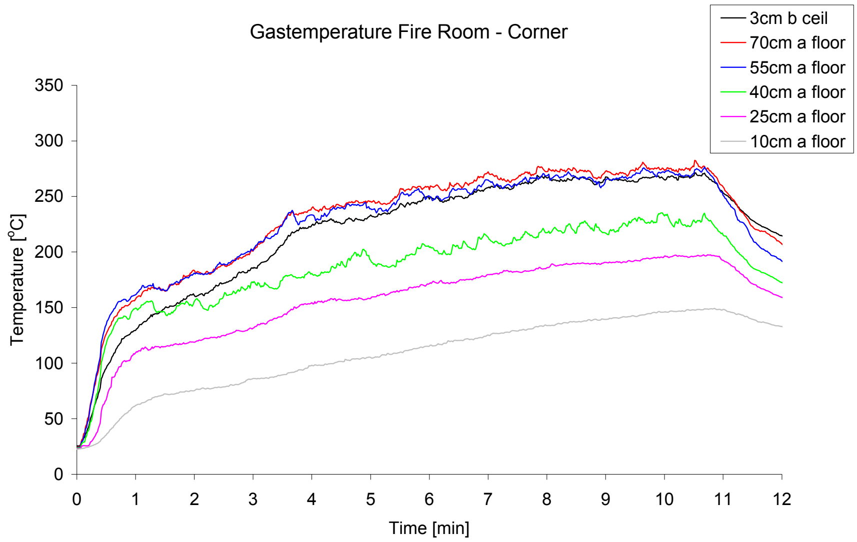

Figure B-64 *Gastemperature in the corner of the fire compartment for test V3.*

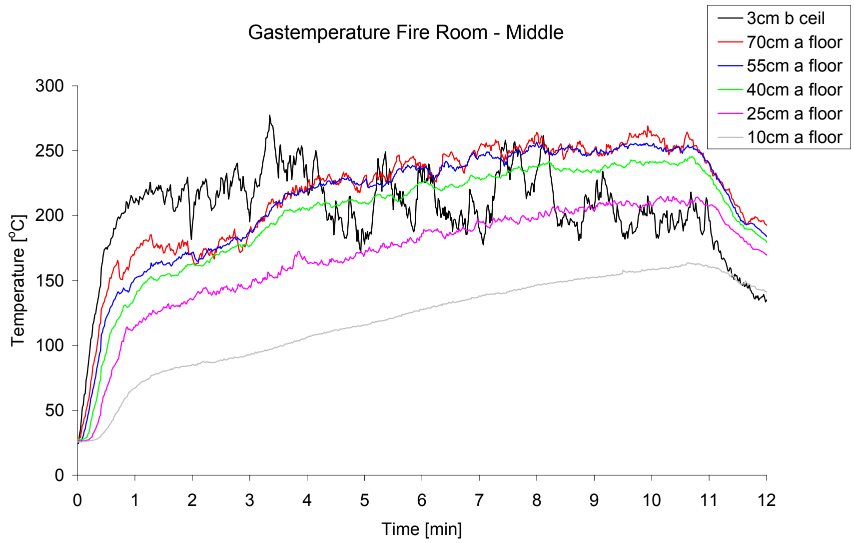

Figure B-65 *Gastemperature in the middle of the fire compartment for test V3*

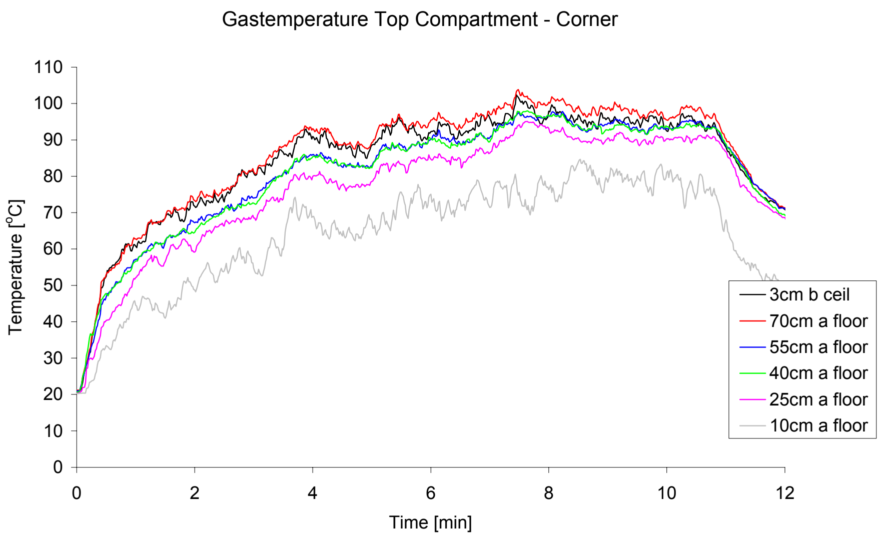

Figure B-66 *Gastemperature in the corner of the top compartment for test V3.*

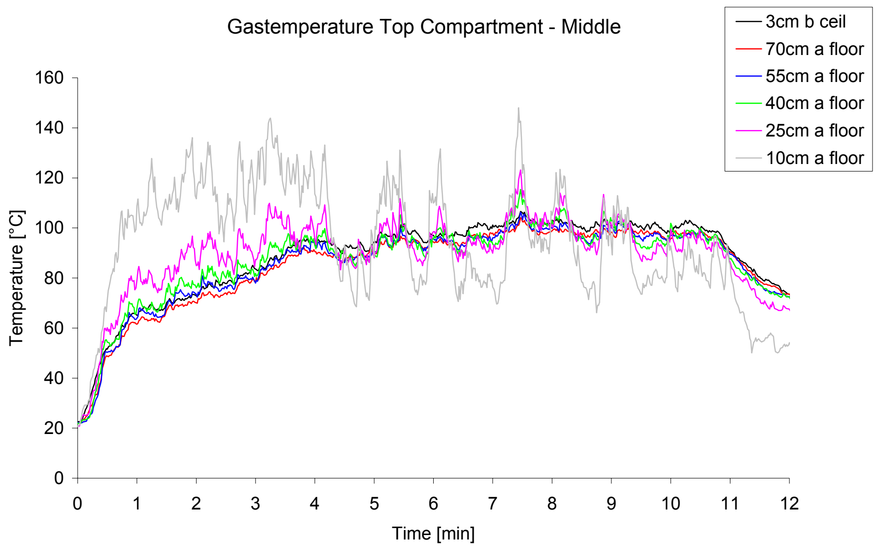

Figure B-67 *Gastemperature in the middle of the top compartment for test V3.*

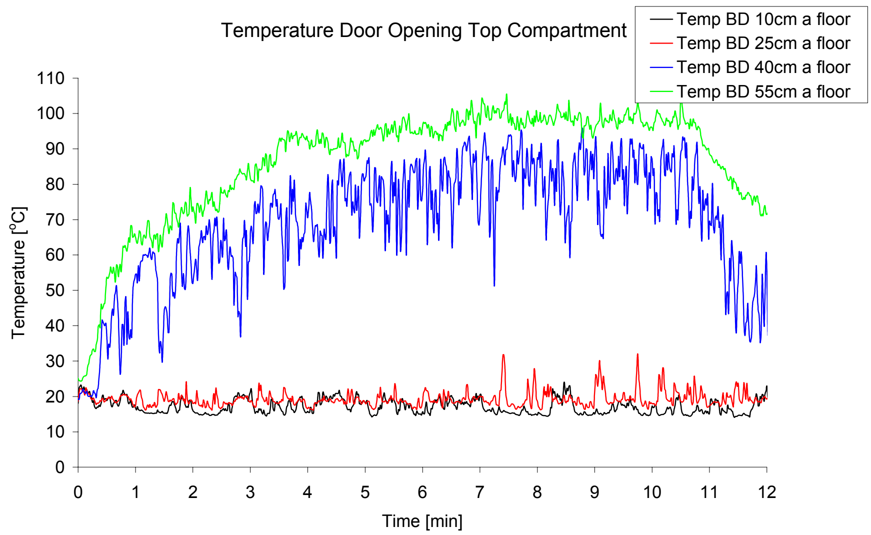

Figure B-68 *Gastemperature in the door opening of the top compartment for test V3.*

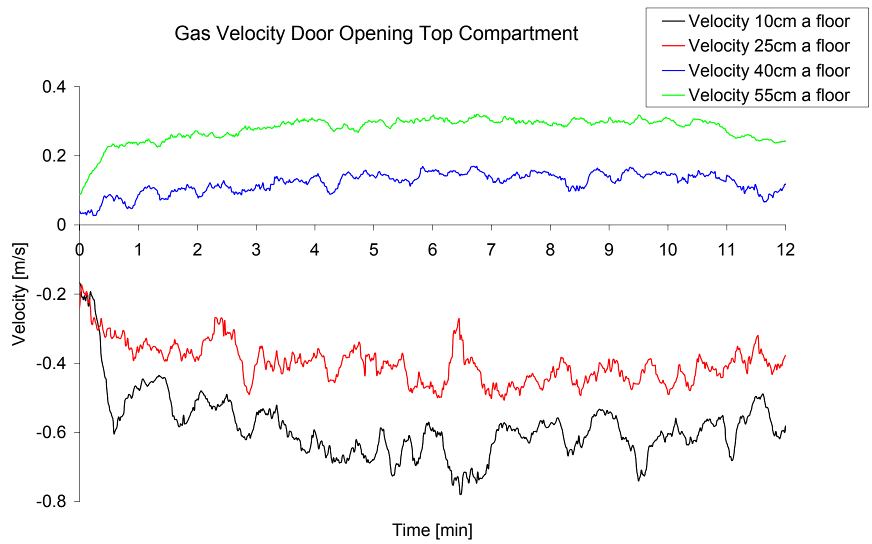

Figure B-69 *Gasvelocity in the door opening of the top compartment for test V3.*

