Anders Lönnermark, Haukur Ingason

Fire Spread in Large Industrial Premises and Warehouses

BRANDFORSK project 630-021

SP Swedish National Testing and Research Institute

SP Fire Technology
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Anders Lönnermark, Haukur Ingason

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Abstract

The aim of the project was to investigate fire spread in rack storages with aid of model scale tests (1:5). The focus was on the fire spread from an initial fire in a rack storage to adjacent racks without interaction of a suppression system. The effects on the fire spread were tested in regard to the enclosure, the ceiling height above the top of the rack storage (clearance height), beams in the ceiling and ventilation. The height of the rack storage as well as the distances between boxes and the thickness of the box material varied. The effects of beams and clearance height on response of virtual sprinklers in the ceiling were explored as well as the risk of fire spread between low-piled goods.

Key words: model scale, rack storage, fire spread, warehouse, sprinkler

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Postal address:
Box 857,
SE-501 15 BORÅS, Sweden
Telephone: +46 33 16 50 00
Telefax: +46 33 13 55 02
E-mail: info@sp.se

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Preface

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Anders Wallin, BRANDFORSK
Ari Santavouri, If Insurance
Bo Andersson, Swedish Rescue Agency (SRV)
Bo Molin, Södra Älvsborgs Räddningstjänstsförbund (SÄRF)
Göran Holmstedt, Lund University (LTH)
Jan Berntsson, Bengt Dahlgrens
Jan Lagerblad, IKEA
Jens Hjort, Swedish Fire Protection Association (SBF)
Kjell Ollson, Lagerstedt & Krantz
Lars Hellsten, Scania
Leif Beisland, Trygg-Hansa
Lennart Håkansson, NVS
Kåre Brandsjö, BRANDFORSK
Olle Norrby, Brandgruppen
Torsten Södergren, If Insurance.

Summary

In order to study the fire spread in large industrial premises and warehouses tests were carried out in a scale 1:5. The aim was to investigate fire spread in rack storages which are not protected by a suppression system. This type of tests without any interference of a suppression system is very difficult to perform in large scale.

The main focus was on the fire spread from an initial fire in a rack storage to adjacent racks. The effects on the fire spread were tested in regard to the enclosure, the ceiling height above the top of the rack storage (clearance height), beams in the ceiling and ventilation. The height of the rack storage as well as the distances between boxes and the thickness of the box material varied. The effects of beams and clearance height on response of virtual sprinklers in the ceiling were explored as well as the risk of fire spread between low-piled goods. The test program presented in the report consisted of six different test series.

1) Cone calorimeter tests of the materials in the cardboard boxes used in the rack storage tests
2) Fire spread tests with one small rack in scale 1:5
3) Free burning tests (without ceiling) with four racks in scale 1:5
4) Study of the influence of the size of the enclosure; wood crib tests in an enclosure with varied dimensions. The ceiling height was 0,925 m, the width was 1 m but the length varied; 1 m, 1,7 m and 2,4 m. The opening was 0,3 m by 0,3 m. The scale of this enclosure is not defined here.
5) Fire spread tests with four racks under a ceiling with varied height and slope, and cases with or without beams in scale 1:5
6) Fire spread tests with low-piled goods in scale 1:1

The results show that the distance between the top of the goods and the ceiling has a decisive importance in determining the rate of spread of fire between the racks. When the flames reach the ceiling, they are deflected to the side and increase radiation to the top of adjacent racks. As a result, these racks catch fire at the top, with the fire spreading downwards from them. The tests show that the fire spreads most rapidly with the distance above the top of the racks equivalent to 3 m in large scale. It took approximately the same time for the fire to spread when the heights above the goods were 1 m or 6 m: the longest time occurred when there was effectively no ceiling above the racks. The fire spread with a clear height equivalent to 1 m above the racks was retarded since the combustion is less complete. When the impinged flames reach the layer of hot fire gases formed below the ceiling, they start to be affected by the lower oxygen levels.

It is clear from the tests performed here that the only way to protect the goods against this type of galloping process is to use sprinkler systems. The tests show that both the vertical and transverse positioning of the sprinklers can be very important, particularly if there are beams in the ceiling. In the tests, a metal bulb was used to simulate ordinary sprinkler bulbs, containing thermocouples that continuously recorded the sprinkler temperatures. The model tests show that the beams effectively produce gastight barriers. They form channels along the ceiling which flames and smoke flowing parallel to the beams and they hindered spread in the transverse direction. The simulated sprinklers installed in the 'channel' in which the flames from the burning bay reach the ceiling reacted somewhat more quickly than in the case with no beams. The effect is the opposite for sprinklers in the other channels, so that they reacted considerably more slowly. The tests also show that the slope of the ceiling had some effects, but not as significant as the beams.

The thickness of the material stored in the racks had also a significant effect on the burning behaviour as well as the flue width and height of the rack storage. These effects have also been seen in previous research [1-5] but were confirmed here. These tests were performed to design the experimental set-up.

An important parameter that affects the global fire spread was the position of ignition. The tests show that the position affects the development of the fire and the Heat Release Rate (HRR) curve.

There was a large difference between the free burning wood crib tests and the tests with wood cribs in an enclosure. The size of the enclosure affected the HRR, but the differences decreased when the enclosure increased.

For low-piled goods, the distance between piles, the height of the piles, and the material of the goods are important parameters for the fire spread.

1 Introduction

Industrial buildings or warehouses with large amounts of stored goods should generally be protected by a suppression system. There are, however, many such buildings today that do not have such protection measures. In many of these buildings, a detection system and/or fire ventilators together with the local fire brigade constitutes the fire safety of the building. Very limited information on fire spread in such large buildings is available. When fires occur in this type of buildings with stored goods, detailed information on the fire spread is nearly impossible to obtain. The damage due to the fire is too extensive or if the fire has been limited the information about the fire development is difficult to interpretate.

Designers of fire safety in large industrial buildings or warehouses are interested to know how the fire will proceed if there is no sprinkler system to stop the fire spread. How large can the fire be? What type of design fire should be used to design the fire ventilation? How will the fire spread between the racks? What is the highest HRR that can be obtained? Will the fire growth continue to follow a fast growing curve such as Ultra Fast after the fire jumps from the first rack to the second etc.? There are many questions to consider here but most of them are not easy to answer. The best would be to carry out large scale tests in warehouse type of a building but that it not possible or at least it would be too expensive.

Most of the large scale tests with rack storages carried out worldwide include tests with sprinkler systems [6-11]. To our best knowledge, no tests have been performed in a large scale where the fire is allowed to spread from the initial rack to adjacent racks without interference of a sprinkler system. Such tests would be too difficult to perform due to risk for damage of the test buildings.

Ingason [1-5] has performed numerous tests in large scale and model scale where the effects of the geometry and type of fuel on the fire growth in four by four pallet rack storages. The test-setup consisted of two pallet wide and four tier high rack storages. Ingason [1-3] has shown that there is a good correspondence between the large scale tests and the model scale tests in scale 1:3.

Therefore, it was decided to perform the tests in a model scale. The most appropriate scale was found to be 1:5, due to practical reasons of the fire hall used. When carrying out tests on model scale, the measured values of the various parameters have to be scaled up to large scale using various physical scaling laws. The technique means that it is possible to investigate fire behaviour in larger stores - i.e. with more and higher racks - relatively cheaply. It also gives greater freedom of varying different parameters. In most of the tests carried out here, the conditions that would be encountered in a large store were simulated by not using any walls around the model stands. However, walls were used in some of the tests, which provided opportunities to investigate such aspects as the effect of fire gas ventilation.

2 Experimental set-up

To study the fire spread in large industrial premises and warehouses the work was divided into six different test series. These test series are summarised in Table 2.1. In Section 2.1, the commodities used in the different test series are described. The experimental set-ups are presented in Section 2.2, while the different measurements performed are described in Section 2.3. More details on the separate tests in the different test series can be found in Table 3.1

Table 2.1 Description of the test series.

Test series	Description
1	Cone calorimeter tests of the materials in the cardboard boxes used in the rack storage tests
2	Fire spread tests with one small rack
3	Free burning tests (without ceiling) with four racks
4	Study of the influence of the size of the enclosure; wood crib tests in an enclosure with varied dimensions
5	Fire spread tests with four racks under a ceiling with varied height and slope, and cases with or without beams
6	Fire spread tests with low-piled goods

2.1 Commodities

For the rack storage tests, cardboard boxes were used as fuel. The boxes were made of 7 mm thick biwell (SIS 210 B+C). Boxes in three different sizes were used. These boxes could be put into each other to increase the mass and thickness of the fuel load. The dimensions of the largest box were 240 mm × 200 mm × 195 mm. After the pre-tests it was decided to use mainly the largest box, but double boxes in the ignition rack storage.

The material in the cardboard boxes was tested in the cone calorimeter [12, 13] at a radiation level of 50 kW/m^2. The results from these tests are presented in Section 4.1.

For the enclosure tests studying the effect of the size of the enclosure and the position of the opening, wood cribs were used as fuel. Pine tree was used for the pieces and the wood cribs were built of 50 pieces with the dimensions 21 mm × 21 mm × 300 mm, 5 pieces in 10 layers. This means that the total height of the wood crib was 210 mm.

In the tests with low-piled goods, cardboard boxes with or without polystyrene cups were used. The commodities were developed for commodity classification tests [14]. The weight of the cardboard boxes was 2 kg and the total weight of the polystyrene cups in one box was 0.8 kg (28.2 g per cup and 30 cups per box). Fifteen boxes were placed on a wooden pallet (weighed approximately 21 kg). In most of the tests two such pallets, with varied distance from each other, were used. In two of the tests two pallets in height (i.e. in total four pallets in the same test) were placed on top of each other (see Table 3.1)

2.2 Set-up

The test set-up for test series 1 is not described in detail. Some information is given in connection with the presentation of the results in Section 4.1. For more details the reader is referred to the test standard [12, 13]. The test set-up of test series 2, 3, and 5 are described in Section 2.2.1. In Section 2.2.2 the experimental set-up for the study of the influence of the size of the enclosure size (test series 4) is presented, while the tests with low-piled goods (test series 6) are described in Section 2.2.3.

2.2.1 Set-up for rack storage tests with ceiling

Formaterade: Punkter och numrering

The influence of the flue width has been studied in a previous project [1, 4]. However, to choose the best suitable flue width for the scale test, some pre-tests were performed (test series 2). The experimental set-up of these tests is shown in Figure 2.1. In tests 2.1 - 2.3 and 2.5 four levels of boxes were used and in these tests gas temperatures were measured in position 2 and 3 and velocity in position 2. In tests 2.6 five levels of boxes were used and in this tests gas temperatures were measured in position 1 and 2 and velocity in position 2.

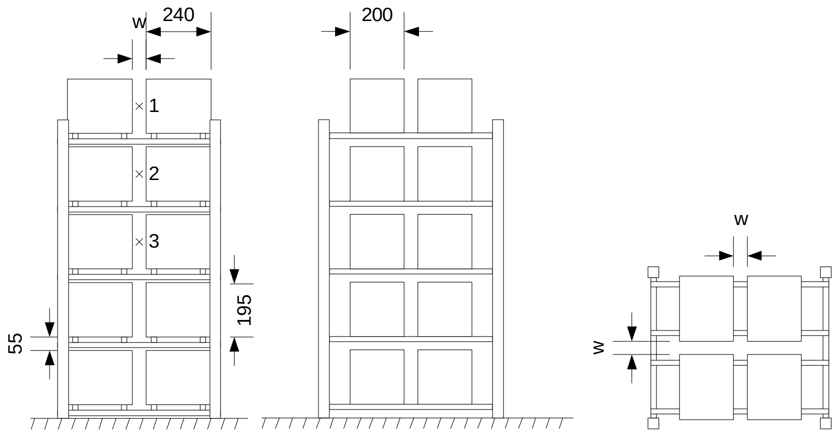

Figure 2.1 Side view, front view, and top view of the experimental set-up used in the pre-tests (test series 2). × represent measurement position. Dimensions in mm.

From the results from the pre-tests it was decided to use a flue width, *w*, of 50 mm. This width was used in all tests. In the main test series (test series 3 and 5), four rack storage systems were placed next to each other to study the fire spread within and, specially, between the rack storages (see Figure 2.2). The distance 0.48 m between the racks corresponds to a distance of 2.4 m in real scale. In the two tests without ceiling (test 3.1 and 3.2) the position for ignition was varied. The ignition took place at the bottom of rack 2. In tests 3.1 the ignition sources were placed in the centre of the rack, while in test 3.2 the ignition sources were placed in the third flue from the right. The ignition sources consisted of pieces of fibre board (10 mm × 10 mm × 12 mm) soaked with 1 mL heptane and wrapped in a piece of polyethene. Four ignition sources were used in each test (see Figure 2.2).

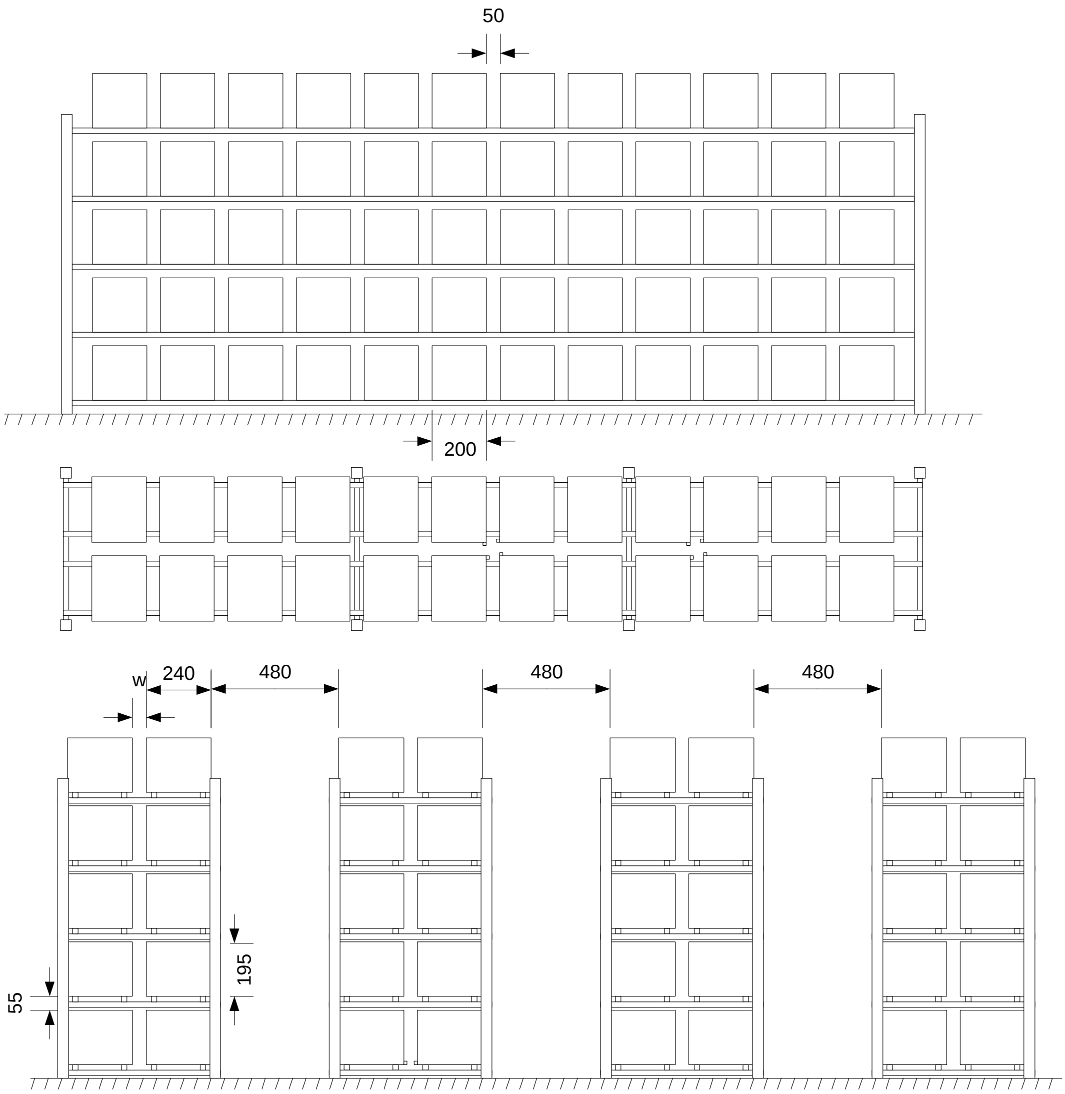

Figure 2.2 Experimental set-up used in the free burning tests, 3.1 and 3.2. Dimensions in mm.