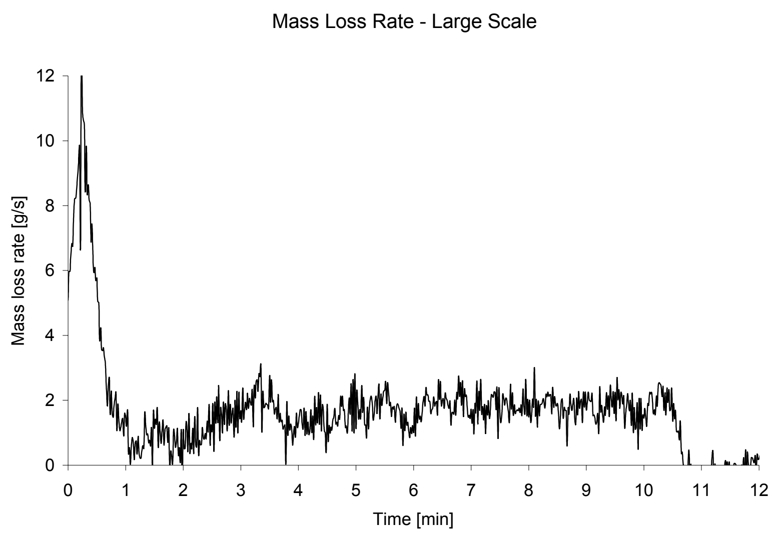

Figure B-70 *Mass loss rate of the linings for test V3.*

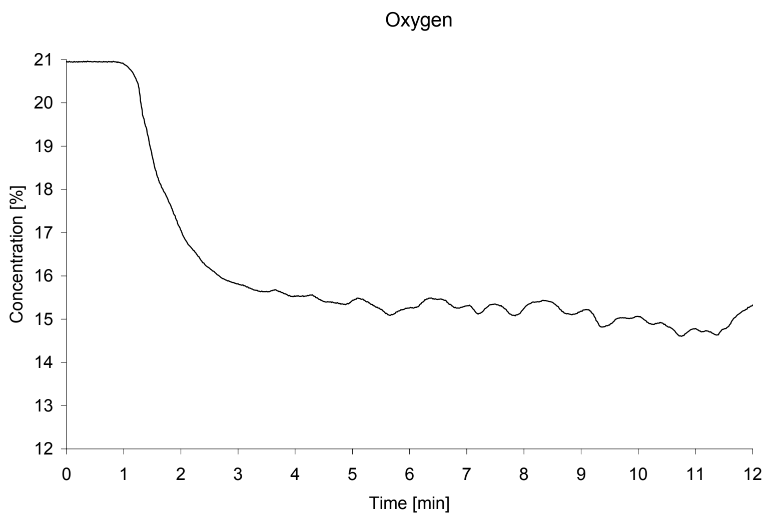

Figure B-71 *Oxygen concentration in the fire compartment for test V3.*

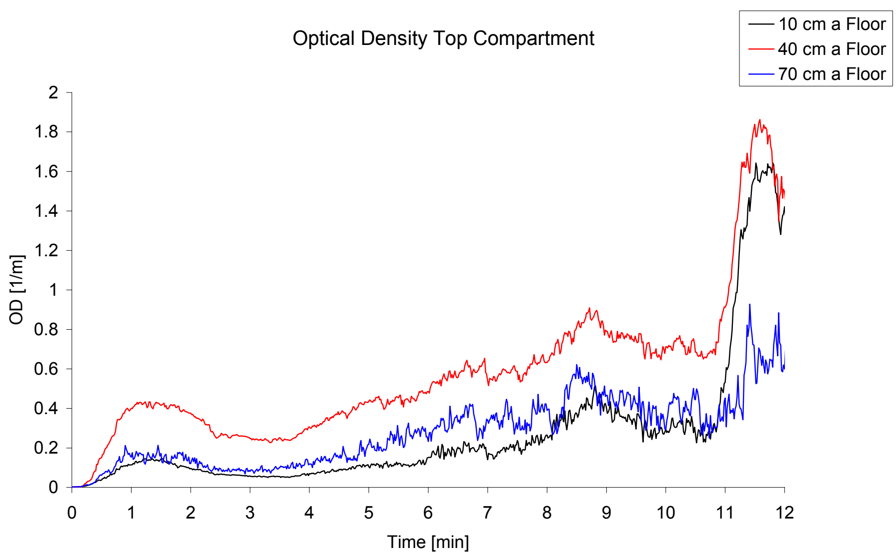

Figure B-72 *Optical density in the top compartment for test V3.*

Time [min:sec]	Event/observation
00:00	Fire start
02:20	First flame enters the upper compartment
02:50	Continuous flame through the opening between the planes
04:25	Flashover of the fire compartment
05:00	Fire spread to the upper compartment is observed after which the test is terminated