In test series 5, the rack set-up was placed under a ceiling. The height, y, between the top of the commodities and the ceiling, and the slope of the ceiling were varied. In some of the tests 18 cm deep beams were installed beneath the ceiling. The beams were placed with 1.2 m between them (see Figure 2.5). In two of the tests walls were raised to construct a room with a door opening (0.6 m × 0.6 m) at the centre of the front wall. In one of the two room tests four ventilation openings (0.24 m × 0.48 m) were opened near the corners of the ceiling (see Figure 2.6).

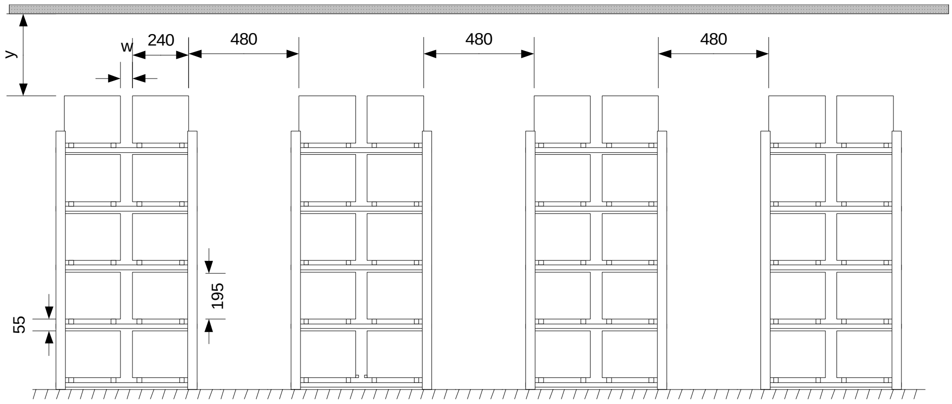

Figure 2.3 *The rack storage set-up was placed under a ceiling. Dimensions in mm.*

Figure 2.4 *Experimental set-up:racks with cardboard boxes under a sloping ceiling (1:16) with beams (test 5.5).*

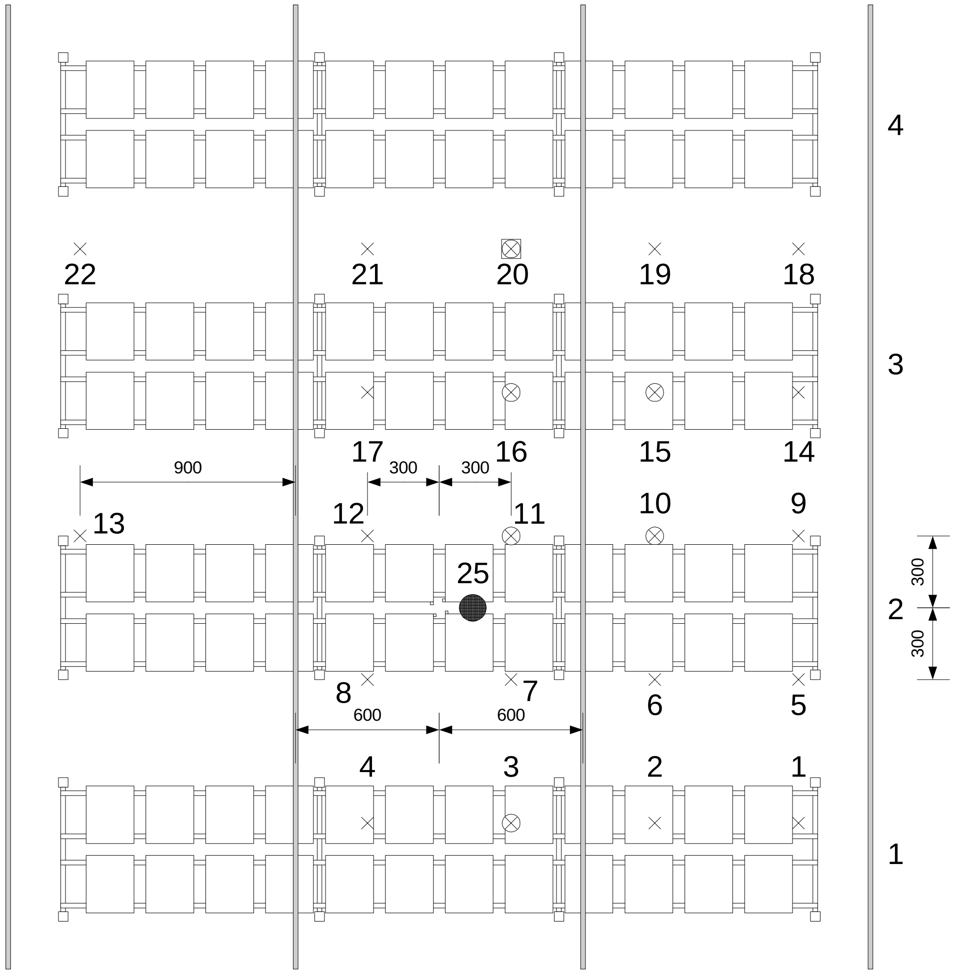

Figure 2.5 Plan view with measurement positions (dimensions in mm). × *= position with thermocouples,* ⊗ *= position with thermocouples and metal bulbs,* ⊠ *= position with thermocouples, metal bulbs and bi-directions probes,* ● *= plate thermometer.*

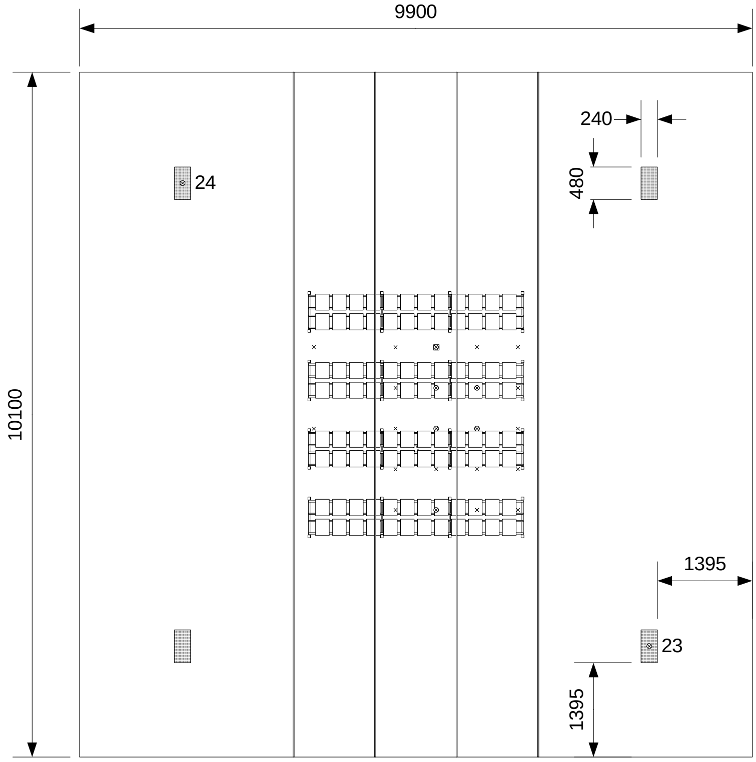

Figure 2.6 Plan view including fire ventilations (dimensions in mm).

2.2.2 Set-up for study of influence of enclosure

Formaterade: Punkter och numrering

The influence of the enclosure on the fire development (test series 4) was studied by varying the volume (length) of an enclosure where a wood crib was used as fuel (see Figure 2.7). The width of the enclosure was in each test 1 m and the height 0.925 m. Three different lengths of the enclosure were used: 1 m, 1.7 m, and 2.4 m, respectively. In most of the tests the opening (0.3 m × 0.3 m) was placed on one of the long sides, but in one case with the largest volume the opening was placed on one of the short sides to study the influence of the distance from the fire to the opening.

The scale of these tests is not defined here. It is, however, possible to give a reasonable idea of the scale. Assuming that the ceiling height of most industrial and warehouse buildings is in the range of 10 m to 30 m, we could estimate that the scale is in the order of 1:10 to 1:30. This means that the size of the opening in large scale would be 3 m by 3 m up to 9 m by 9 m. This would correspond to an opening area of 9 m^2 up to 81 m^2. The floor area (volume) of the building would vary from 100 m^2 (925 m^3) up to 240 m^2 (2220 m^3) in scale 1:10 and from 900 m^2 (24775 m^3) up to 2160 m^2 (59940 m^3) in scale 1:30.

The enclosure was equipped with five thermocouples: one in the opening and four in a thermocouple tree. The thermocouple in the opening was placed 5 cm below the soffit of the opening, on the vertical centreline. The thermocouple tree was placed 10 cm from each wall in one of the front corners in the enclosure case with the dimensions 1 m × 1 m × 0.925 m. The thermocouple tree was left in the same position when the short walls were moved outwards. The thermocouples in the tree were positioned 5 cm, 10 cm, 20 cm, and 50 cm respectively, below the ceiling.

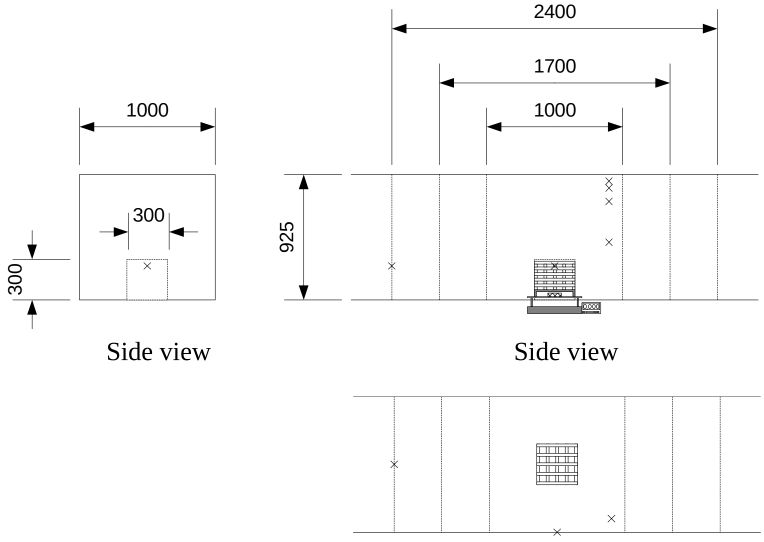

Figure 2.7 Side views and top view of the experimental set-up for study of the influence of the enclosure. The dashed lines indicate different positions of the short walls (dimensions in mm). The mark (×) indicates position of thermocouple; the mark over a line represents a thermocouple in the opening (different positions of the opening were used).

2.2.3 Set-up for tests with stored goods with low heights

In test series 6, the fire spread between low-piled goods was studied, This set-up corresponds to a storage configuration when the effects of the ceiling can be ignored. Cardboard boxes were placed on wooden pallets and the fire spread from one pallet load to one a certain distance, *d*, away was studied (see Figure 2.8). The parameters varied were the type of commodities (with or without plastic cups inside the cardboard boxes), the height of the fuel load (one or two pallets in height, each with 15 cardboard boxes), and the distance between the pallets. The measurements are presented in Section 2.3.

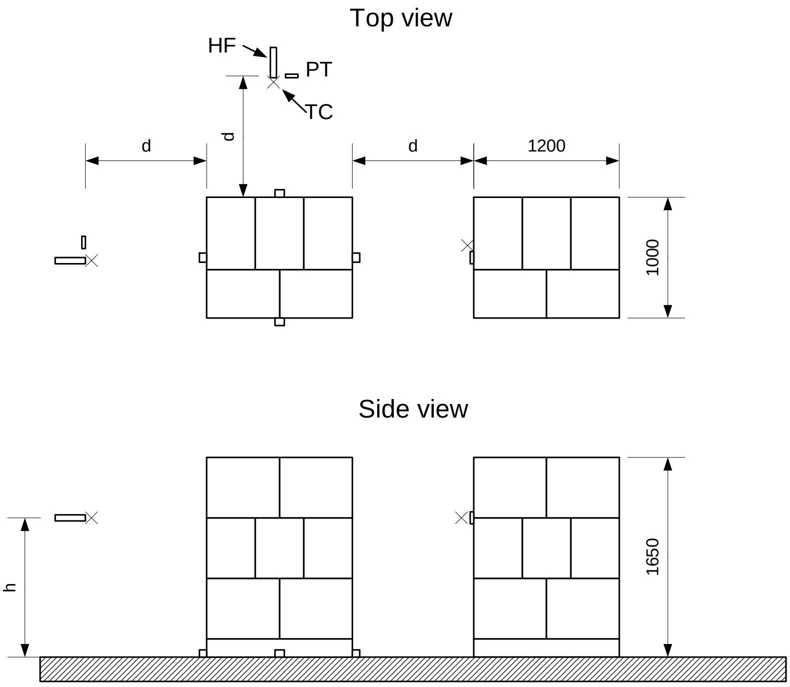

Figure 2.8 Experimental set-up in the test series with low-piled goods (test series 6). TC = thermocouple, PT = plate thermometer, HF = heat flux meter. Dimensions in mm.

2.3 Measurements

The material in the cardboard boxes used as fuel, was tested in the cone calorimeter to obtain information on flammability and thermal response properties of the material. Parameters measured were: time to ignition, time to extinction, heat release rate, developed energy, smoke production, mass loss rate, total mass loss, and heat of combustion.

In **test series 2**, the gas temperature was measured with thermocouples (0.25 mm, type K) in two positions (see Figure 2.1). The velocity in the flue was measured by using a bi-directions probe in one position. In addition the heat release rate (HRR) was measured by oxygen calorimetry [15, 16]. The fire gases were collected by a hood and guided through a pipe where the gas temperature and gas flow were measured and the concentrations of oxygen, carbon dioxide and carbon monoxide were analysed. The hood system is described in the standard ISO 9705 [17].

The **test series 3** was performed for several reason, e.g. to study the effect on the fire development of the position of the ignition sources. The main reason was, however, to measure the HRR from the experimental set-up with four racks. When the ceiling later was added the HRR could no longer be measured accurately. The HRR was in test series 3 measured according to the same principles as in test series. However, in test series 3 the set-up was placed under the SP Industry calorimeter [18, 19]. In addition to the HRR, the heat flux towards the commodity surface in rack 1 was measured by a heat flux meter. The purpose of this meter was to register the total heat flux before and at the time of the fire spread. The heat flux meter (Medtherm prod no 1211864) was placed in the centre flue of the fifth level of cartons in rack 1. The heat flux meter was facing rack 2 and the front of the meter was in level with the sides of the cartons facing rack 2.

In **test series 4** the effect of the size of the enclosure on the fire development was studied. The HRR was measured in the same way as in test series 2. The main measurements were thermocouples inside the enclosure and in the opening (see Figure 2.7). The wood cribs used as fuel were placed on a scale measuring the mass loss rate.

In **test series 5** a ceiling was placed above the rack storage set-up (see Figure 2.3). In this test series temperatures were the main measurements. Thermocouples were placed in 24 different positions beneath the ceiling (see Figure 2.5). In 16 of these positions a single thermocouple was placed 3 cm from the ceiling. In five positions three thermocouples were placed at different heights: 3 cm, 6cm, and 9 cm, respectively. In the same positions metal cylinders (simulating sprinkler bulbs; further described below) were placed at the same different heights. In one position (position 20) thermocouples and metal cylinders were placed at four different heights: 3 cm, 6 cm, 9 cm, and 12 cm from the ceiling. In the same position four bi-directional probes were placed (at the same four different heights) to measure the gas flow under the ceiling. In position 23 and 24, a thermocouple and a metal cylinder were placed 3 cm under the ceiling. In position a circular plate thermometer (11.3 cm in diameter) was placed in level with the ceiling.

One aim of the tests was to study how the estimated time to activation of a sprinkler would be affected by variation of different conditions, e.g. the height of the ceiling, the slope of the ceiling, and, most importantly, whether beam are present at the ceiling or not. To simulate sprinkler bulbs, special metal cylinders with thermocouples in the centre were designed. In the beginning of the test series the material in the cylinders was brass, but due to the effect of the high temperature on the cylinders a majority of the cylinders were from test 5.3 replaced by steel cylinders. However, in two positions (Pos. 15, 3 cm and Pos. 24) both brass and steel cylinders were used to compare the response of the different types of cylinders.

The cylinders were 14 mm long and 4 mm in diameter. At one of the ends of the cylinder a hole (1.3 mm in diameter) was drilled to mount a thermocouple inside the cylinder. The cylinders were tested in a type of a “plunge test” and the corresponding RTI values were calculated from the results. The calculated RTI values for the brass cylinder varied between 36 $m^{1/2}s^{1/2}$ and 39 $m^{1/2}s^{1/2}$ with and average of approximately 37 $m^{1/2}s^{1/2}$ (corresponds to an RTI value between 120 $m^{1/2}s^{1/2}$ and 130 $m^{1/2}s^{1/2}$ in real scale). The calculated RTI value for the steel cylinder was approximately 45 $m^{1/2}s^{1/2}$ (corresponds to a value of 150 $m^{1/2}s^{1/2}$ in real scale).

In **test series 6** with low-piled goods the fire spread between piles of goods was the main effect of interest. To relate the observation to quantified measurements, thermocouple, plate thermometers, and heat flux meters were used. The heat flux meters were placed at the same distance, *d*, from the good as the distance between the two piles (see Figure 2.8). At the same distance from the goods, plate thermometers (10 cm × 10 cm) were positioned. The centre to centre distance between the meters was 15 cm. At the target pile of goods at plate thermometer was placed facing the ignition pile. The heights of the meters varied depending on the heights of the piles and are given in Table 3.1. From test 6.7 thermocouples were added at the three different measurement positions. At the positions with heat flux meters the thermocouples were placed 15 cm below the centre of the meter and 5 cm out from surface of the meter (closer to the goods). The thermocouple at the large pile was place approximately 10 cm from the centre of the plate thermometer (measured within the surface plane) and 5 cm out from the plate thermometer (closer to the ignition pile).

The experimental set-up was placed under the SP Industry calorimeter [18] and HRR was measured during all of the test in test series 6.

3 Experiments

Within each test series numerous tests were performed. The experimental set-ups are presented in Section 2. However, the differences between the individual tests are presented in Table 3.1, where a complete list over all tests carried out is given.

Table 3.1 List of tests performed.

Test id	Description
1.1	Cone calorimeter test (ISO 5660) with one layer of cardboard
1.2	Cone calorimeter test (ISO 5660) with two layers of cardboard
1.3	Cone calorimeter test (ISO 5660) with three layers of cardboard
1.4	Cone calorimeter test (ISO 5660) with three layers of cardboard
2.1	One rack, 2 × 2 × 4 boxes, single boxes, 5 cm flue width
2.2	One rack, 2 × 2 × 4 boxes, double boxes, 5 cm flue width
2.3	One rack, 2 × 2 × 4 boxes, triple boxes, 5 cm flue width
2.4	One rack, 2 × 2 × 4 boxes, double boxes, 7.5 cm flue width (interrupted)
2.5	One rack, 2 × 2 × 4 boxes, double boxes, 7.5 cm flue width
2.6	One rack, 2 × 2 × 5 boxes, double boxes, 5 cm flue width
3.1	Four racks, 2 × 12 × 5 boxes in each rack, single boxes in rack 1,3 and 4, double boxes in rack 2, ignition at the bottom of the centre flue in rack 2; 5 cm flue width
3.2	Four racks, 2 × 12 × 5 boxes in each rack, single boxes in rack 1,3 and 4, double boxes in rack 2, ignition at the bottom of the third flue from the right in rack 2, three boxes off centre (see Figure 2.2); 5 cm flue width
4.1	Wood crib, free burning on a scale
4.2	Wood crib burning inside enclosure, 1 m × 1 m × 0.925 m
4.3	Wood crib burning inside enclosure, 1 m × 1.7 m × 0.925 m
4.4	Wood crib burning inside enclosure, 1 m × 2.4 m × 0.925 m
4.5	Wood crib burning inside enclosure, 1 m × 2.4 m × 0.925 m; door opening on the short side
5.1	Four racks, 2 × 12 × 5 boxes in each rack, single boxes in rack 1,3 and 4, double boxes in rack 2, ignition at the bottom of the centre flue in rack 2; 5 cm flue width; 1.2 m distance between ceiling and top of boxes.
5.2	Four racks, 2 × 12 × 5 boxes in each rack, single boxes in rack 1,3 and 4, double boxes in rack 2, ignition at the bottom of the centre flue in rack 2; 5 cm flue width; 0.2 m distance between ceiling and top of boxes.
5.3	Four racks, 2 × 12 × 5 boxes in each rack, single boxes in rack 1,3 and 4, double boxes in rack 2, ignition at the bottom of the centre flue in rack 2; 5 cm flue width; 0.6 m distance between ceiling and top of boxes. (The rack storages were displaced 50 cm)
5.4	Four racks, 2 × 12 × 5 boxes in each rack, single boxes in rack 1,3 and 4, double boxes in rack 2, ignition at the bottom of the centre flue in rack 2; 5 cm flue width; 0.6 m distance between ceiling and top of boxes. Four beams added beneath the ceiling.
5.5	Four racks, 2 × 12 × 5 boxes in each rack, single boxes in rack 1,3 and 4, double boxes in rack 2, ignition at the bottom of the centre flue in rack 2; 5 cm flue width; 0.6 m distance between ceiling and top of boxes. Four beams added beneath the ceiling. Tilted ceiling

Test id	Description
	(1:16).
5.6	Four racks, 2 × 12 × 5 boxes in each rack, single boxes in rack 1,3 and 4, double boxes in rack 2, ignition at the bottom of the centre flue in rack 2; 5 cm flue width; 0.6 m distance between ceiling and top of boxes. (Retesting of test 5.3; the rack storages were in test 5.3 not positioned exactly the same way as in the rest of the tests)
5.7	Four racks, 2 × 12 × 5 boxes in each rack, single boxes in rack 1,3 and 4, double boxes in rack 2, ignition at the bottom of the centre flue in rack 2; 5 cm flue width; 0.6 m distance between ceiling and top of boxes. Tilted ceiling (1:16). No beams.
5.8	Four racks, 2 × 12 × 5 boxes in each rack, single boxes in rack 1,3 and 4, double boxes in rack 2, ignition at the bottom of the centre flue in rack 2; 5 cm flue width; 0.6 m distance between ceiling and top of boxes. Walls with one opening 0.6 m × 0.6 m.
5.9	Four racks, 2 × 12 × 5 boxes in each rack, single boxes in rack 1,3 and 4, double boxes in rack 2, ignition at the bottom of the centre flue in rack 2; 5 cm flue width; 0.6 m distance between ceiling and top of boxes. Walls with one opening 0.6 m × 0.6 m and four fire ventilation openings in the ceiling (each 0.24 m × 0.48 m).
6.1	Low piled goods, Polystyrene cups in cardboard boxes on wood pallets (1 pallet in height, distance = 1 m, height of heat flux meters = 0.8 m) Wind effect! (see 6.3)
6.2	Low piled goods, Polystyrene cups in cardboard boxes on wood pallets (1 pallet in height, distance = 2 m, height of heat flux meters = 0.8 m) Wind effect! (see 6.4)
6.3	Low piled goods, Polystyrene cups in cardboard boxes on wood pallets (1 pallet in height, distance = 1 m, height of heat flux meters = 1.15 m). Re-test of 6.1
6.4	Low piled goods, Polystyrene cups in cardboard boxes on wood pallets (1 pallet in height, distance = **2** m, height of heat flux meters = 1.15 m) Re-test of 6.2
6.5	Low piled goods, Polystyrene cups in cardboard boxes on wood pallets (1 pallet in height, distance = **1.5** m, height of heat flux meters = 1.15 m).
6.6	Low piled goods, Cardboard boxes on wood pallets (1 pallet in height, distance = 1.5 m, height of heat flux meters = 1.15 m. **No polystyrene cups**.
6.7	Low piled goods, Cardboard boxes on wood pallets (1 pallet in height, distance = **1** m, height of heat flux meters = 1.15 m. **No polystyrene cups**.
6.8	Low piled goods, Polystyrene cups in cardboard boxes on wood pallets (**2** pallet in height, distance = **2** m, height of heat flux meters = 1.8 m) Effected by cartons falling down (see 6.9)
6.9	Low piled goods, Polystyrene cups in cardboard boxes on wood pallets (**2** pallet in height, distance = **2** m, height of heat flux meters = 1.8 m). Re-test of 6.8

4 Results

4.1 Test series 1 - Cone calorimeter tests

The cardboard material in the boxes was tested in the cone calorimeter according to ISO 5660. Pieces of the size 100 mm × 100 mm were tested. The thickness of one layer was 6 mm. The pieces were tested horizontally and were exposed to a radiation of 50 kW/m^2. The results from the tests are presented in Table 4.1.

Table 4.1 Results from the cone calorimeter tests.

Parameter	**Test 1.1**	**Test 1.2**	**Test 1.3**	**Test 1.4**
Time to ignition (min:s)	0:05	0:07	0:06	0:07
Extinction (min:s)	1:08	1:51	3:39	3:56
Total test time (min:s)	3:08	3:51	5:39	5:56
Max. heat release rate (kW/m^2)	206	247	242	186
Average HRR, 3 min (kW/m^2)	72	125	148	133
Total developed energy (MJ/m^2)	13.0	23.9	34.4	35.6
Max. smoke production rate (m^2/(m^2s))	1.1	0.7	1.6	0.9
Average mass loss rate (g/(m^2s))	4	6.8	6.7	6.7
Total mass loss (g)	6.4	13.4	19.8	20.4
Effective heat of combustion (MJ/kg)	17.7	15.7	15.3	15.4
Specific smoke production (m^2/kg)	21	17	12	6

4.2 Test series 2 - Pre-tests with small rack storage

In test series 2, the flue width in the rack storage, the height of the rack (number of levels), and the wall thickness of the boxes (single, double or triple boxes) were varied. Time resolve graphs for the different parameters measured during the test series are given in Appendix 1. No protocols are given for this test series. In Figure 4.1 the HRR curves for the five tests 2.1-2.3 and 2.5-2.6 are given (test 2.4 was interrupted and no results are given for this test.

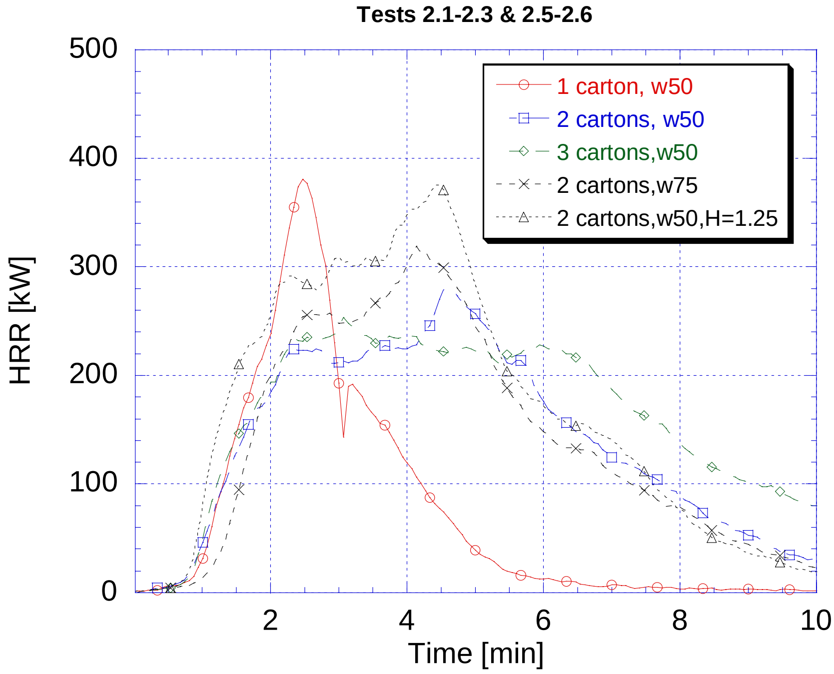

Figure 4.1 Comparison of HRR for the tests in test series 2.

4.3 Test series 3 - Free burning rack storages

Two free burning tests with four racks were performed beneath the industry calorimeter. The difference between the two tests was the position of the ignition sources. The ignition sources were placed in the central flue of rack 2 and in the third fuel from the end in rack 2, respectively (see Figure 2.2). There was some difference in the rate of the fire spread. This can be seen both in the HRR graphs (Figure 4.2 and Appendix 1) and in the visual observations from the tests (Appendix 2). The initial fire spread is similar in the two tests, but in test 3.1, the HRR reach a much higher maximum value. On the other hand the test 3.2 has a broader HRR curve which leads to a higher total release of energy (see Table 4.2). This leads to a higher heat of combustion. The calculation is based on the assumption that all of the boxes were consumed. This is not fully true, but the mass of the remainders was small.

Table 4.2 Total energy released and heat of combustion for the free burning tests with four storage racks.

Test id	Q_{tot} [MJ] (0 – 18 min)	Δh_c [MJ/kg][a)]
3.1	1238	8.75
3.2	1348	9.53

a) Assuming total consumption of all the boxes.

Ingason [20] has shown that heat release rate per square meter for cartons in several cases is 118 kW/m^2. If this value is used for test 3.1 this means the burning surface at the time of the maximum HRR corresponds to 129 boxes, i.e somewhat more than one storage rack (120 boxes).

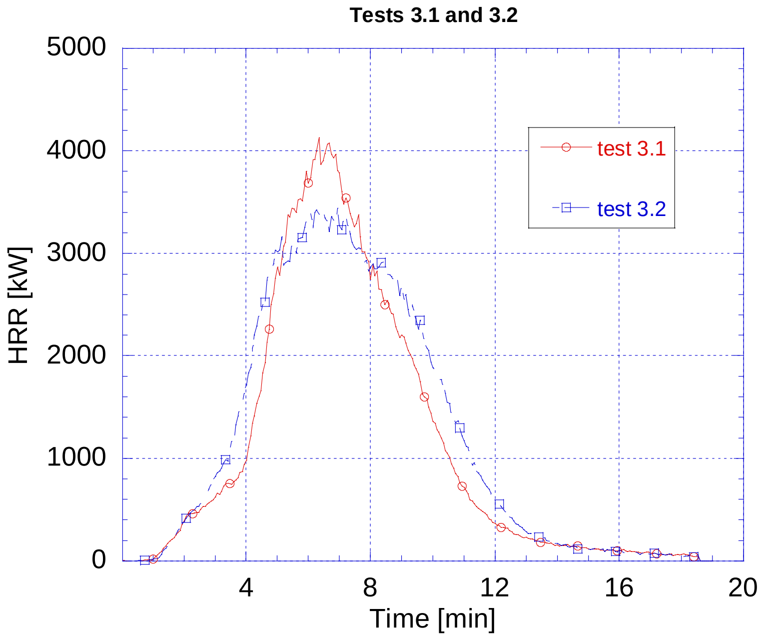

Figure 4.2 Comparison of HRR for the tests in test series 3.

4.4 Test series 4 - Influence of size of enclosure and position of opening

For the tests with a wood crib burning inside an enclosure, there was a large difference in the heat release rate curve compared to the free burning case. The case with the smallest volume corresponds to the slowest burning rate, but there was almost no difference between the cases with a length of the enclosure of 1.7 m and 2.4 m, respectively. The case with the largest volume had the slowest fire development. The position of the door opening had in this set-up only a small influence on the results.

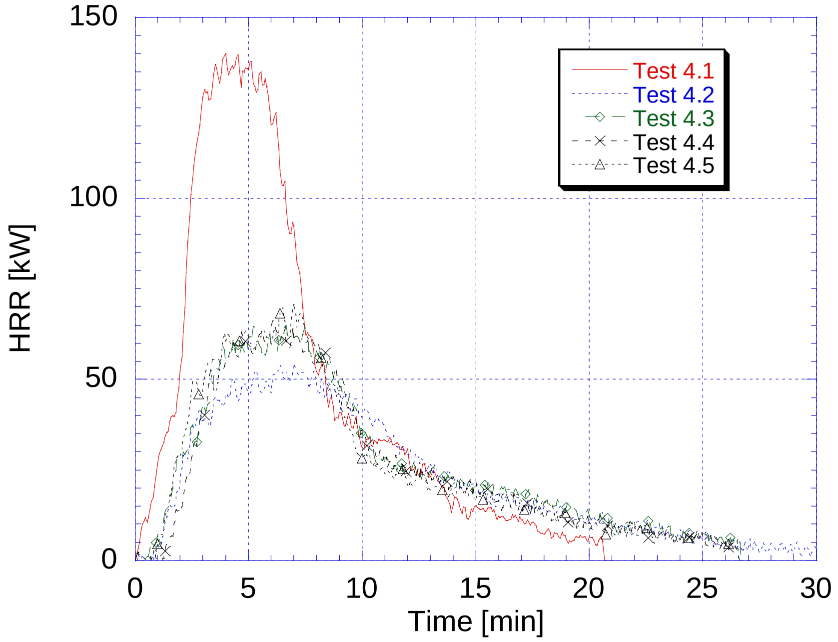

Figure 4.3 Comparison of heat release rates for the tests in test series 4.