Table B-9 *Main events during test V4.*

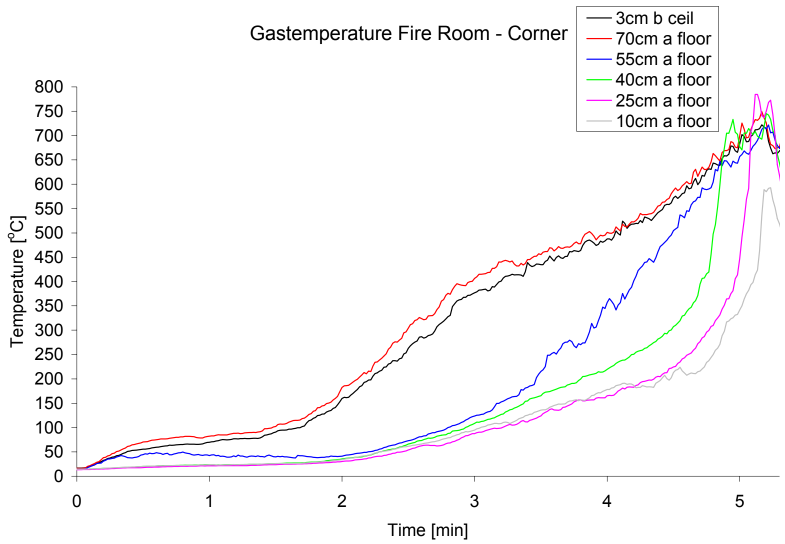

Figure B-73 *Gastemperature in the corner of the fire compartment for test V4.*

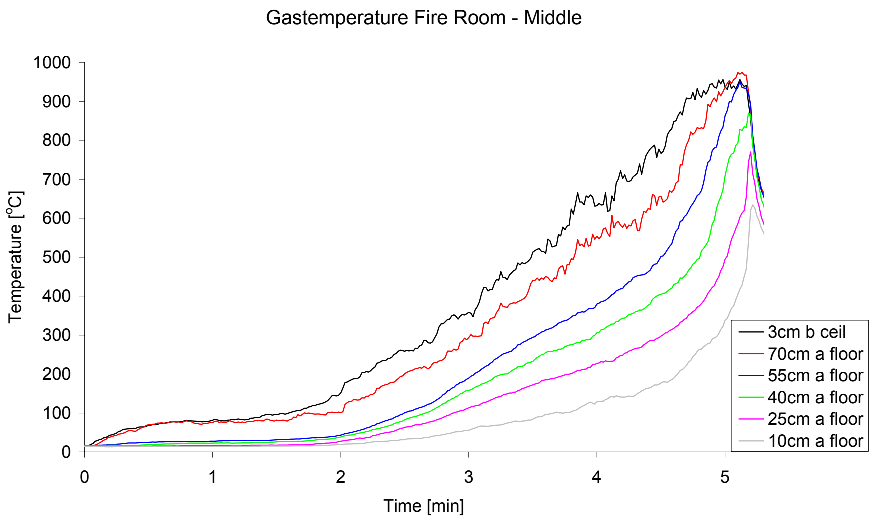

Figure B-74 *Gastemperature in the middle of the fire compartment for test V4.*

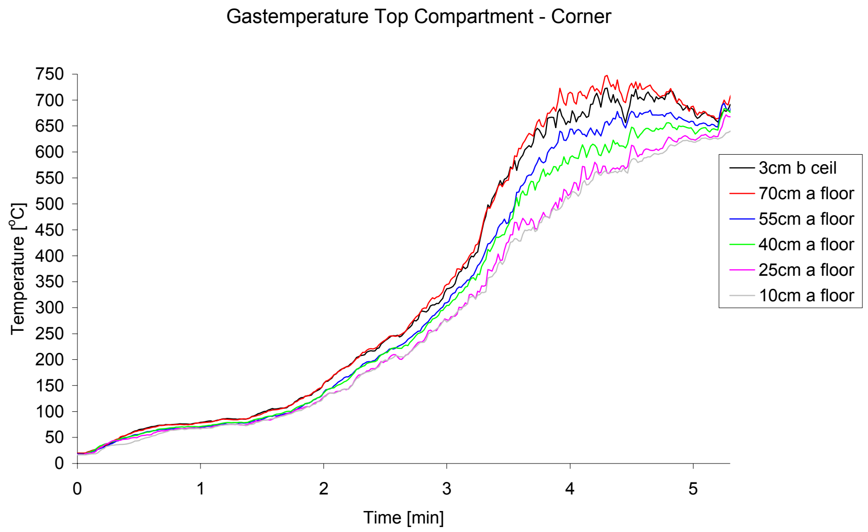

Figure B-75 *Gastemperature in the corner of the top compartment for test V4.*

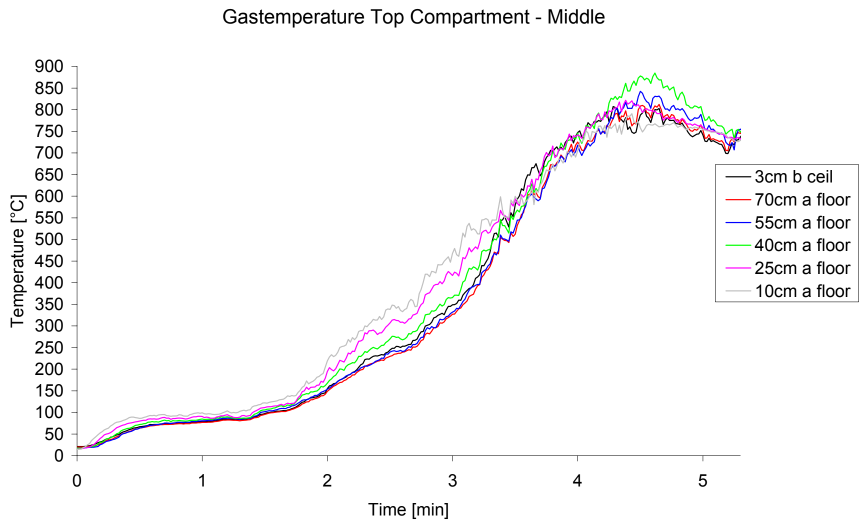

Figure B-76 *Gastemperature in the middle of the top compartment for test V4.*

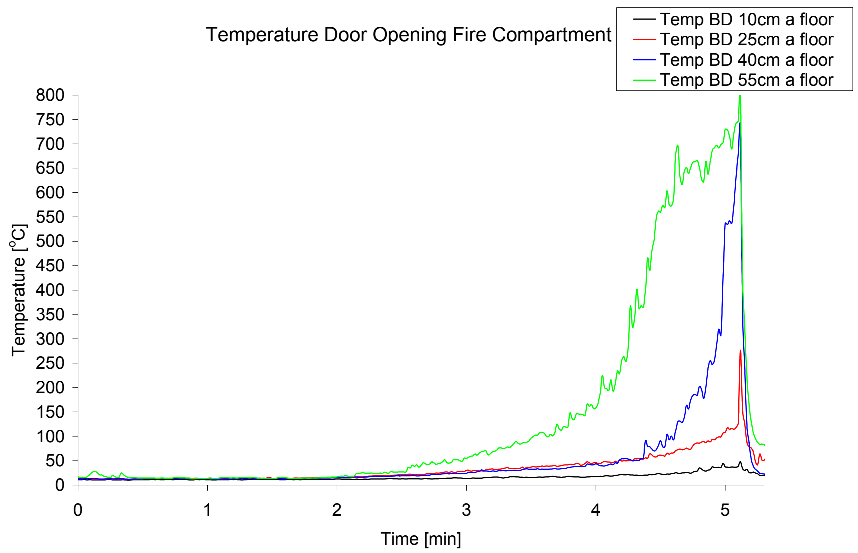

Figure B-77 *Gastemperature in the door opening of the fire compartment for test V4.*

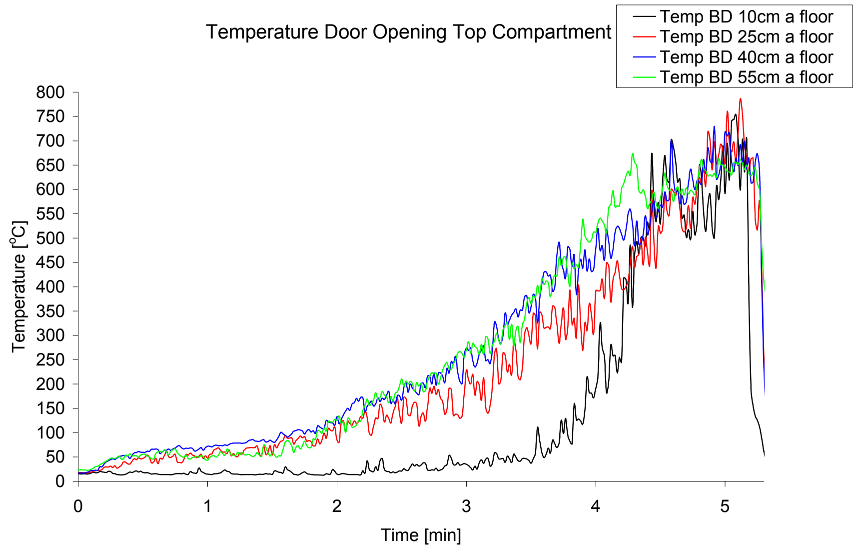

Figure B-78 *Gastemperature in the door opening of the top compartment for test V4.*

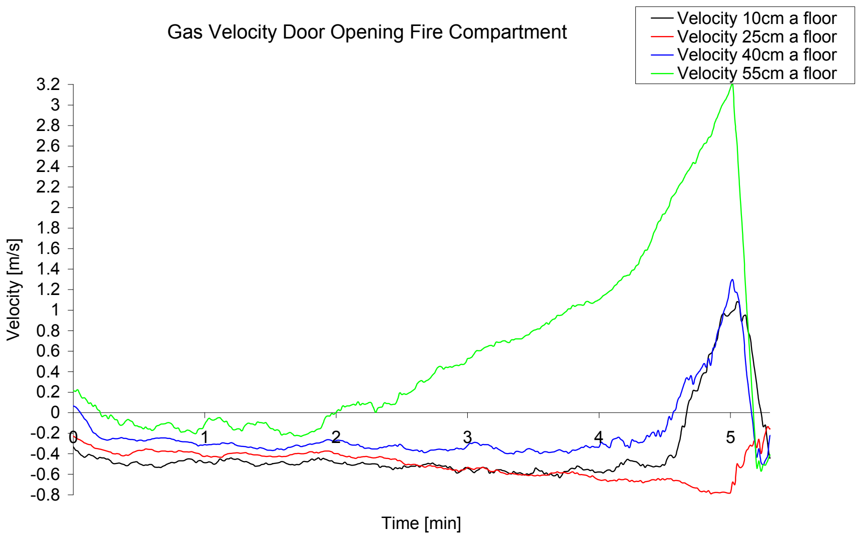

Figure B-79 *Gas velocity in the door opening of the fire compartment for test V4.*

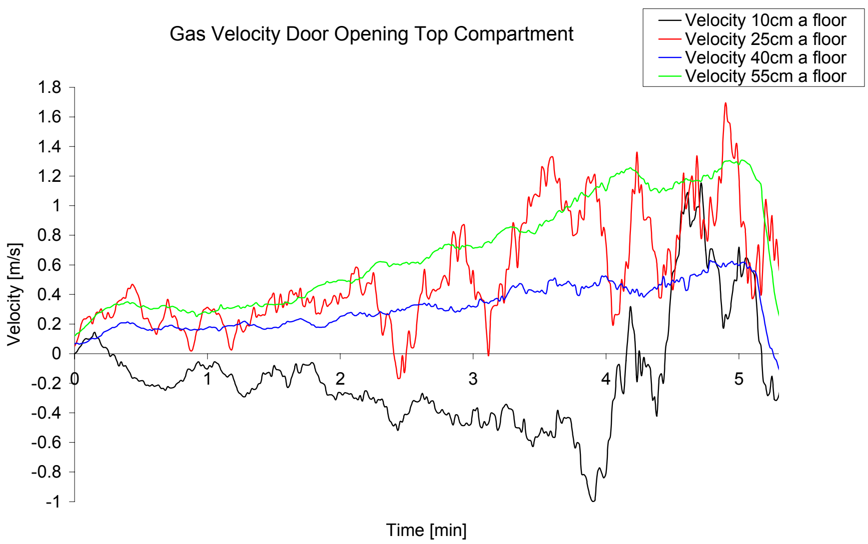

Figure B-80 *Gas velocity in the door opening of the top compartment for test V4.*

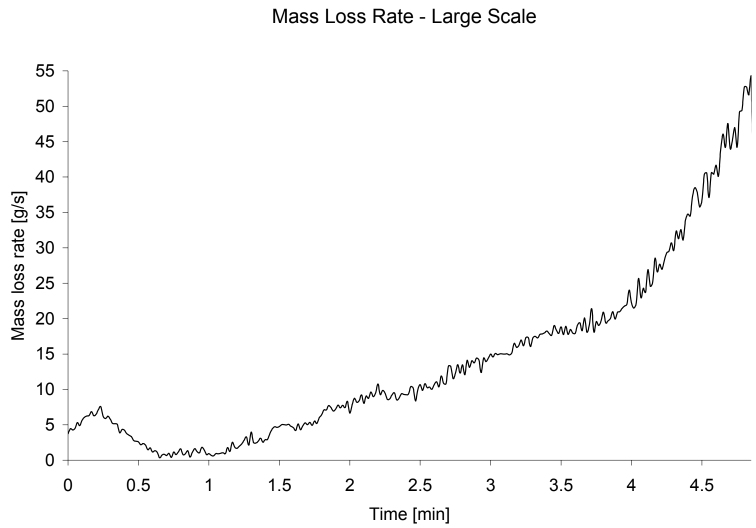

Figure B-81 *Mass loss rate of the linings for test V4.*

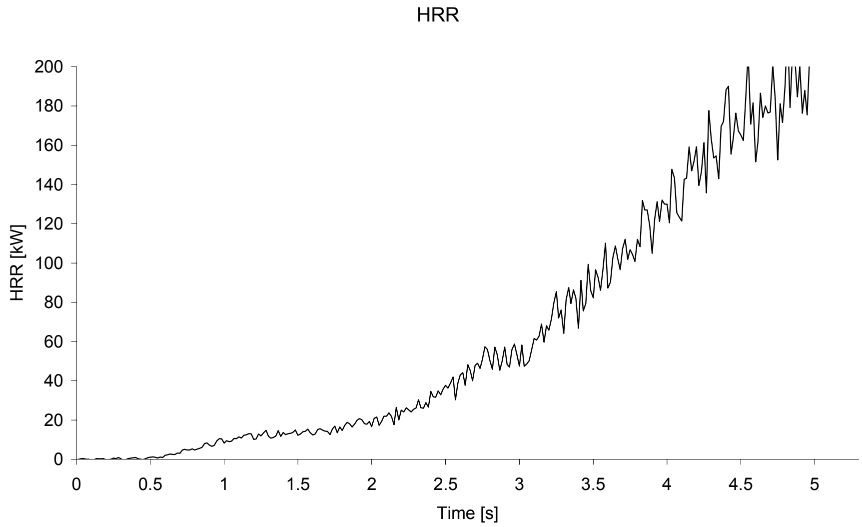

Figure B-82 *Heat release rate for test V4.*

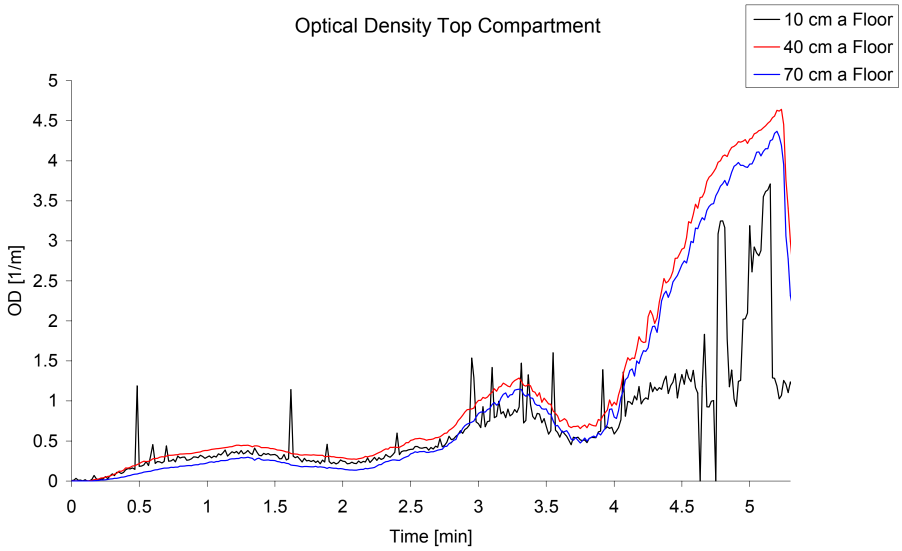

Figure B-83 *Optical density in the top compartment for test V4.*

Time [min:sec]	**Event/observation**
00:00	Fire start
03:35	Flashover of the fire compartment after which the test is terminated

Table B-10 *Main events during test V5.*

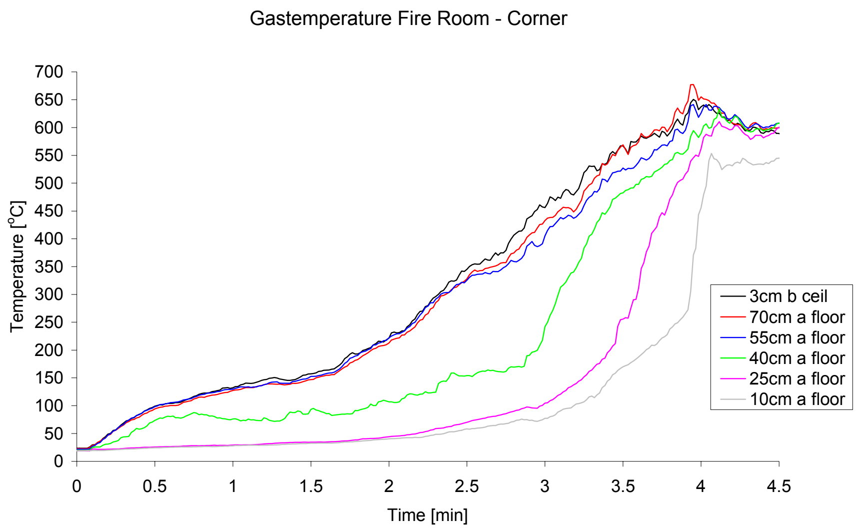

Figure B-84 *Gastemperature in the corner of the fire compartment for test V5.*

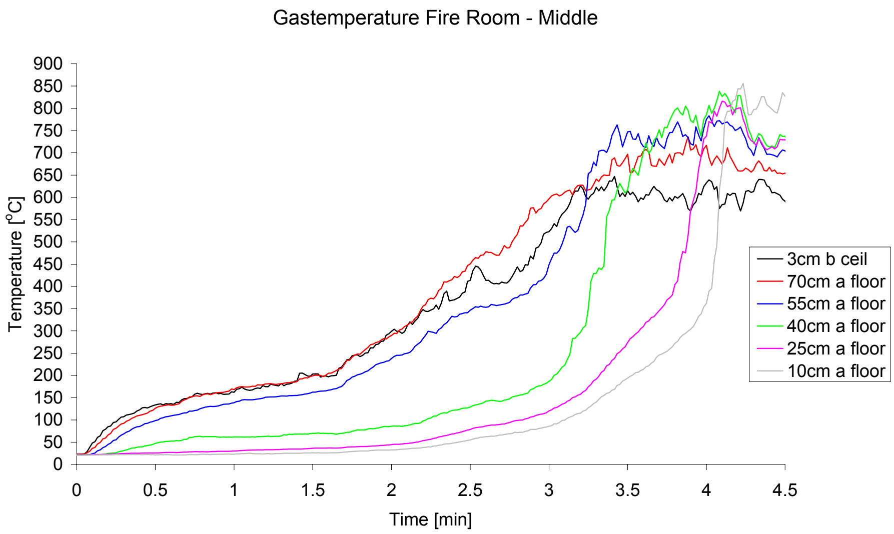

Figure B-85 *Gastemperature in the middle of the fire compartment for test V5.*

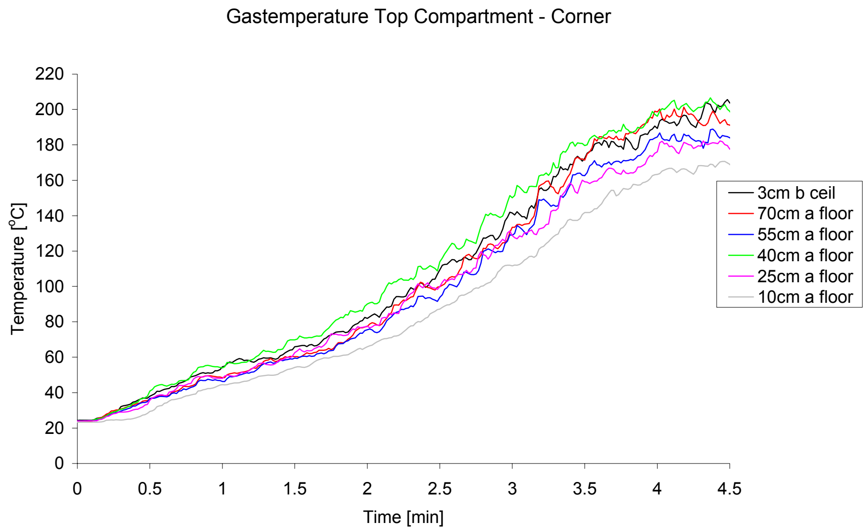

Figure B-86 *Gastemperature in the corner of the top compartment for test V5.*

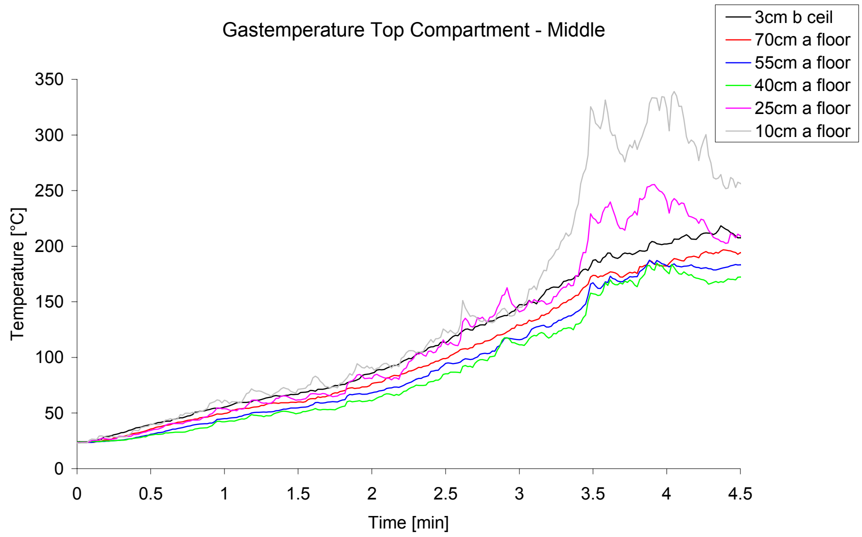

Figure B-87 *Gastemperature in the middle of the top compartment for test V5.*

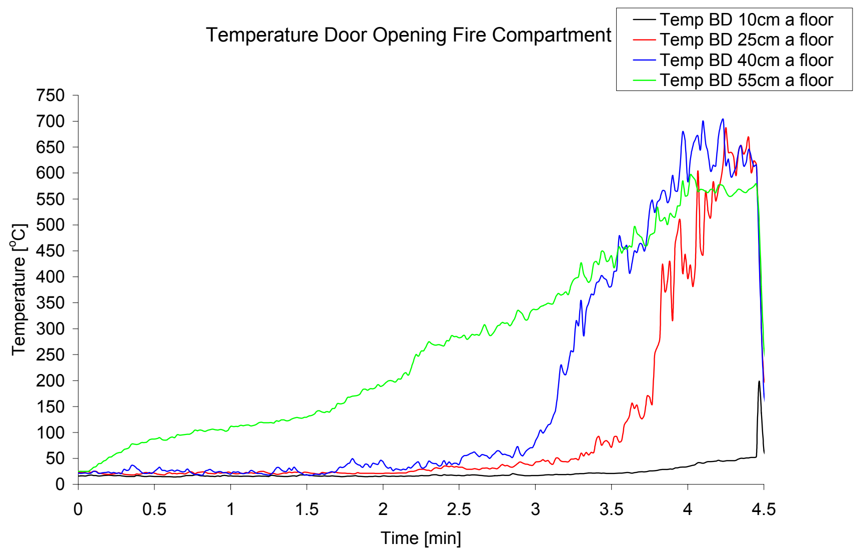

Figure B-88 *Gastemperature in the door opening of the fire compartment for test V5.*