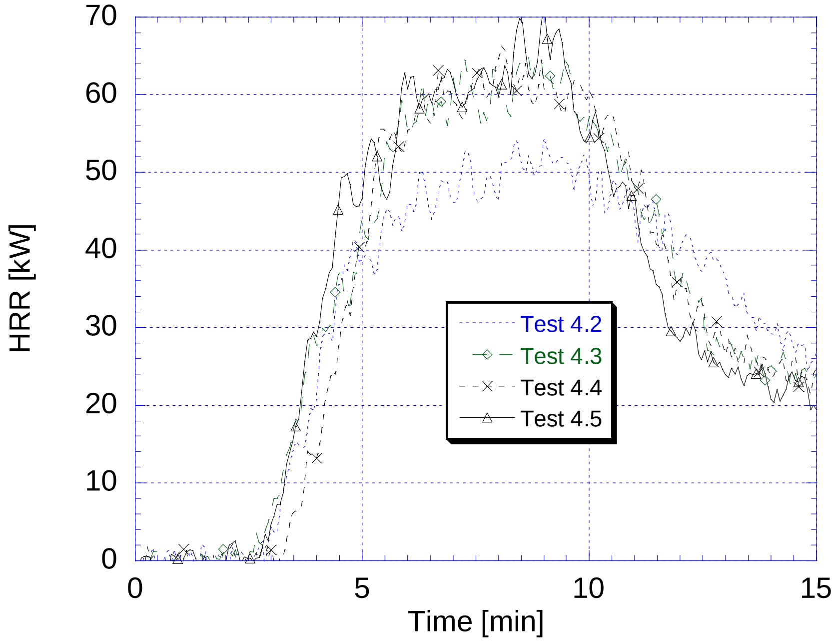

Figure 4.4 Comparison of heat release rates for the tests in test series 4 (resolved scales).

Table 4.3 Maximum HRR and total mass loss for selected time periods. Calculated values have been used to estimate the heat of combustion.

Test id	HRR_{max} [kW]	Evaluated time period [min]	Δm [g][a)]	Δh_c [MJ/kg][a)]
4.1	140.1	0 - 13.17	3240	16.66[b)]
4.2	54.4	0 - 30	3144	12.54
4.3	65.0	0 - 26	3037	12.90
4.4	66.2	0 - 26	3194	12.48
4.5	71.0	0 - 26	3259	12.52

a) The values have been corrected for mass loss of the incombustible board under the wood crib; see also comment b).

b) This is the uncorrected value. If a mass loss of the incombustible board of 100 g is assumed the corrected value of the heat of combustion will be 17.19.

4.5 Test series 5 - Rack storage tests with ceiling

In this test series the effect on the results of the distance between the commodities and the ceiling, the slope of the ceiling, and the presence of beams under the ceiling were studied. Two main features were of special interest: the time for fire spread from one rack to the next and the conditions (gas temperature and flow rate) near the ceiling. The process of fire spread is illustrated in Figure 4.5. The time when the fire spread to the different racks was registered. These times are summarized in Table 4.4. There was a difference in flame spread within rack 2 (the rack where ignition took place), which means that the time for the flames to reach the ceiling varied between the tests. Since the flames in the ceiling are important for the fire spread, the time to flames reaching the ceiling have been subtracted from the times to fire spread and the results are presented in Table 4.5.

Table 4.4 Time to flame reaching ceiling and flame spread between racks.

Test id	Flames reach ceiling [min:s]	Fire spread to rack 1 [min:s]	Fire spread to rack 3 [min:s]	Fire spread to rack 4 [min:s]
5.1	1:15	3:39	3:37	4:50
5.2	0:57	2:40	2:38	2:58
5.3	0:49	2:15	2:17	2:50
5.4	1:03	2:22	2:17	2:57
5.5	1:12	2:31	2:24	2:56
5.6	1:11	2:24	2:24	2:54
5.7	1:09	2:34	2:32	3:04
5.8	1:30	3:15	3:03	3:38
5.9	1:03	2:26	2:24	2:50

Table 4.5 Time to flame reaching ceiling and flame spread between racks; the time when the flames reach the top of the commodities in rack 2 is subtracted from the times for each test.

Test id	Flames reach ceiling [min:s]	Fire spread to rack 1 [min:s]	Fire spread to rack 3 [min:s]	Fire spread to rack 4 [min:s]
5.1	0:15	2:39	2:37	3:50
5.2	0:02	1:45	1:43	2:03
5.3	0:09	1:35	1:37	2:10
5.4	0:08	1:27	1:22	2:02
5.5	0:07	1:25	1:19	1:51
5.6	0:09	1:22	1:22	1:52
5.7	0:05	1:30	1:28	2:00
5.8	0:07	1:52	1:40	2:15
5.9	0:08	1:31	1:29	1:55

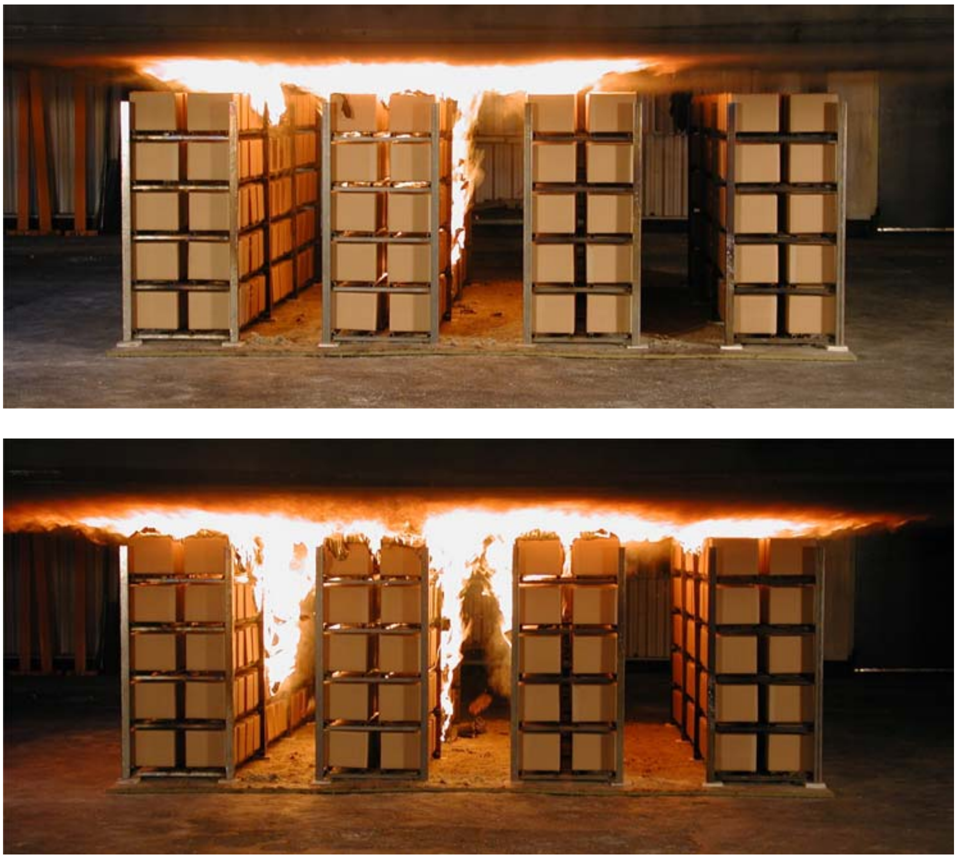

Figure 4.5 The fire was started in rack 2. It the spread first to rack 1 and 3 and later to rack 4.

In Figure 4.6 the gas temperature in position 11 (3 cm below the ceiling) is presented for three different distance between the commodities and the ceiling. It can be seen that distance affects the fire development. The fastest development is obtained for the case with a distance of 0.2 m, i.e. the shortest distance tested. However, after a while the increase is stopped and a period of relatively constant temperature follows. During this period the temperature for the case with a distance of 0.6 m is higher. In the end of the test the temperature in the 0.2 m case is again the highest one. The case with a distance of 1.2 m is slower than the two other cases but reaches approximately the same maximum temperatures as the 0.2 m case. In the end of the tests the temperatures for the 0.6 m case and the 1.2 meter case are approximately the same. The differences in fire spread between case with different distance to the ceiling can also be seen in Table 4.5, where the time to fire spread to the other racks are much longer in the 1.2 m case (Test 5.1). The 0.6 m case (Test 5.6) obtain the fastest fire spread. The fire spread in the 0.2 m case (Test 5.2) is approximately 20 s lower than in the 0.6 m case.

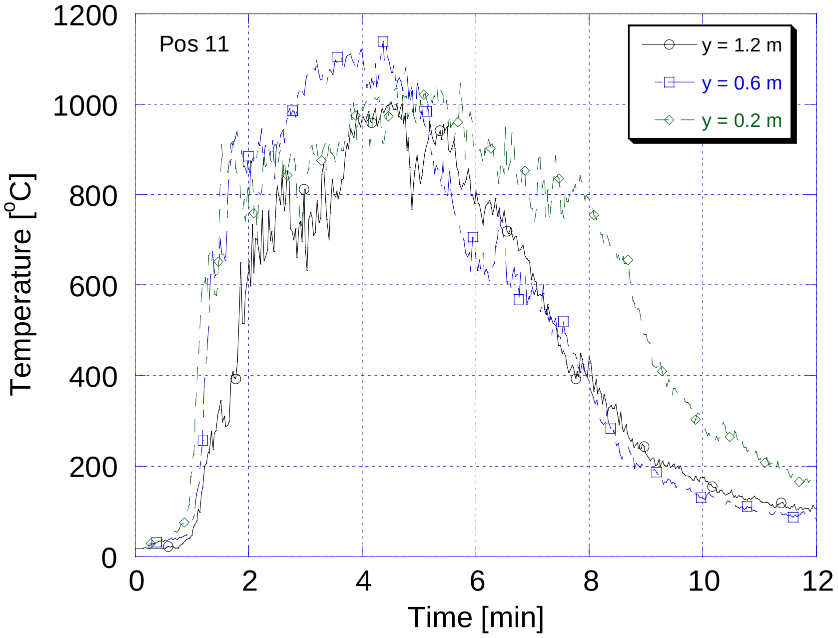

Figure 4.6 Comparison between gas temperature measurements in position 11 with different distances (y) between the top of the commodities and the ceiling.

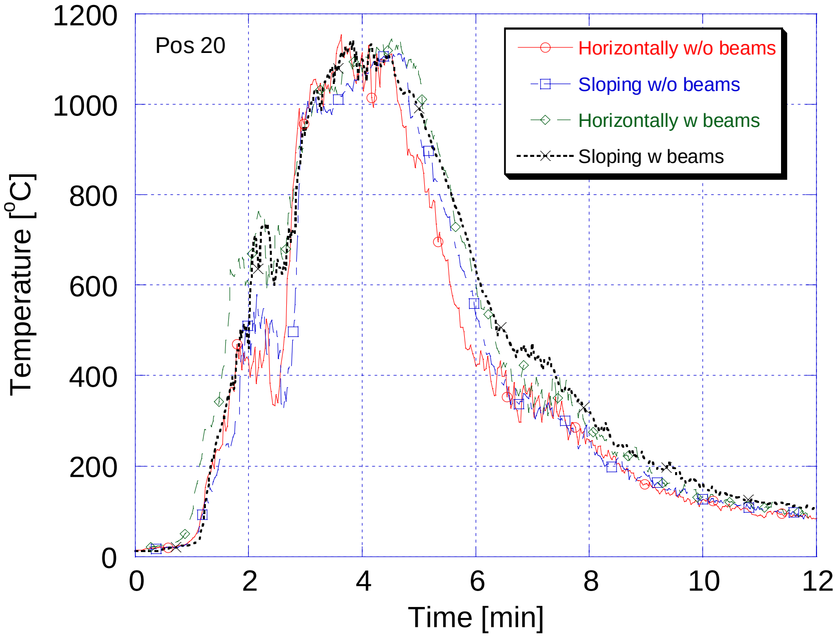

Figure 4.7 Comparison between temperatures in position 20 with different slope of the ceiling and with and without beams, respectively.

In Figure 4.7 the gas temperature 3 cm below the ceiling in position 20 is given for four different cases: sloping and non-sloping ceiling, and with or without beams. The beams collect the hot smoke and increase the temperature, at least in the beginning and in the later part of the tests. The effect of the slope is not as large but could still be seen, increasing the temperature in position 20.

The time to activation was estimated by using metal cylinders with a thermocouple in the centre. The cylinders were designed to have a RTI value corresponding to sprinkler bulbs in the scaled set-up. In Figure 4.8 the times to activation of sprinklers at different positions are presented. For each position two numbers are given. These correspond to the cases without (left) and with (right) beams, respectively. Note that only the sprinkler bulbs were simulated. No real sprinkler was activated, i.e. not water was applied.

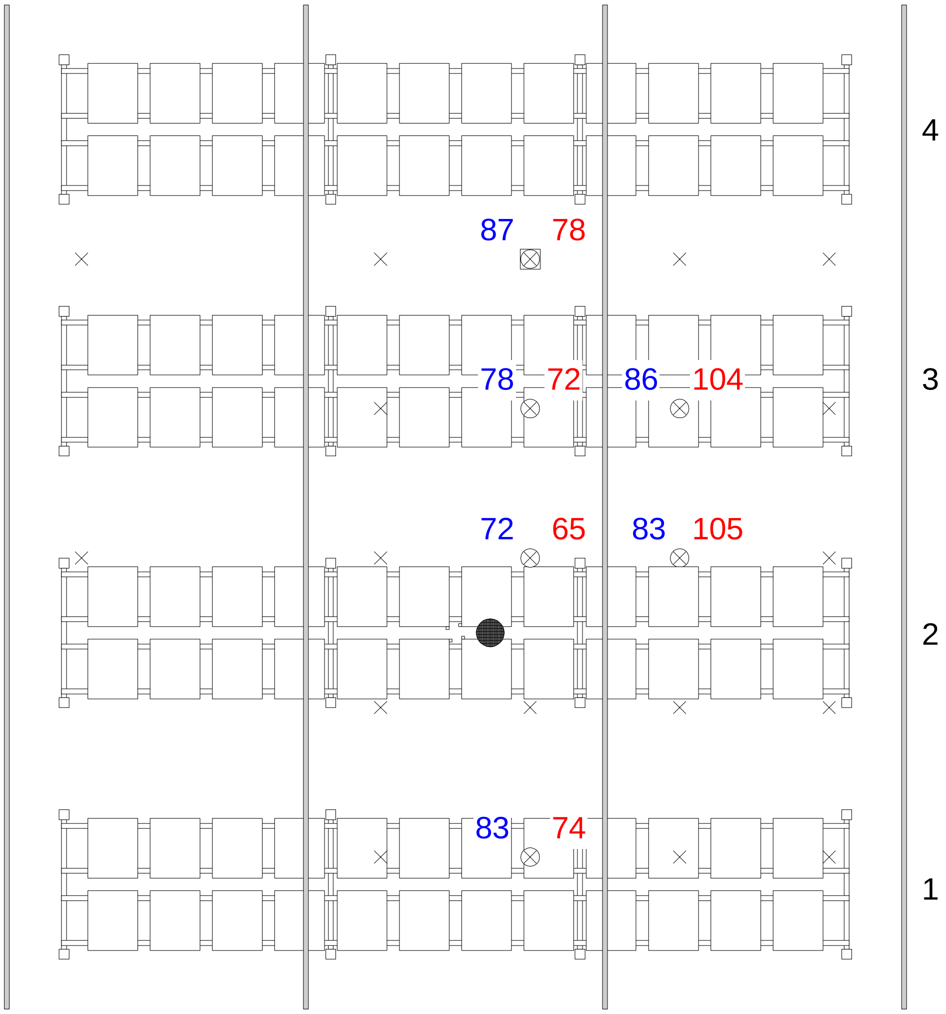

Figure 4.8 Comparison of times to activation of sprinkler without (left = blue) and with (right = red) beams, respectively.