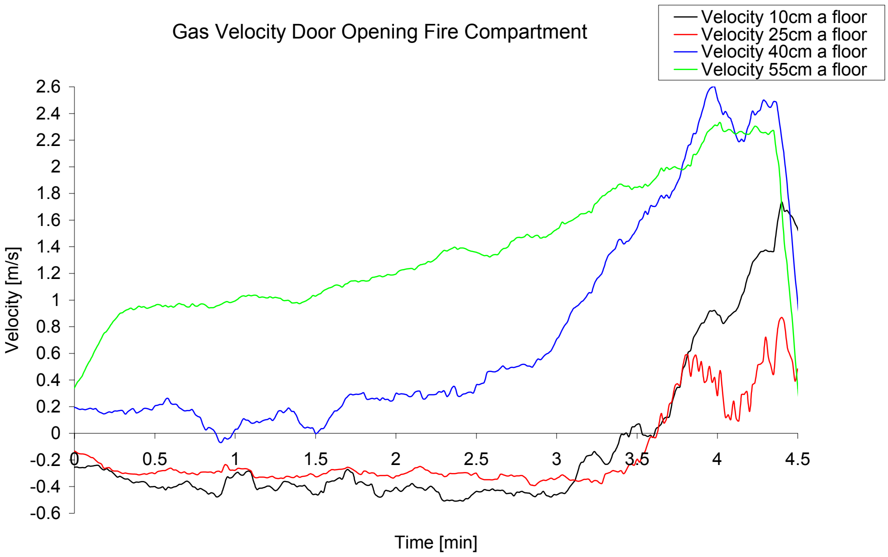

Figure B-89 *Gas velocity in the door opening of the fire compartment for test V5.*

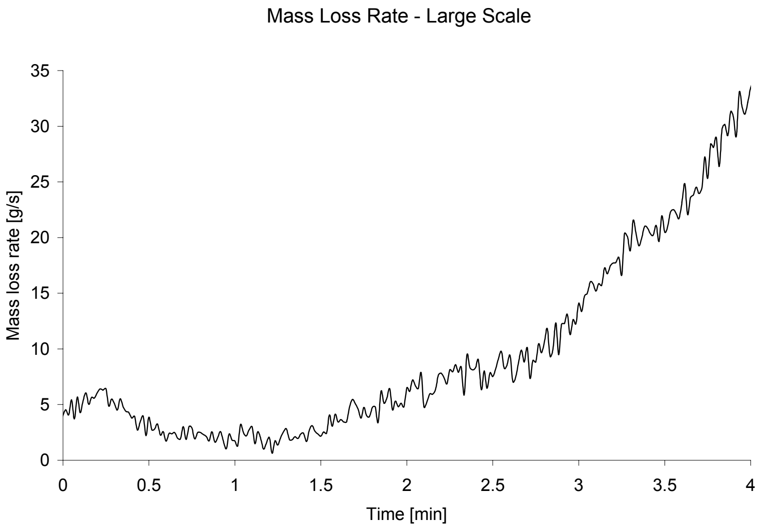

Figure B-90 *Mass loss rate of the linings for test V5.*

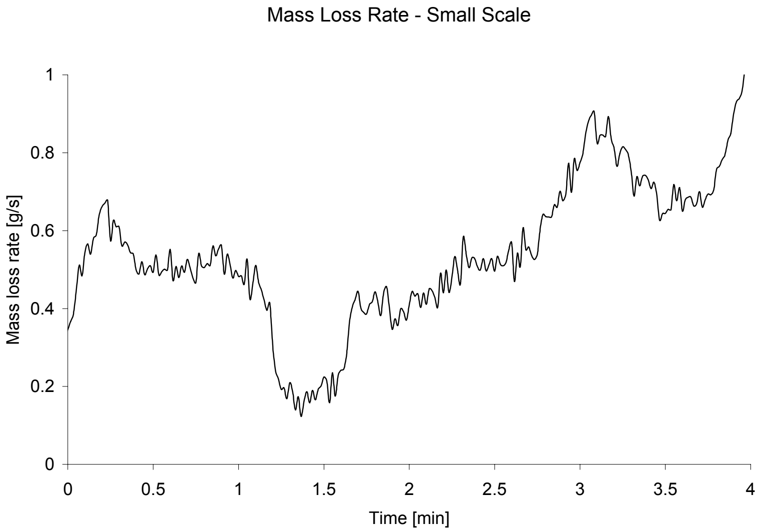

Figure B-91 *Mass loss rate of the small scale for test V5.*

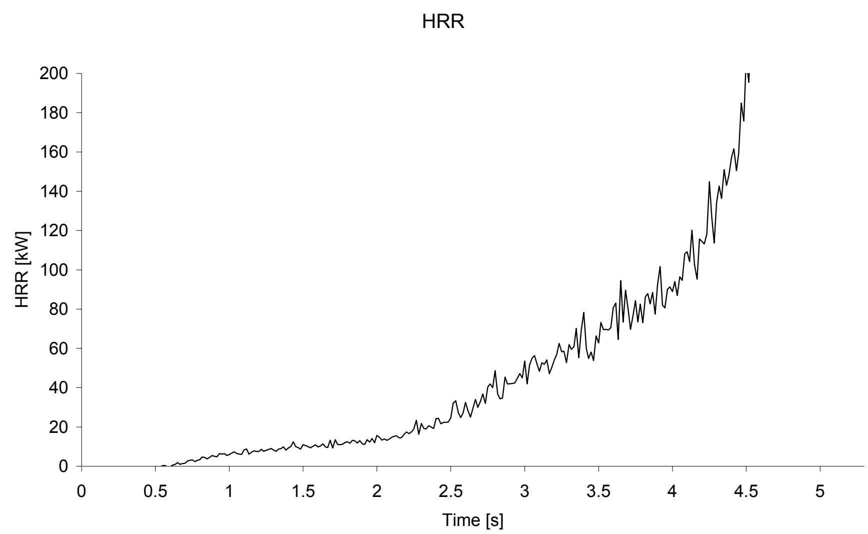

Figure B-92 *Heat release rate for test V5.*

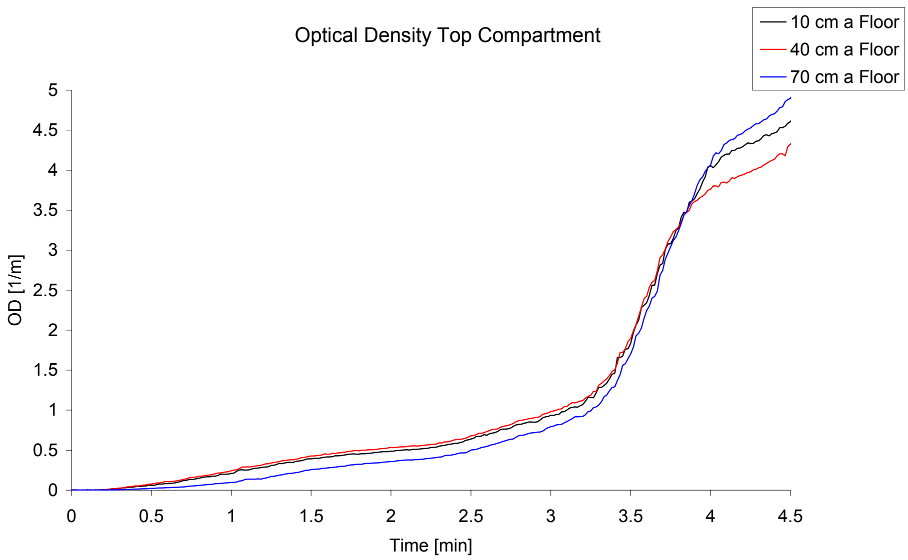

Figure B-93 *Optical density in the top compartment for test V5.*

Time [min:sec]	Event/observation
00:00	Fire start
01:35	Continuous flame reaches the ceiling of the fire room
03:10	Combustion of the lower smoke gas layer
03:45	Smoke gas layer at floor level in fire room
07:50	First flame enters adjacent compartment
08:25	Fire spreads to the adjacent compartment
08:30	Flashover of the adjacent compartment