4.6 Test series 6 - Low-piled goods

In the tests with low-piled goods, the temperature was measured with plate thermometers and in some tests with thermocouples. In addition heat flux meters were used. The time resolved results from these measurements are presented in Appendix 1.

In this section comparison in measured results and times to fire spread for the different cases are given. Varied parameters are distance between piles, height of piles, and whether the cardboard boxes contain polystyrene cups or not. In Table 4.6 a summary of the tests and some interesting times are given.

Table 4.6 Summary of the tests with low-piled goods.

Test	No. of Pallets in height	Distance between pallets (m)	Cups	Smoke from pile 2 (min:s)	Falling of goods (min:s)	Ignition of pile 2 (min:s)	Comments
6.1	1	1	Yes	9:50	12:10	12:37	Wind effects[a)]
6.2	1	2	Yes	10:30	10:15	-	Wind effects[a)]
6.3	1	1	Yes	<3		4:37	Re-test of 6.1
6.4	1	2	Yes	~4:30		-	Re-test of 6.2
6.5	1	1.5	Yes	3:12		8:30	
6.6	1	1.5	No	~4		-	
6.7	1	1	No	2:37		5:30	
6.8	2	2	Yes	3:50	4:18	4:33	Falling pallet
6.9	2	2	Yes	4:00		6:05	Re-test of 6.8

a) Non-symmetric burning due to draft in the fire hall.

In Figure 4.9 to Figure 4.11 the heat flux measured in the position facing the long side of the pile of ignition are presented for different cases. In Figure 4.9 the results for different distances between the piles (the same distance between the heat flux meter and the pile) are presented. The effect of the distance is clearly seen.

The effect of the material in the commodity is shown in Figure 4.10 where the heat flux results for one case with polystyrene cups in the boxes and one case without cups are given. Again the heat flux is significantly affected with a higher heat flux in the case with cups.

The final comparison is made between different heights of the piles. The heat flux results in Figure 4.11 clearly show that higher values are obtained for higher piles.

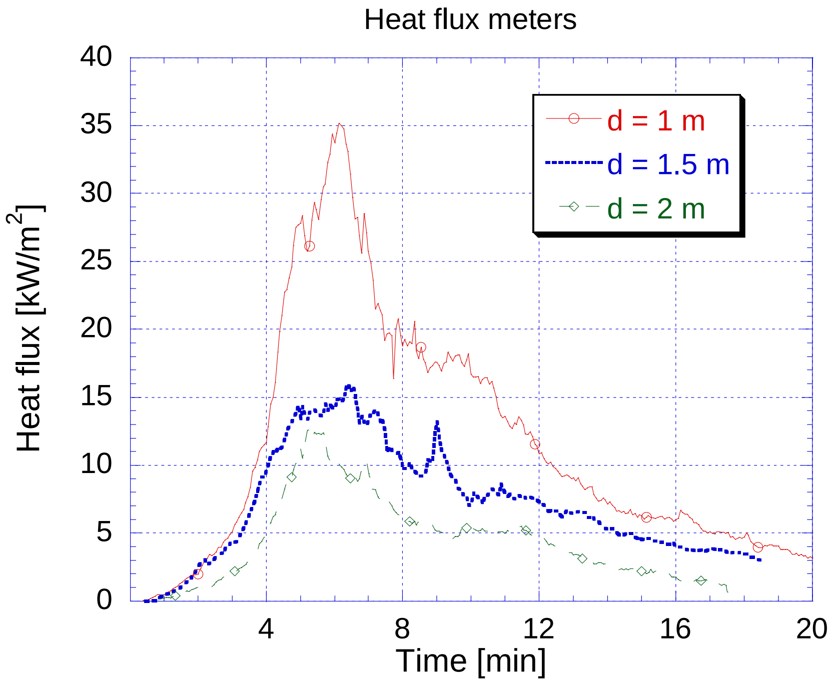

Figure 4.9 Low piled goods: comparison of heat flux with different distances between the piles.

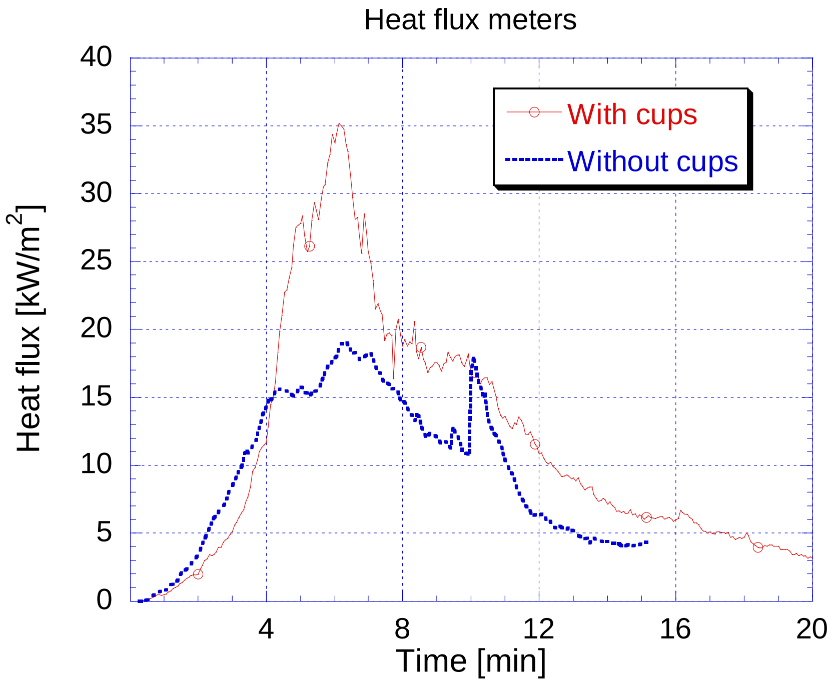

Figure 4.10 Low piled goods: comparison of heat flux between the cases with and without cups in the cardboard boxes.

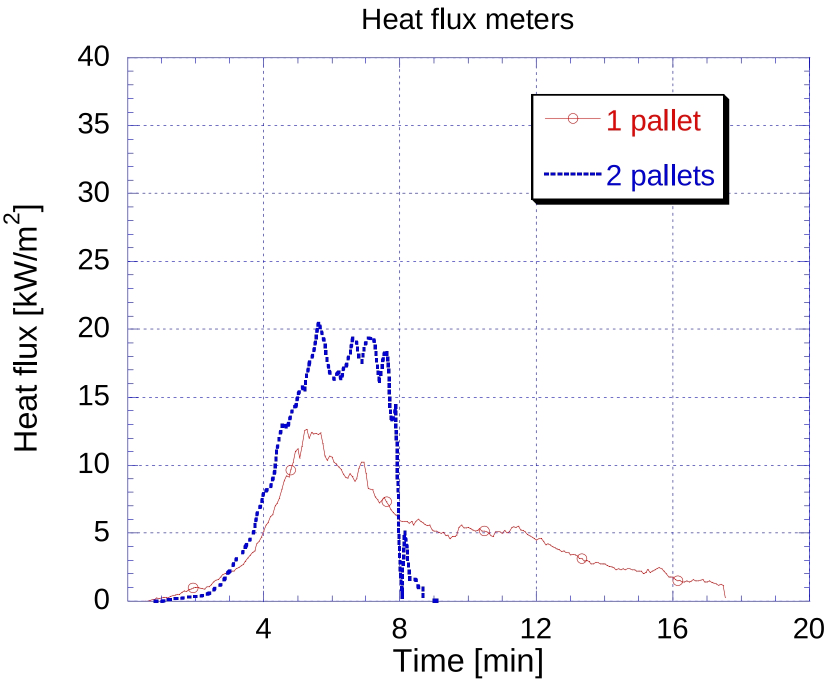

Figure 4.11 Low piled goods: comparison of heat flux between the cases with one or two pallets in each pile.

5 Discussion

Test series 2 was performed as pre-tests for the rack storage tests with for long racks. In test series 2 the thickness of the walls of the boxes, the flue width, and the height of the rack were varied. The variation of the wall thickness affected the results significantly. The test with single boxes (Test 2.1) had a fast increase in HRR and a high maximum HRR. The reason for this behaviour is that the flames more easily burns through the box wall leading to an increased exposed surface area. The low amount of fuel made the material burn out relatively quickly.

The test with double and triple boxes (Test 2.2 and 2.3, respectively) burned similarly to each other in the beginning of the test. Test 2.2 had a somewhat higher maximum HRR while test 2.3 with a larger mass of material burned longer.

The increase in flue width from 50 mm to 75 mm slowed down the increase rate in HRR and test 2.5 with the flue width 75 mm had the slowest increase in HRR of all the test in the series 2. The maximum HRR was, however, somewhat higher than the corresponding test with a flue width of 50 mm (Test 2.2).

The fastest increase in HRR was obtained in the test (Test 2.6) with five levels of boxes (H=1.25 m) instead of four. The ‘chimney effect’ had a significant influence on the result and the maximum HRR was approximately the same as the test with four levels of single boxes (Test 2.1) and 34 % higher than the test with four levels of double boxes.

The fire behaviour of the case with five levels of double boxes and a flue width of 50 mm suited best the purposes with large racks and therefore it was decided to use dimensions corresponding to this case in the other test series with rack storages.

The free burning tests with four racks (without ceiling) showed that the fire development depends on the position of the ignitions sources. A higher maximum HRR was reached when the ignition was in the centre of the rack. The heat flux from rack 2 towards rack one was measured with heat flux meters. The results show that the heat flux to the meter was approximately 23 kW/m^2 at the time of fire spread to rack 1 in both the tests (3.1 and 3.2).

In the test series with rack storage under a ceiling, differences in the temperature measurements at different height can be seen, at least during the development phase of the fire. There is also a significant difference between the thermocouples and the temperature inside the metal bulbs, the latter being lower in the beginning of the test and higher than the thermocouple measurements in during the decreasing phase. The difference between the brass bulb measurement and the steel bulb measurement in the same position is, however, very small.

The ceiling height had a significant influence on the fire spread. The case with the longest distance to the ceiling had the slowest fire spread. This can be explained by in this case the lower radiation from the flames and gases near the ceiling towards the other racks, which is an important process for the fire spread. By the same reasoning the case with the lowest height should have had the fastest fire spread. The explanation for this case being slower than the medium height case is that in the case with the short distance between the commodities and the ceiling the fresh air does not easily reach the combustion zone. Instead the flames are embedded in smoke, which means that the combustion conditions are poorer in this case.

The tests inside an enclosure with varied size show that the HRR is affected by the enclosure. The HRR in the free burning case is much higher than the HRRs for the cases where the wood crib was place inside an enclosure. The size of the enclosure also affected the results. The case with the smallest enclosure (1 m × 1 m × 0.925 m) reached the lowest maximum HRR. For the other cases with larger enclosures the difference in maximum HRR was rather small. There is also a difference in time to the fast increase in HRR. This difference is probably due to the difference in fill-up time for the smoke in the enclosure and therefore a difference in time before the smoke exits the enclosure an reaches the measurement station for HRR.

The effect of the enclosure was also seen in Test 5.8 when the four long racks were surrounded by walls which together with the already existing ceiling made up an enclosure. In this case the fire development and spread was significantly slower than in the corresponding case without walls. The gas temperature near the ceiling is approximately 400 ºC during a large part of the test. It is almost only in the beginning of the test and around 29 minutes after ignition (when the fire spreads to rack 4) the temperatures are higher. In Test 5.9 fire ventilation was opened when the thermocouples inside the metal cylinders at the fire ventilation had reached 94 ºC. This made a significant difference for the fire development. The gas temperatures near the ceiling were higher and the fire developed and spread in a similar way as the corresponding tests without walls (and without fire ventilation).

It has been shown that for the low-piled goods the different parameters varied can significantly change the results. The distance between the piles is very important. The polystyrene cups increase the fire load, but is also a material the radiate more than the cardboard alone and thereby increase the risk for fire spread. A similar conclusion can be drawn from the case with higher pile; the higher pile means a higher fire load, but also a larger view factor from the target pile, and again the risk for fire spread is increased.

From the time resolved results in Appendix 1 it can be seen that the heat flux measurements at the two different locations are similar to each other (but for Test 6.8 when the pile was collapsed). At the time of ignition, the registered heat fluxes were between 15 kW/m^2 and 20 kW/m^2.

6 Conclusions

The aim of the project presented here was to investigate fire spread in rack storages. The focus was on the fire spread from an initial fire in a rack storage to adjacent racks without interaction of a suppression system. The effects on the fire spread in regard to the enclosure, the ceiling height above the top of the rack storage (clearance height), beams in the ceiling and ventilation are tested. The height of the rack storage as well as the distances between boxes and the thickness of the box material varied. The effects of beams and clearance height on response of virtual sprinklers in the ceiling were explored as well as the risk of fire spread between low-piled goods.

The tests show that the thickness of the material stored in the racks has a significant effect on the burning behaviour. So does also the flue width and height of the rack storage. These effects have also been seen in previous research but were confirmed here in the tests performed to decide the experimental set-up.

The position of ignition affects the development of the fire and the HRR curve.

Especially the height of the ceiling affects the fire spread. There seems to be an optimum height between the stored goods and the ceiling. If the height is higher the radiation towards the commodities is decreased. If the height is lower the combustion conditions change and decreases the combustion efficiency.

Beams affect the time to activation of sprinklers. The slope of the ceiling has some effects, but not as significant.

There was a large difference between the free burning wood crib tests and the tests with wood cribs in an enclosure. The size of the enclosure affected the HRR, but the differences decreased when the enclosure increased.

For low-piled goods, the distance between piles, the height of the piles, and the material of the goods are important parameters for the fire spread.

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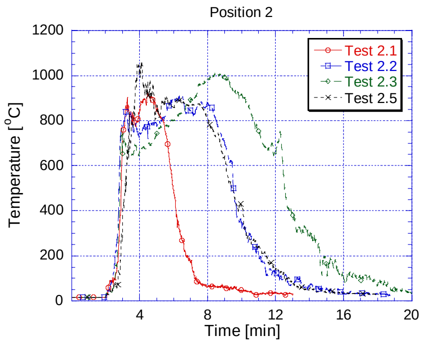
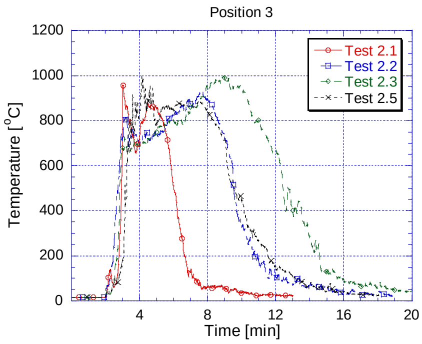
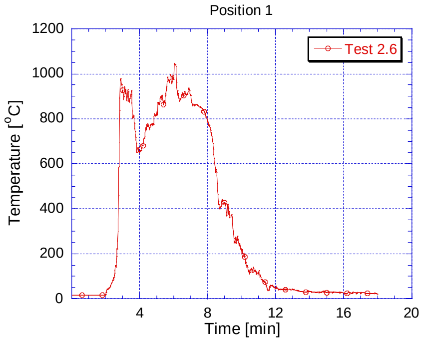
Appendix 1 Time-resolved results

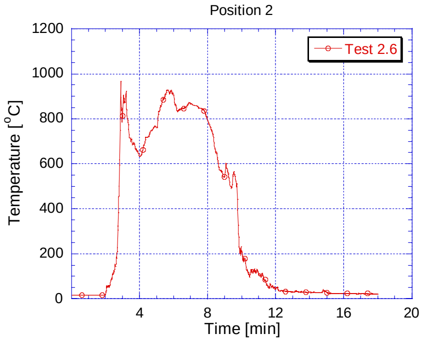
Test series 2 - Pre-tests with one rack

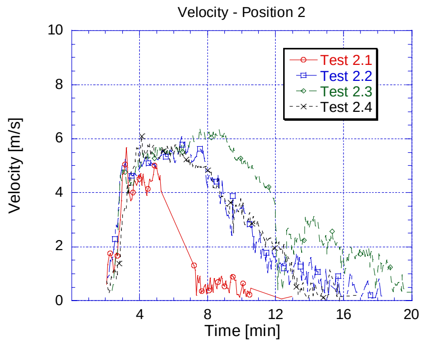
Observe that the times in the graphs for test series 2 are from measurement start and not ignition (2 minutes after measurement start)

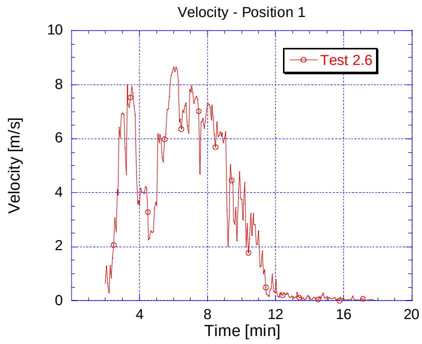






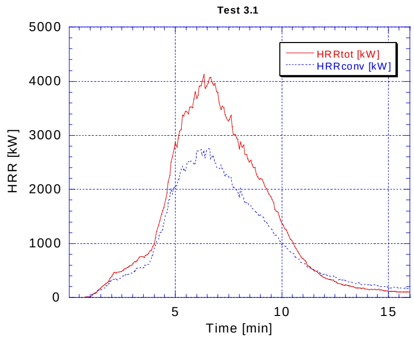


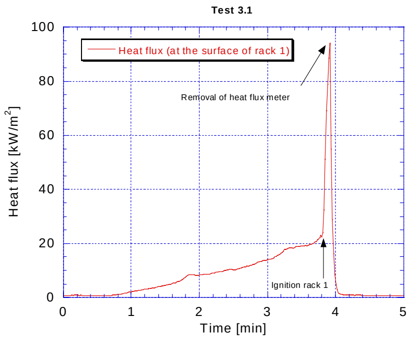




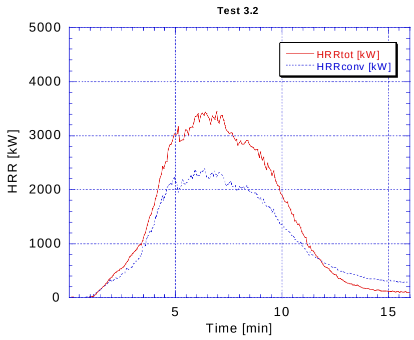
Test series 3

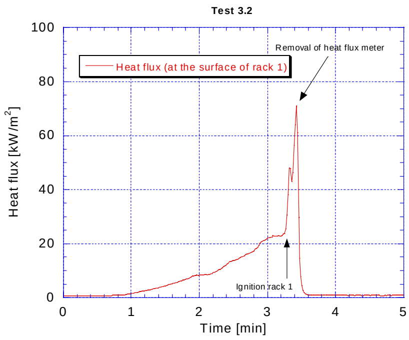
Test id: 3.1 – Four racks free burning





Test id: 3.2 – Four racks free burning

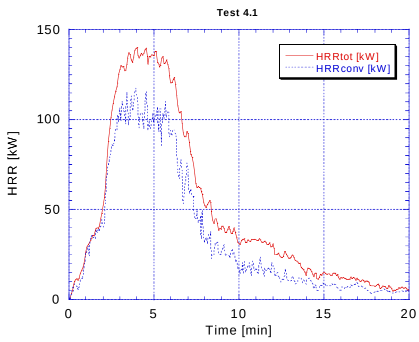


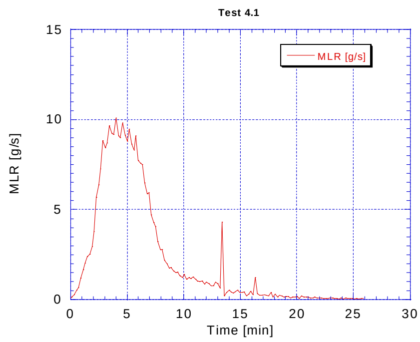


Test series 4

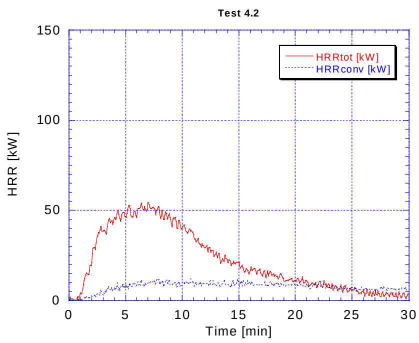
Observe that the times in the temperature graphs for test series 4 are from measurement start and not ignition (2 minutes after measurement start)

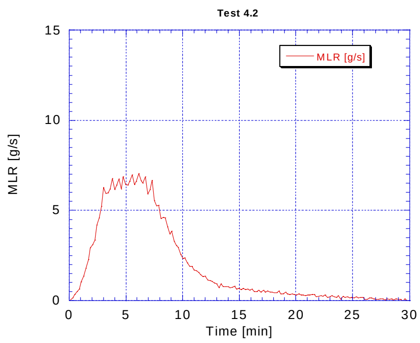
Test id: 4.1 – wood crib inside enclosure

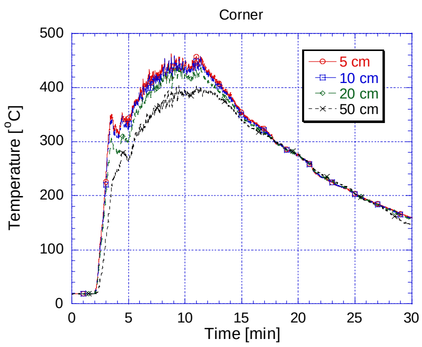


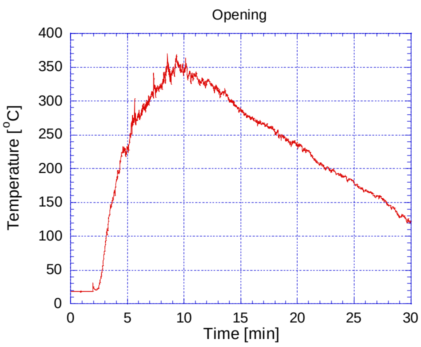


Test id: 4.2 – wood crib inside enclosure

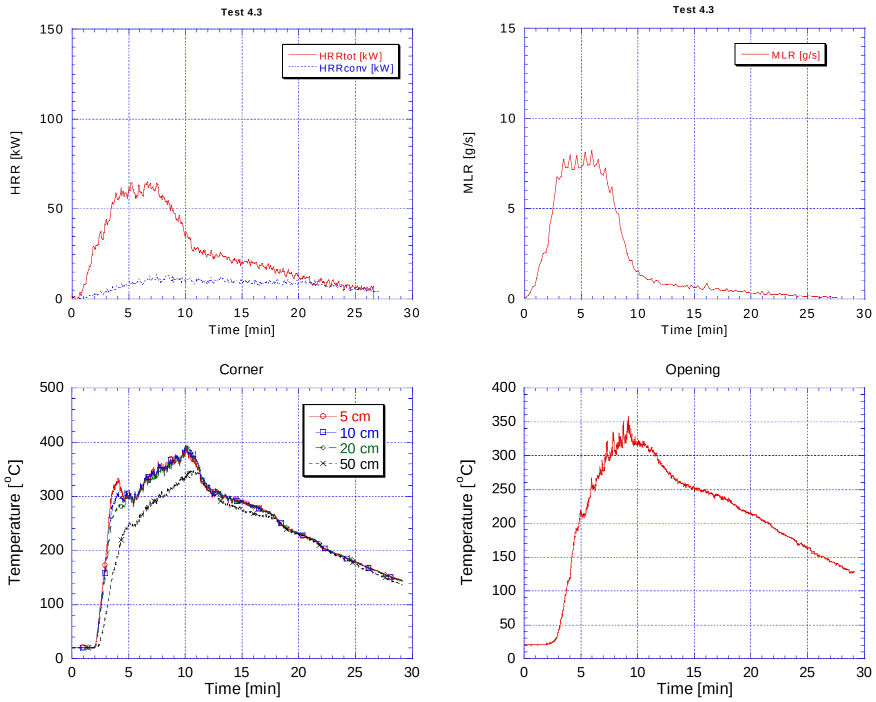




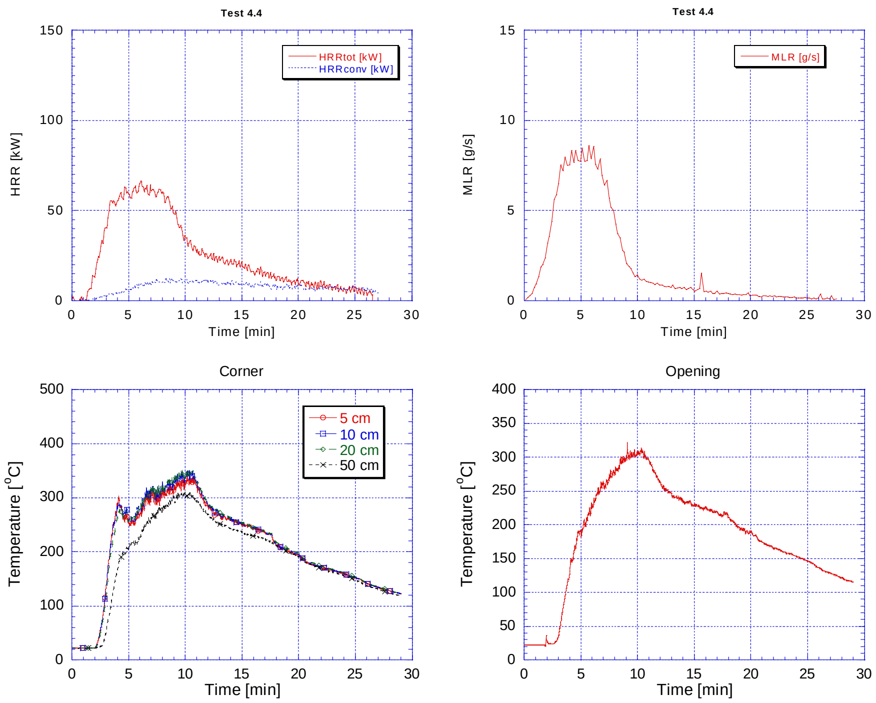




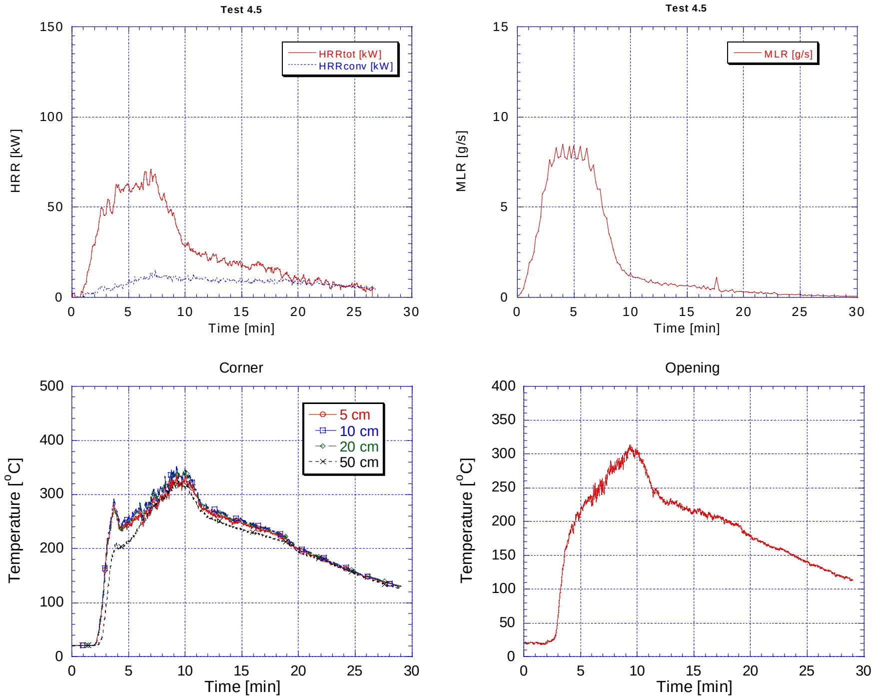
Test id: 4.3 – wood crib inside enclosure



Test id: 4.4 – wood crib inside enclosure

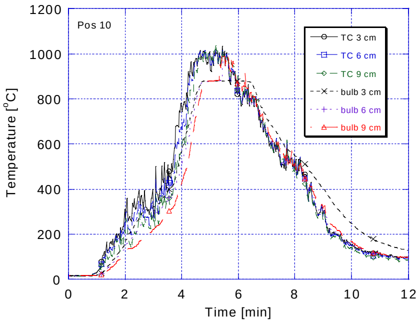


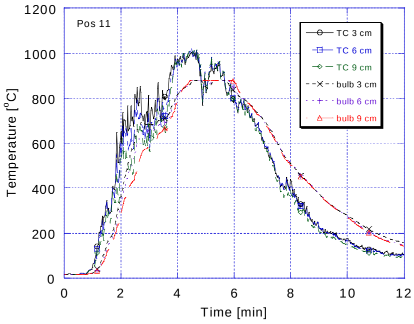
Test id: 4.5 – wood crib inside enclosure

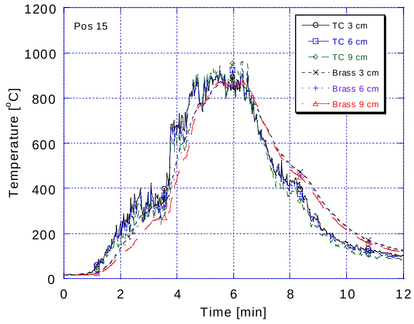


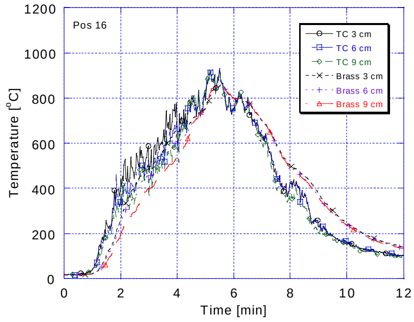
Test series 5

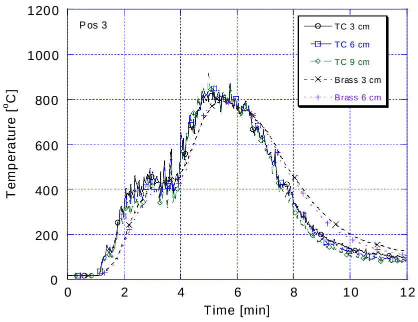
Test id: 5.1 – rack storage beneath ceiling