Table B-11 *Main events during test H1.*

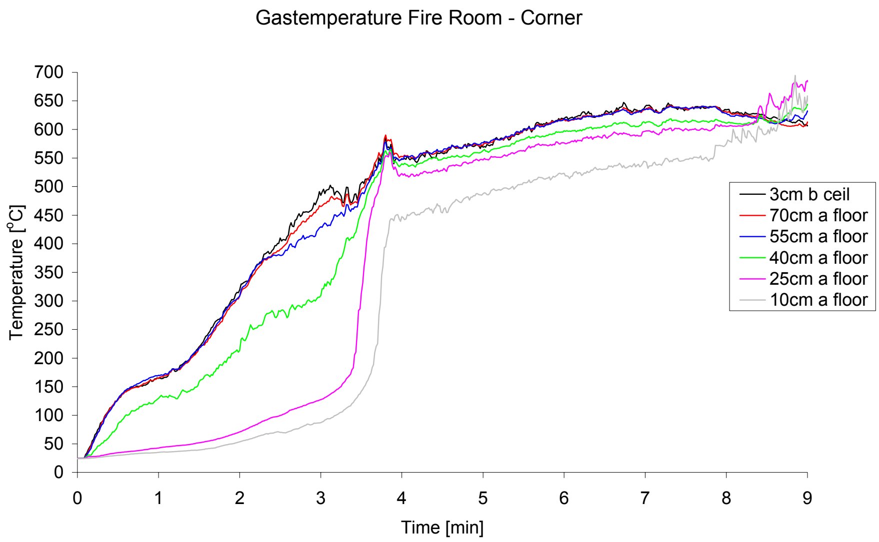

Figure B-94 *Gastemperature in the corner of the fire compartment for test H1.*

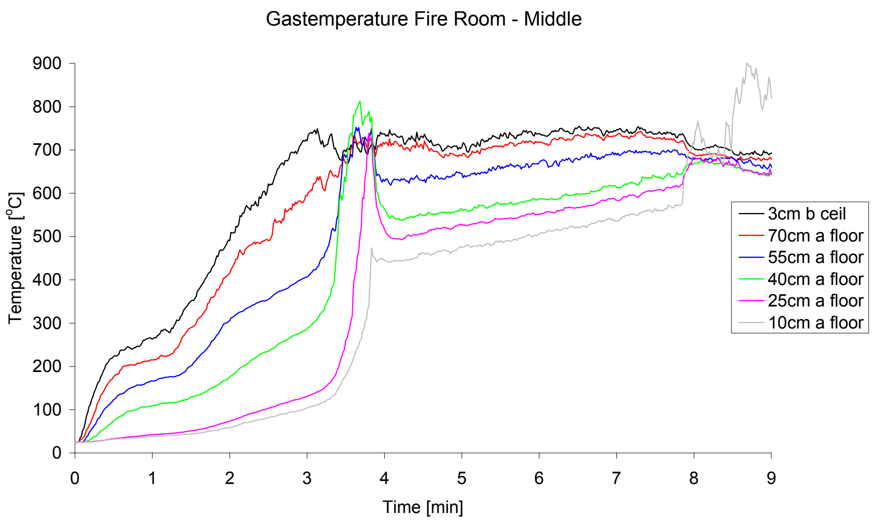

Figure B-95 *Gastemperature in the middle of the fire compartment for test H1.*

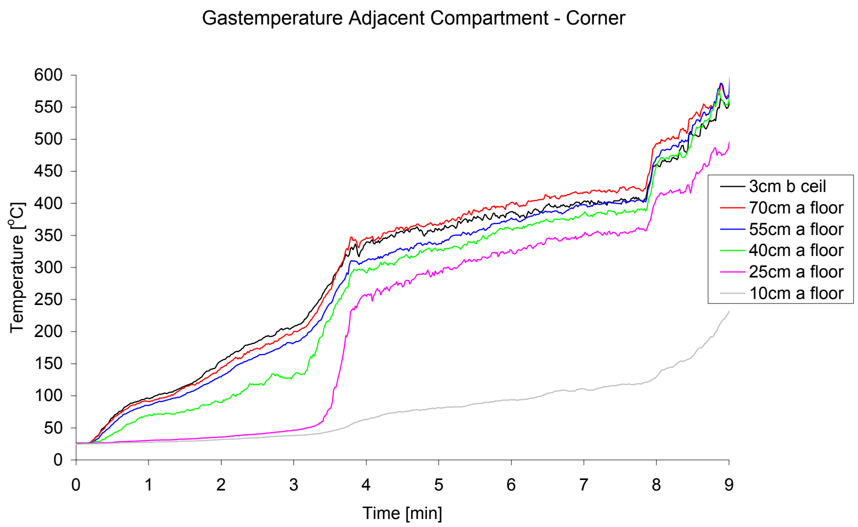

Figure B-96 *Gastemperature in the corner of the adjacent compartment for test H1.*

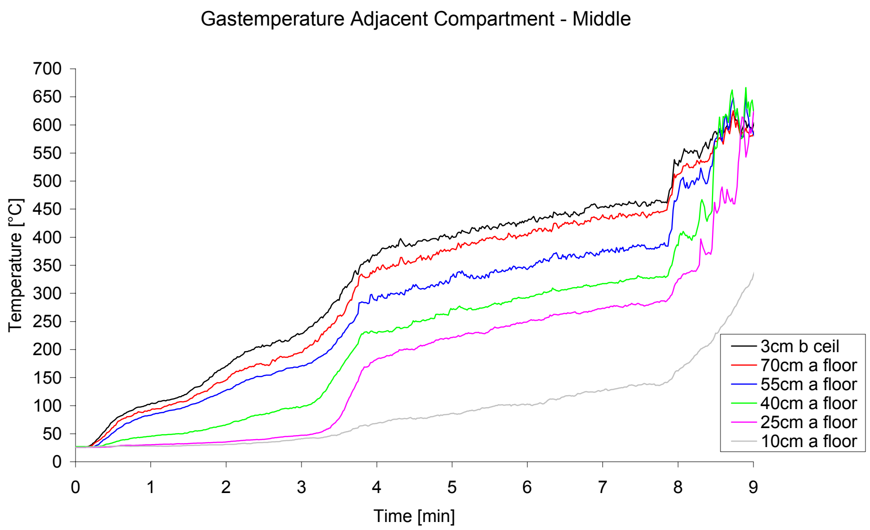

Figure B-97 *Gastemperature in the middle of the adjacent compartment for test H1.*

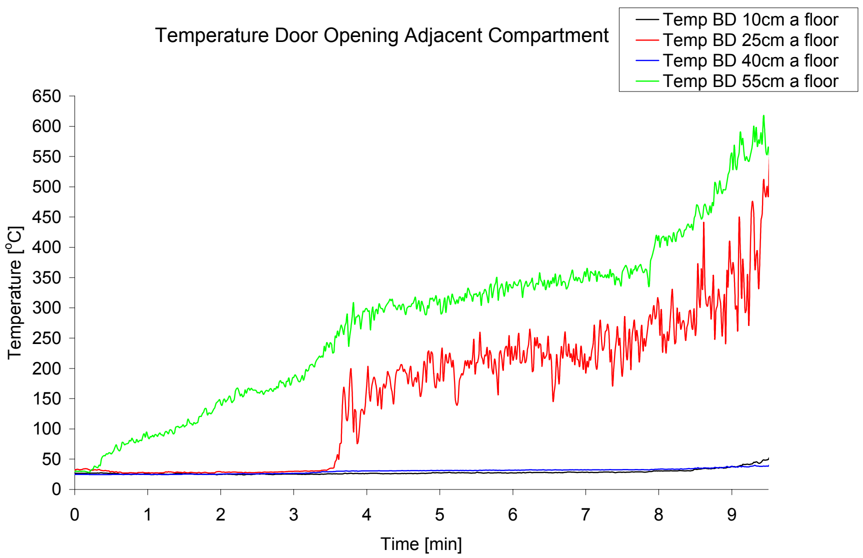

Figure B-98 *Gastemperature in the door opening of the adjacent compartment for test H1.*

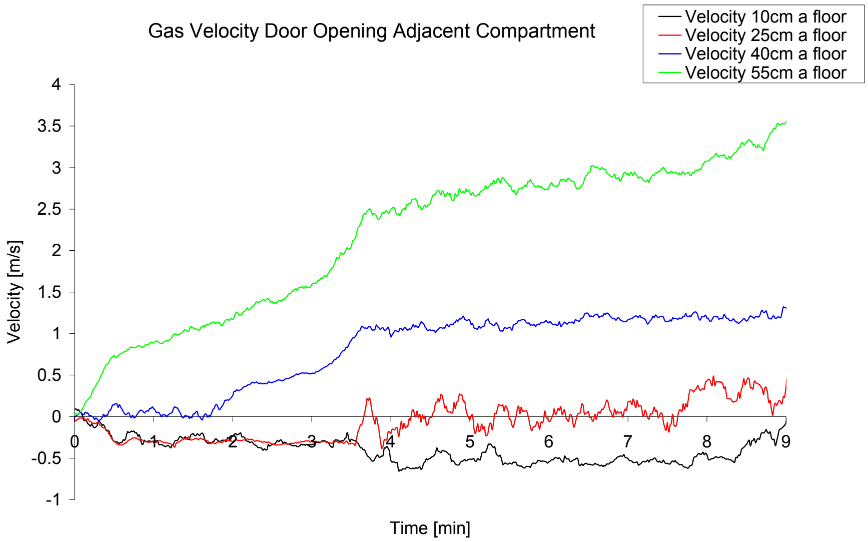

Figure B-99 *Gas velocity in the door opening of the adjacent compartment for test H1.*