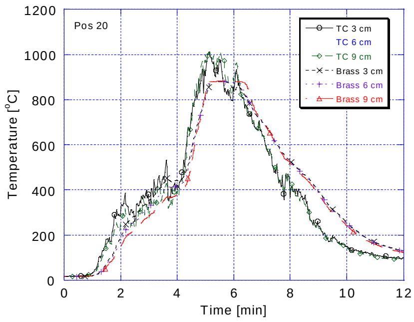


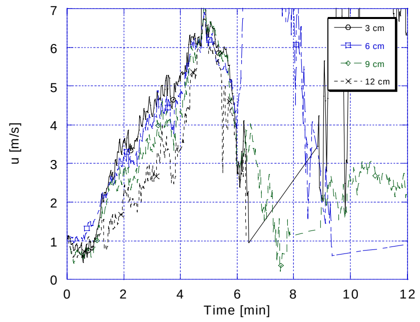




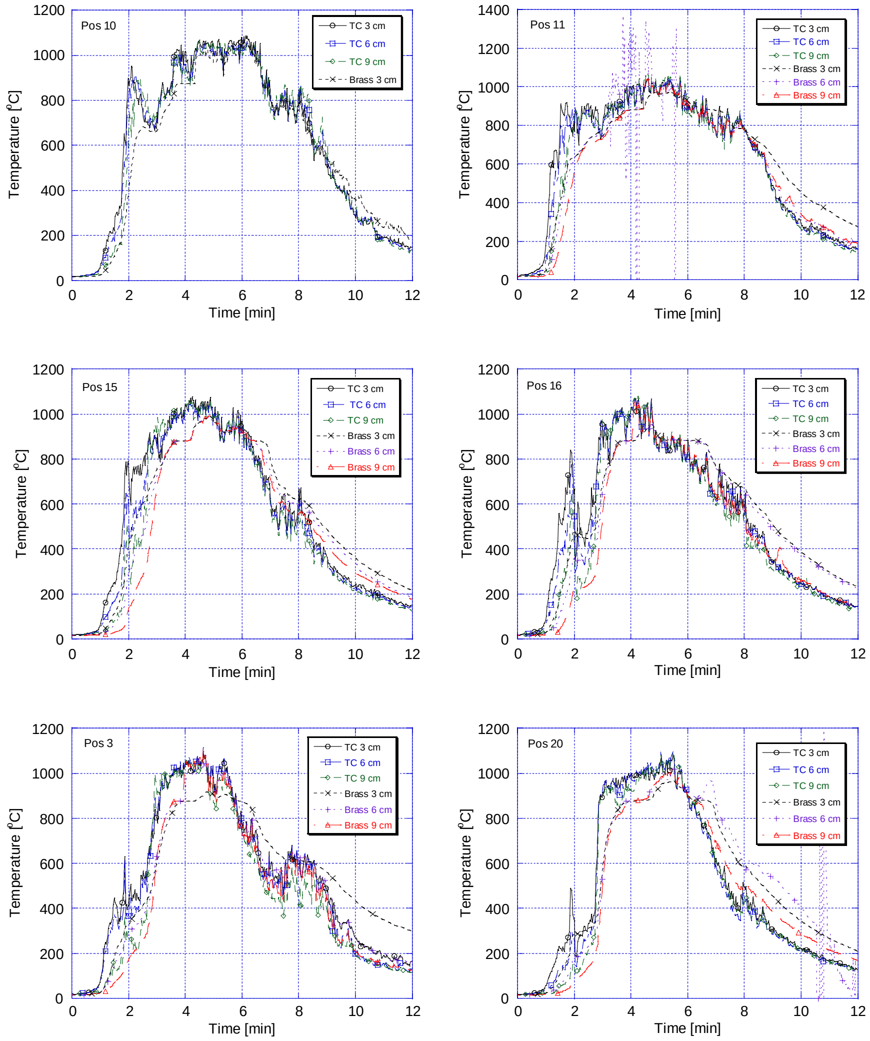


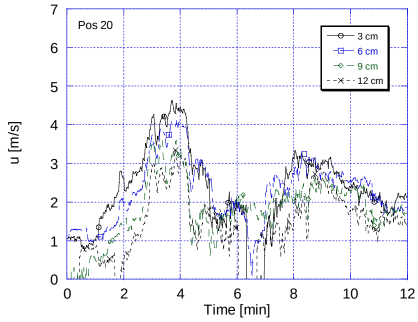




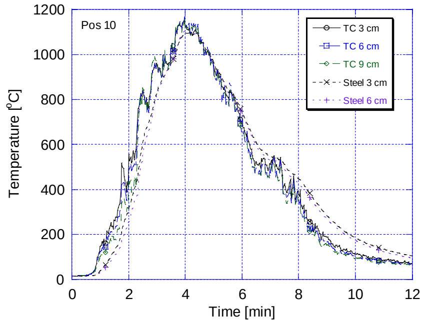


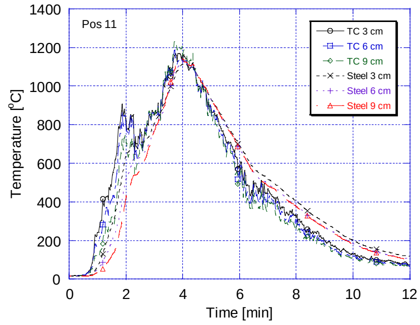
Test id: 5.2 – rack storage 0.2 m beneath ceiling

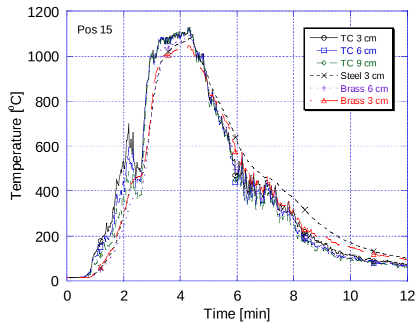


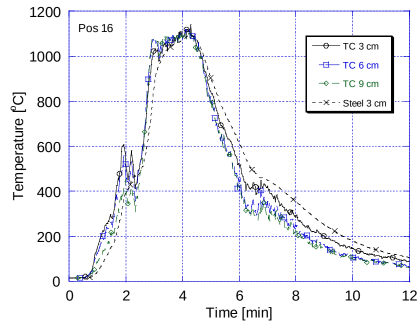


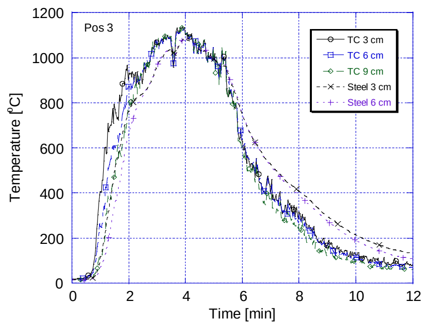
Test id: 5.3 – rack storage 0.6 m beneath ceiling

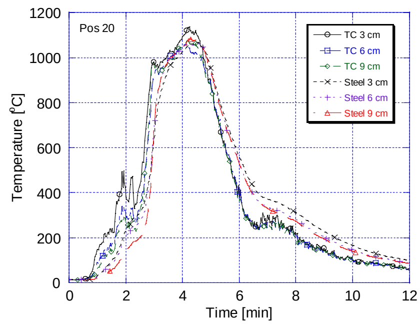


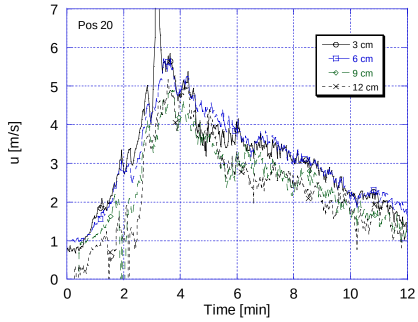




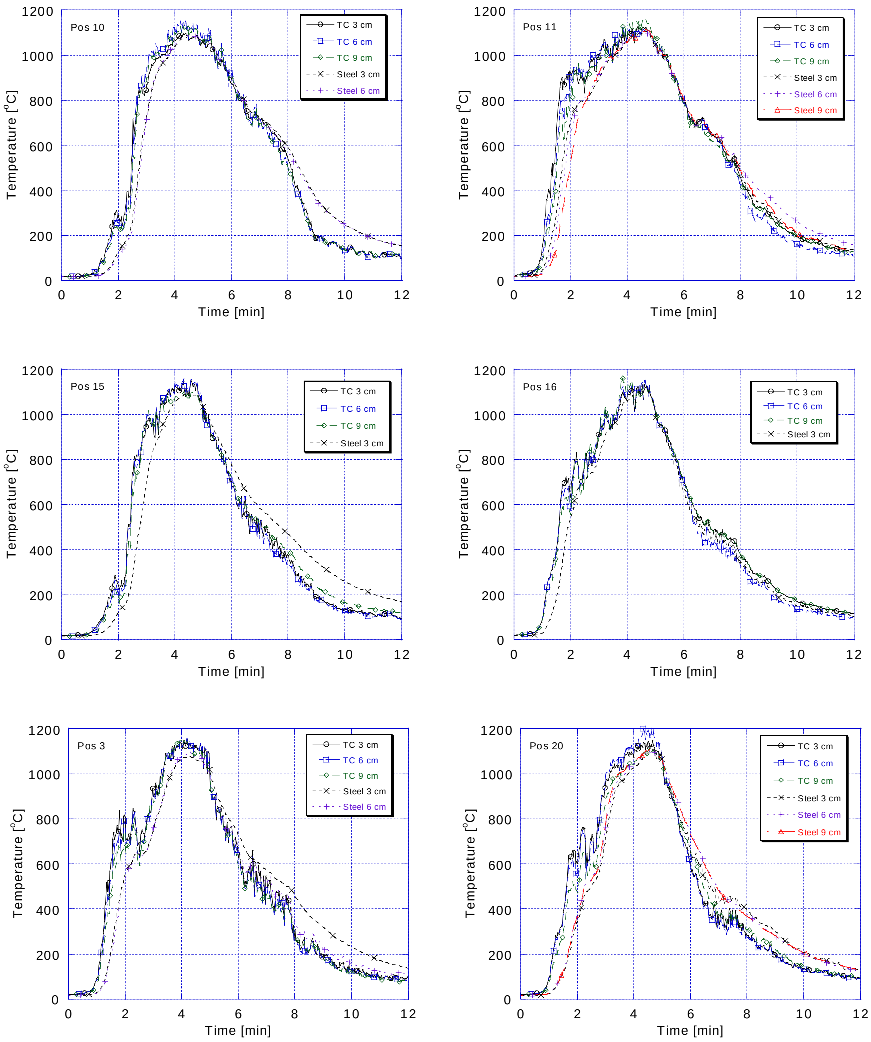


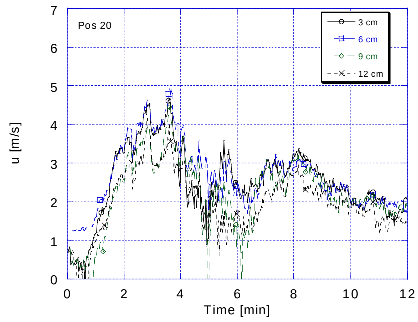




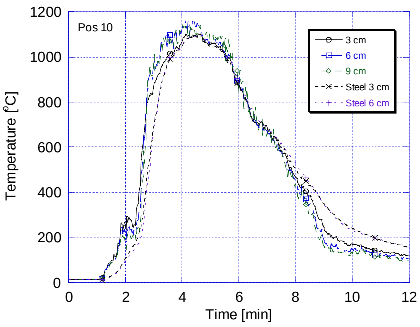


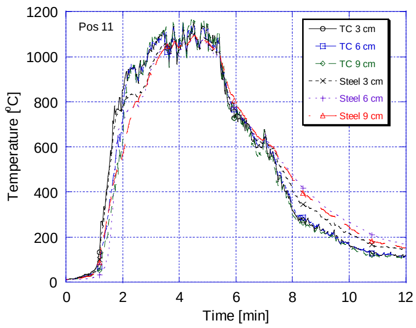
Test id: 5.4 – rack storage 0.6 m beneath ceiling with beams

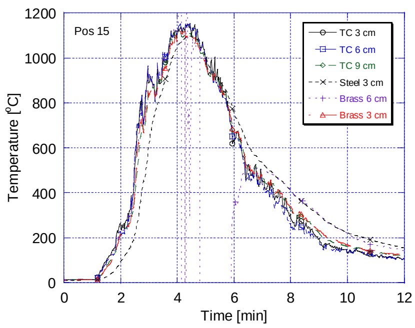


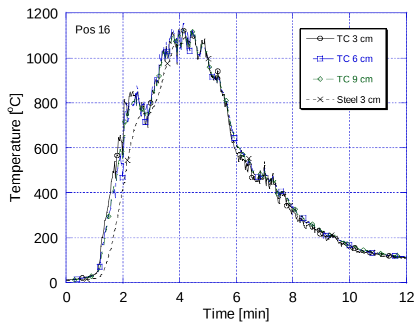


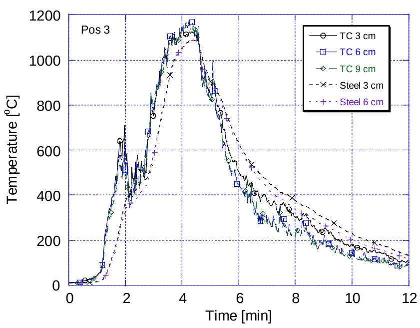
Test id: 5.5 – rack storage sloped ceiling with beams

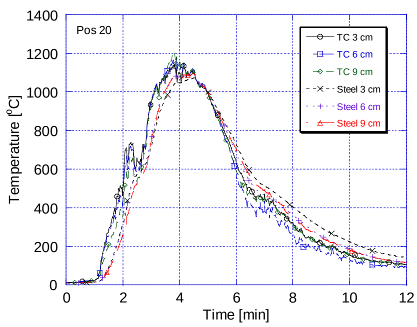


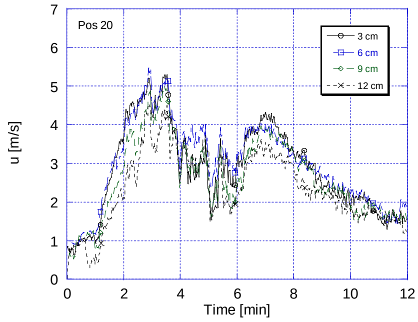




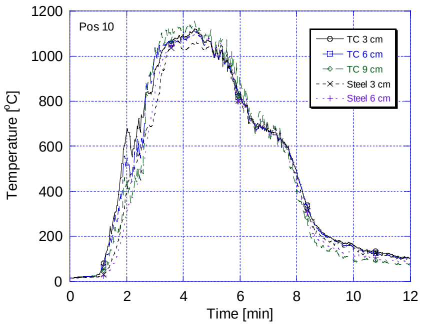


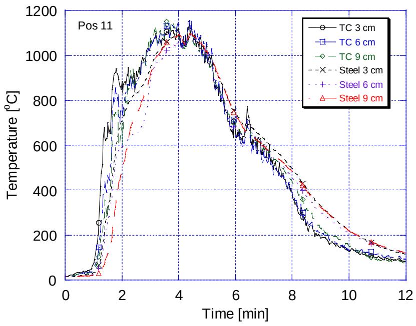


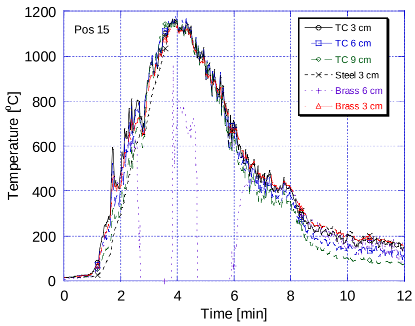


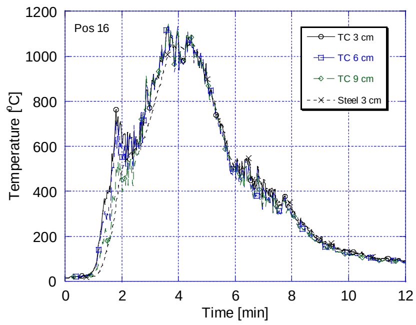


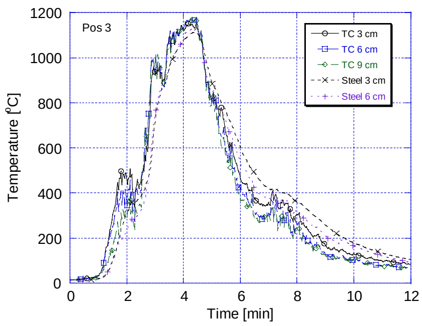
Test id: 5.6 – rack storage sloped ceiling without beams

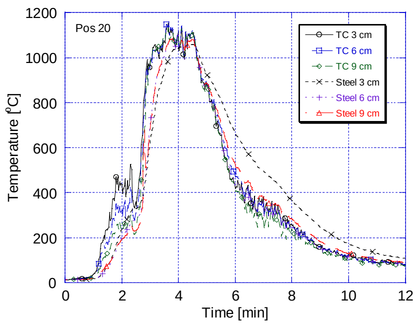


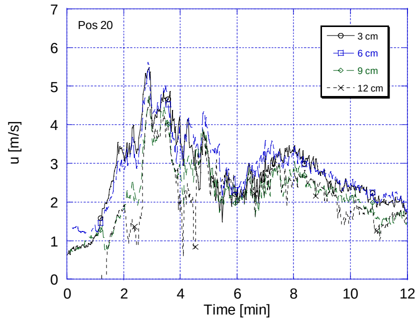




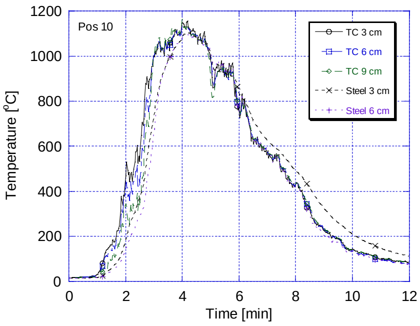


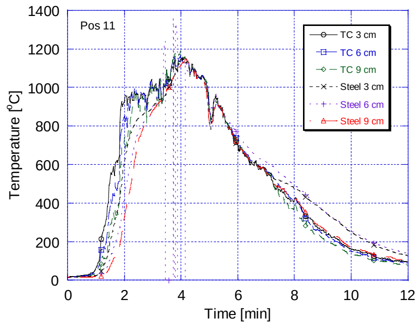


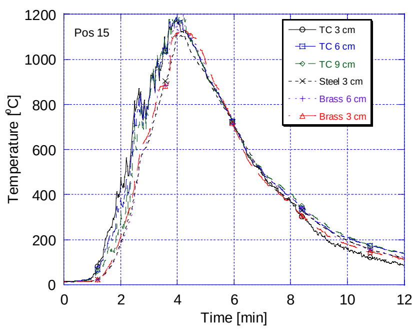


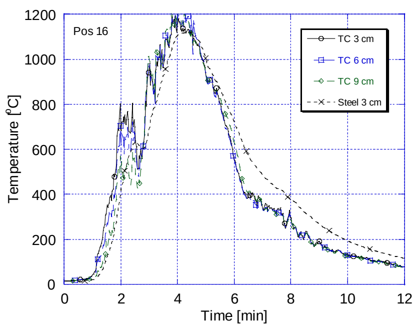


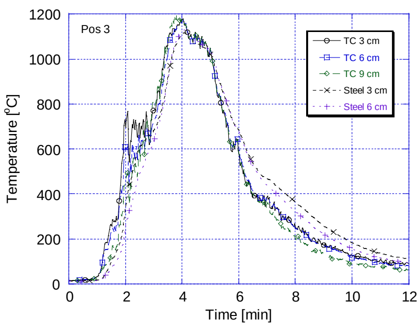
Test id: 5.7 – rack storage 0.6 m beneath ceiling