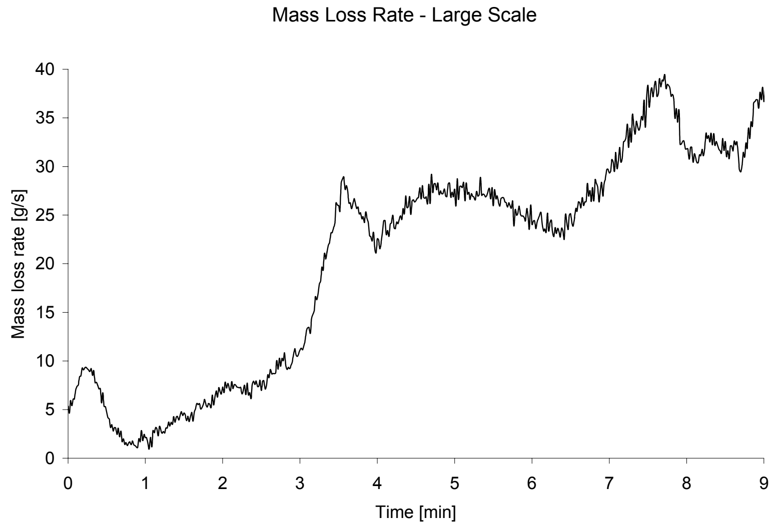

Figure B-100 *Mass loss rate of the linings for test H1.*

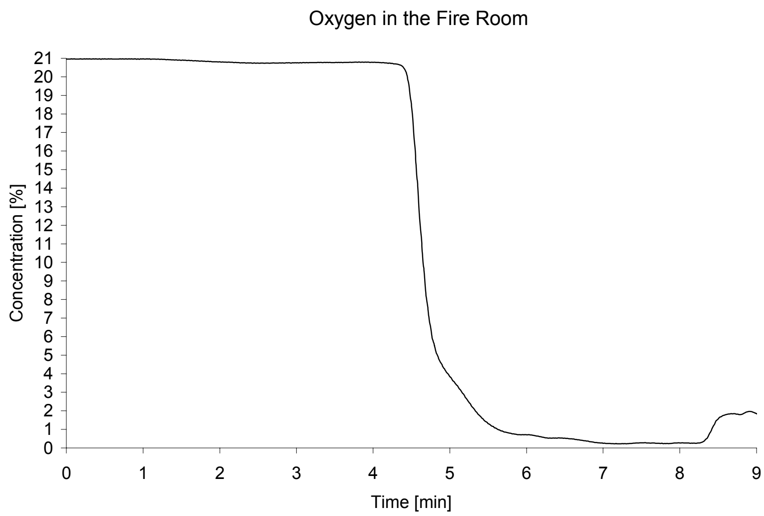

Figure B-101 *Oxygen concentration in the fire compartment for test H1.*

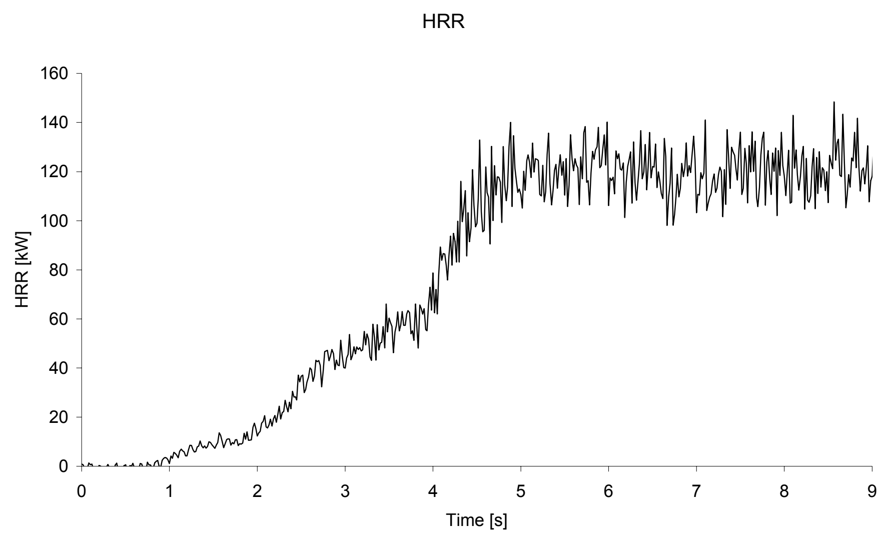

Figure B-102 *HRR for test H1.*

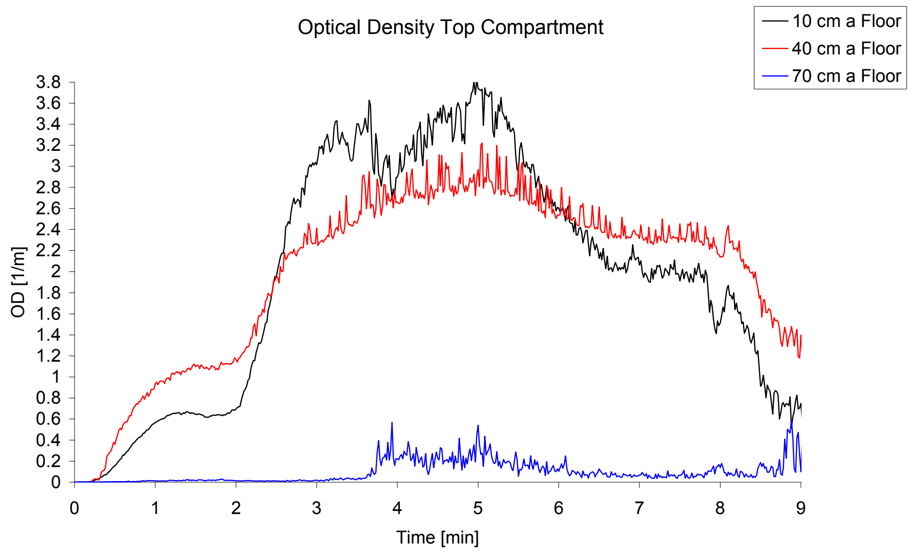

Figure B-103 *Optical density in the adjacent compartment for test H1.*

Time [min:sec]	Event/observation
00:00	Fire start
14:00	Collaps of walls in fire compartment, test is terminated

Table B-12 *Main events during test H2.*

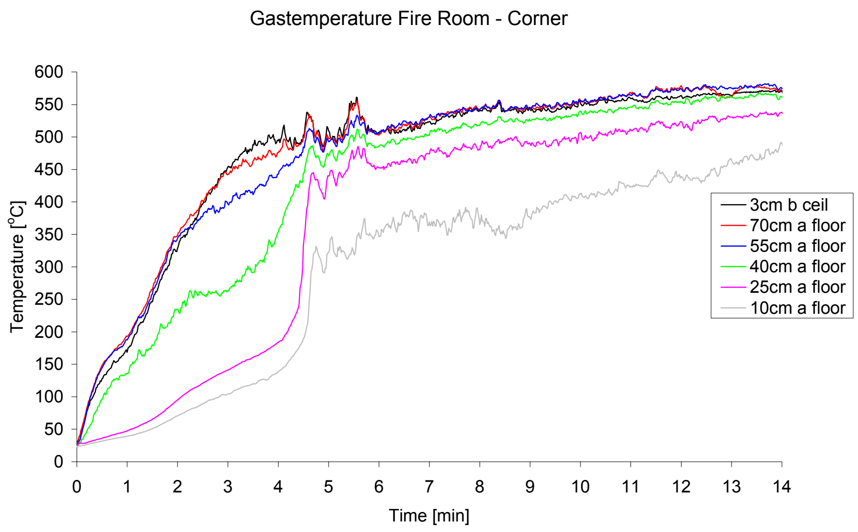

Figure B-104 *Gastemperature in the corner of the fire compartment for test H2.*

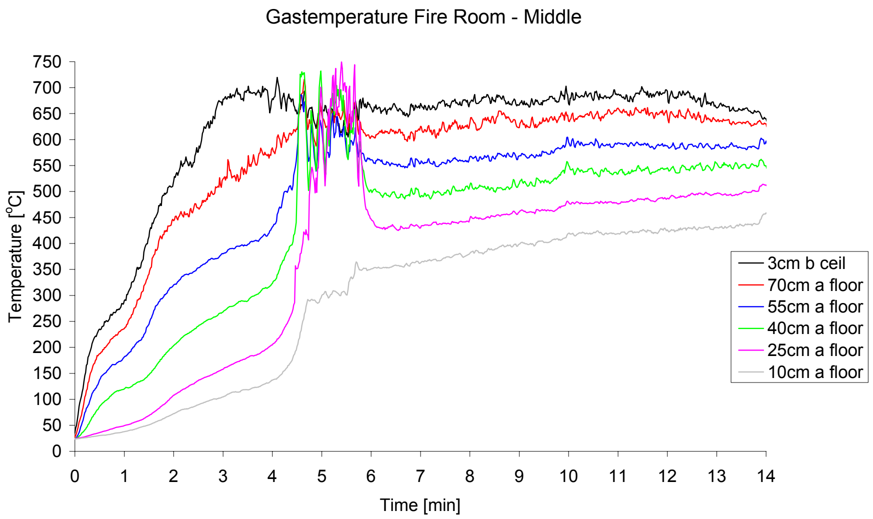

Figure B-105 *Gastemperature in the middle of the fire compartment for test H2.*

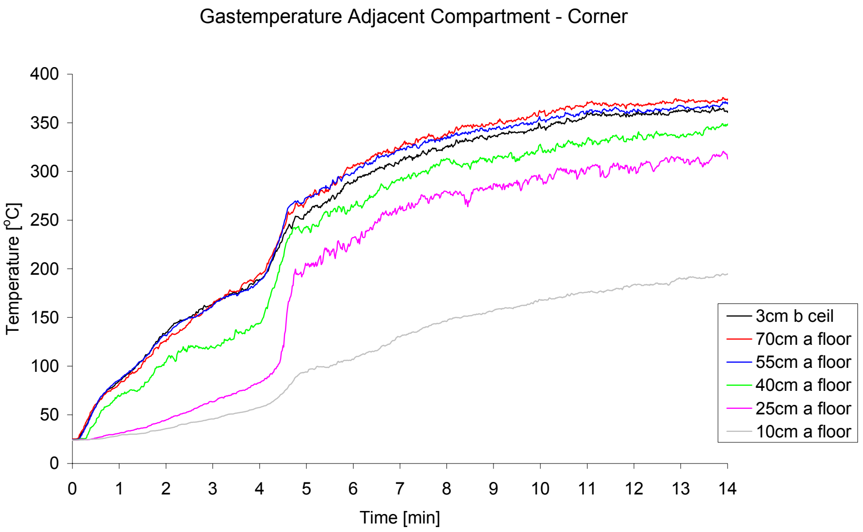

Figure B-106 *Gastemperature in the corner of the adjacent compartment for test H2.*

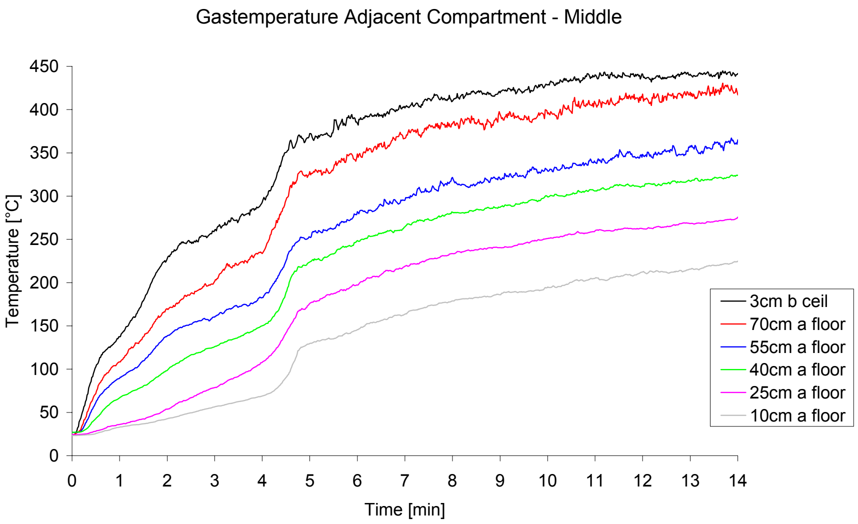

Figure B-107 *Gastemperature in the middle of the adjacent compartment for test H2.*

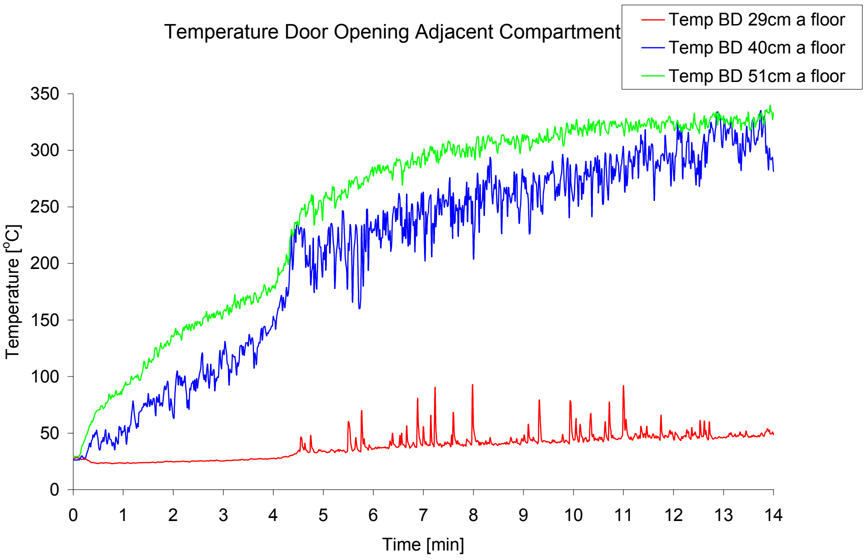

Figure B-108 *Gastemperature in the door opening of the adjacent compartment for test H2.*

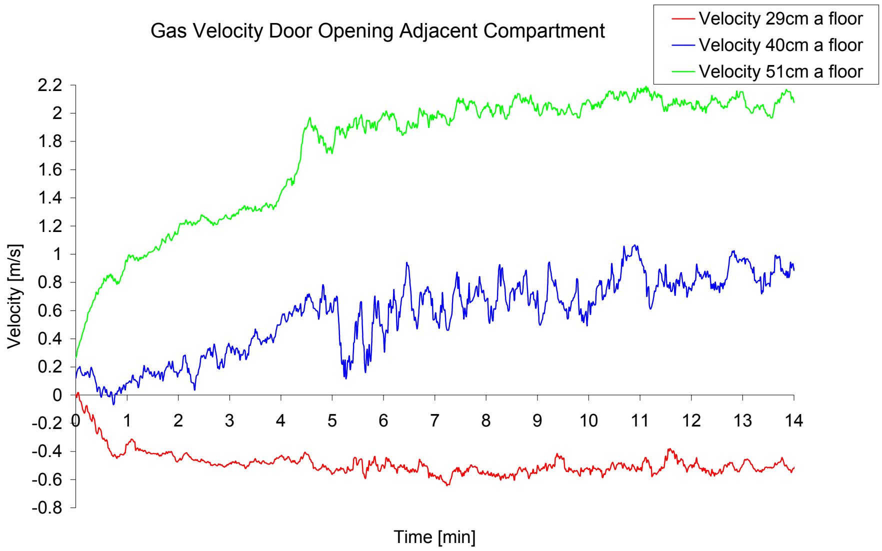

Figure B-109 *Gas velocity in the door opening of the adjacent compartment for test H2.*

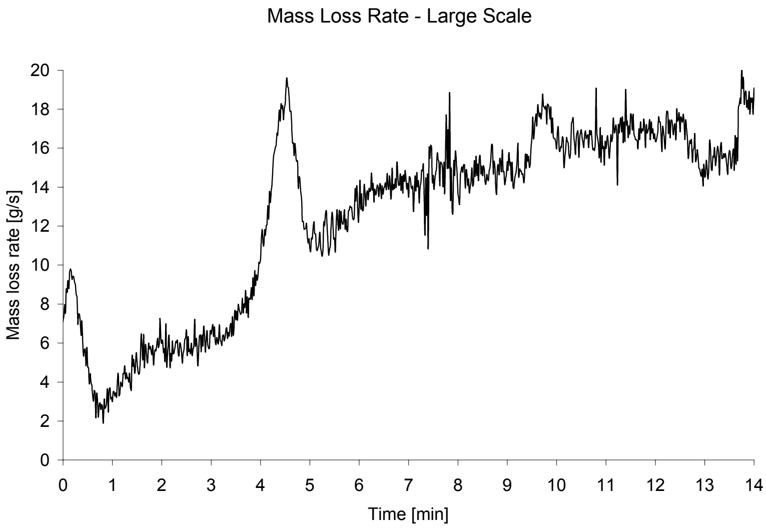

Figure B-110 *Mass loss rate of the linings for test H2.*

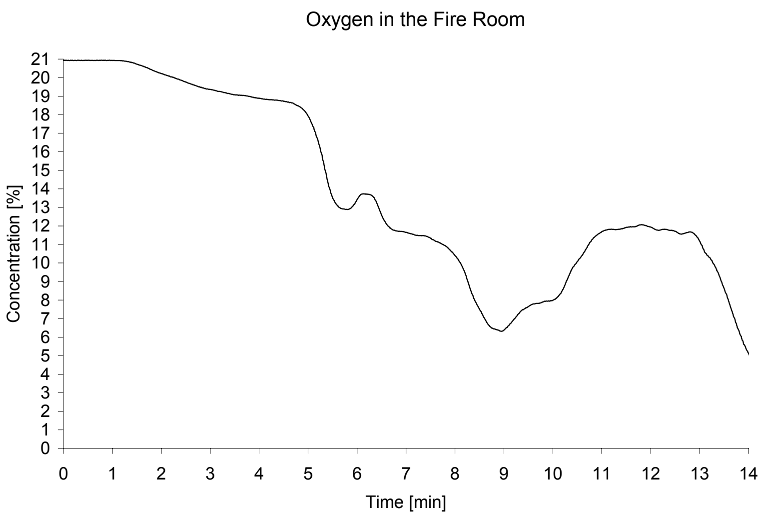

Figure B-111 *Oxygen concentration in the fire compartment for test H2.*

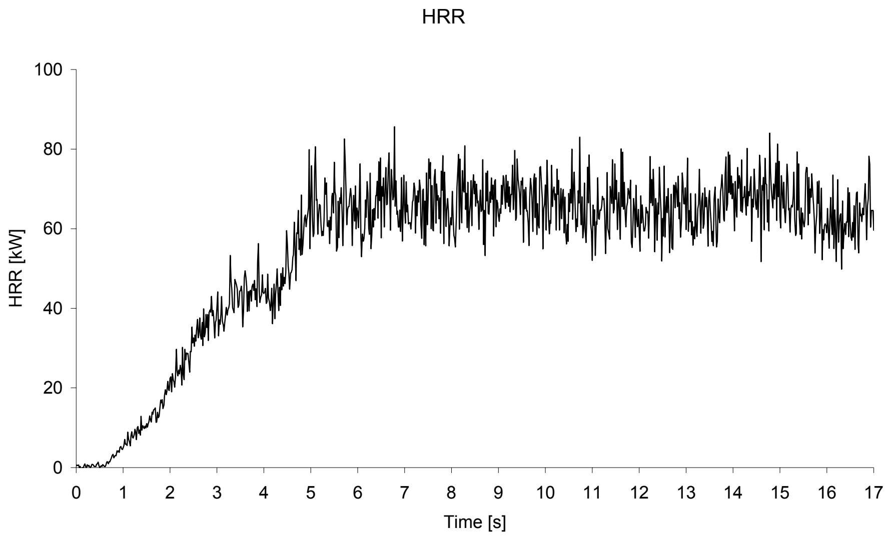

Figure B-112 *HRR for test H2.*

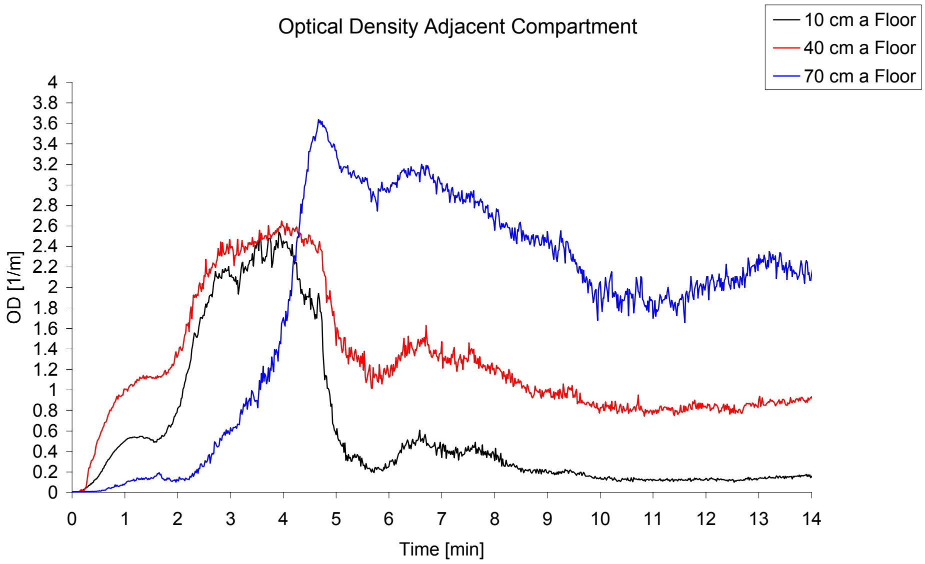

Figure B-113 *Optical density in the adjacent compartment for test H2.*