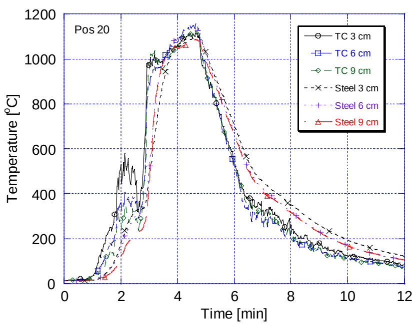


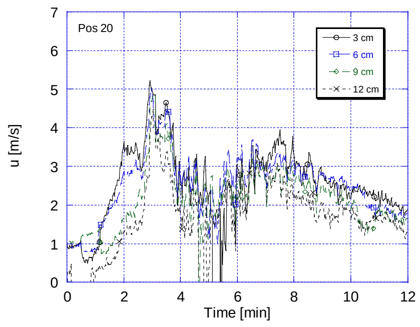




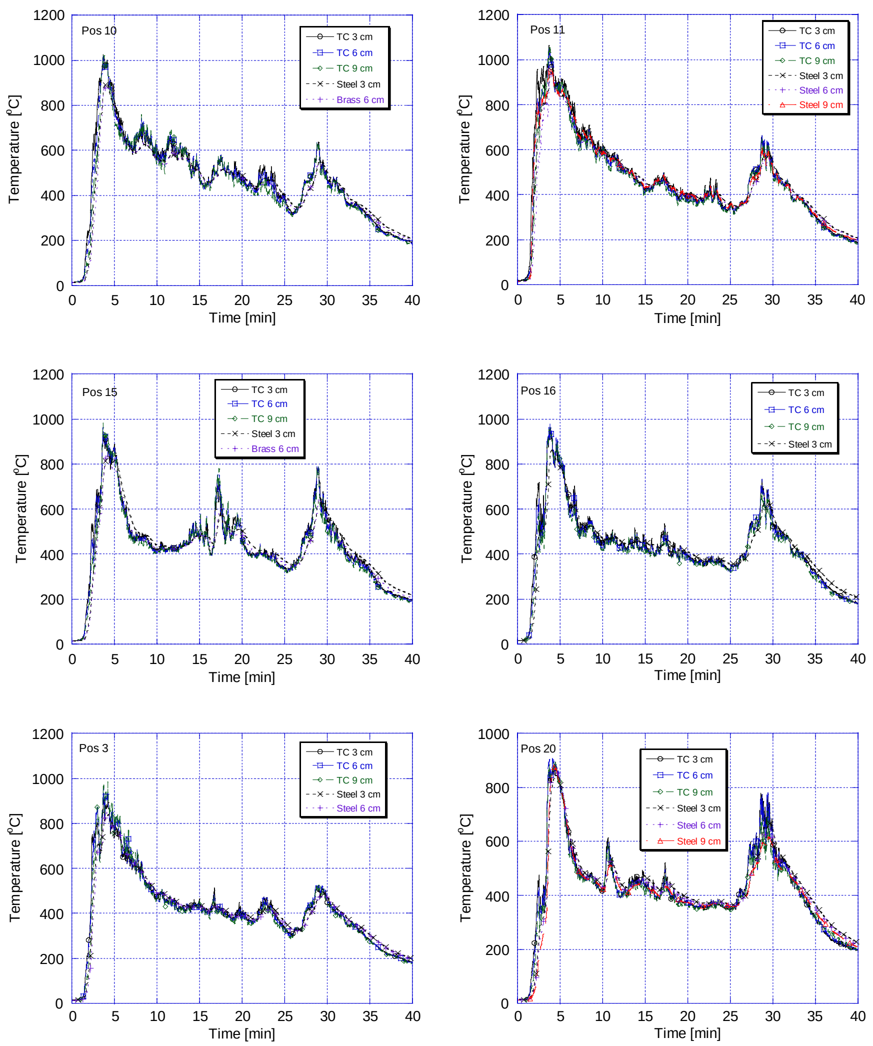


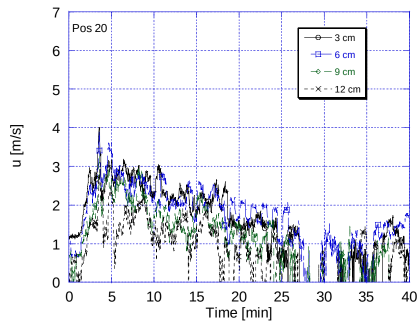




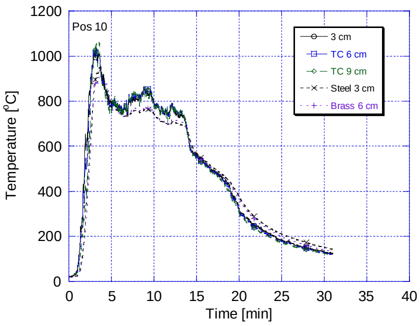


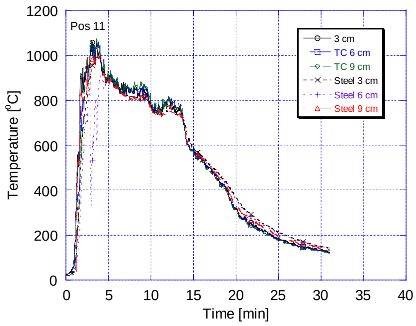
Test id: 5.8 – rack storage inside room

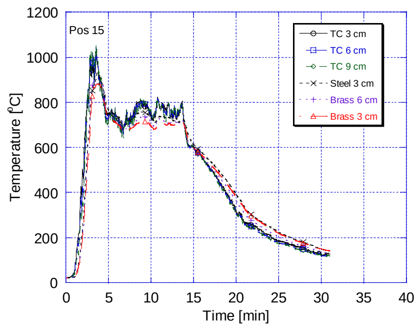


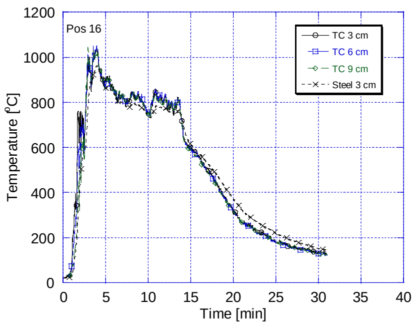


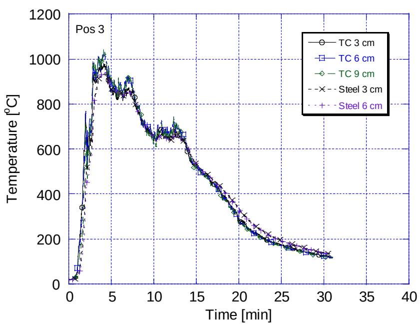
Test id: 5.9 – rack storage inside room, fire ventilation

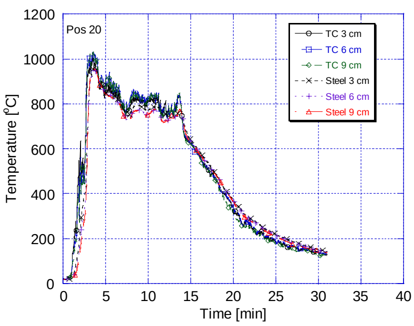


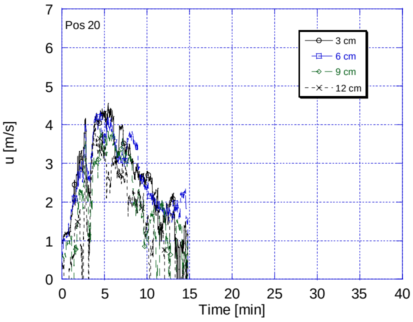








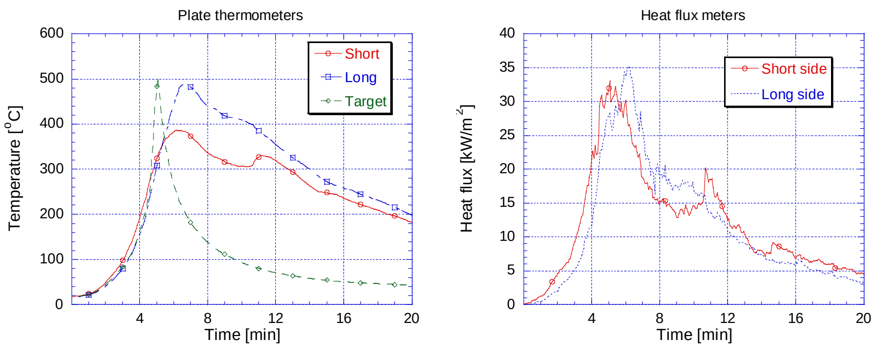



Pos 20
3 cm
6 cm
9 cm
12 cm
u [m/s]
Time [min]
0
1
2
3
4
5
6
7
0
5
10
15
20
25
30
35
40

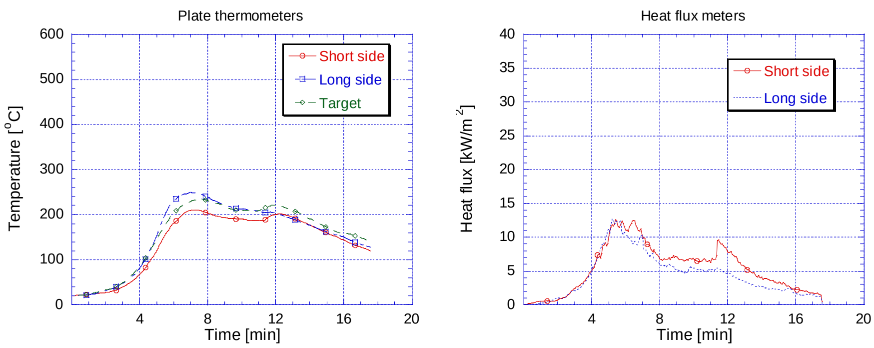
Test series 6

No graphs are given for Tests 6.1 and 6.2. The notation ‘short side’ in the graphs refers to the instrument facing the short side of the pile, while ‘long long’ refers to the long side and ‘target’ means the instrument at the target facing the pile of ignition.

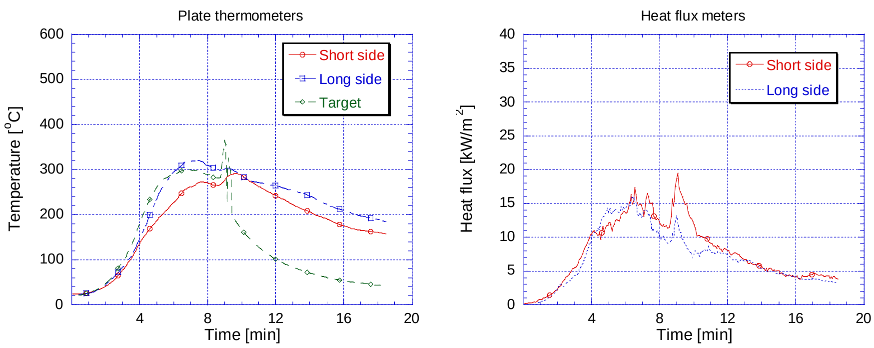
Test id: 6.3 – Low pile goods: 1 pallet, d = 1 m



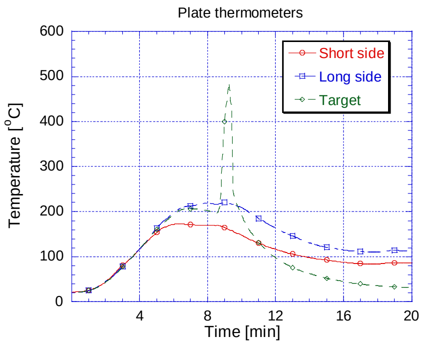
Test id: 6.4 – Low pile goods: 1 pallet, d = 2 m

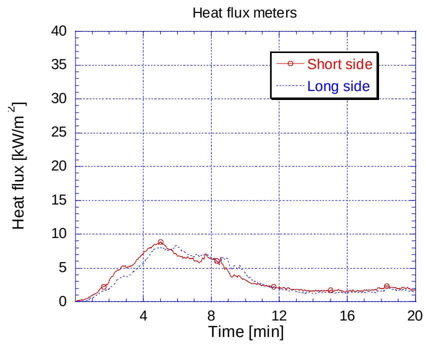


Test id: 6.5 – Low pile goods: 1 pallet, d = 1.5 m

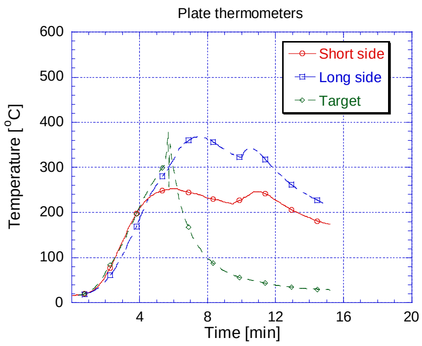


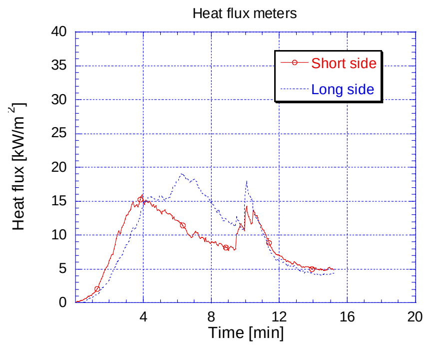
Test id: 6.6 – Low pile goods: 1 pallet, d = 1.5 m, no cups

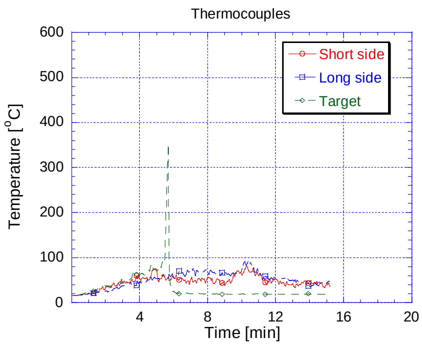




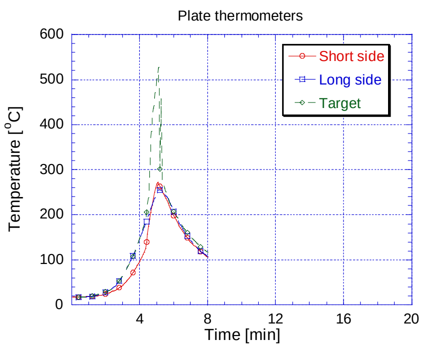
Test id: 6.7 – Low pile goods: 1 pallet, d = 1 m, no cups

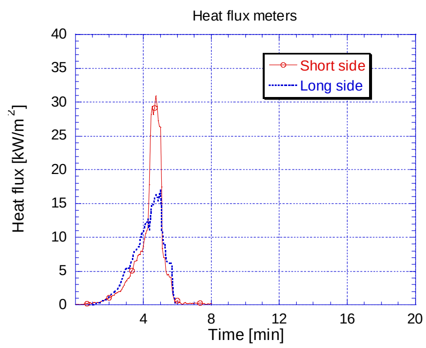


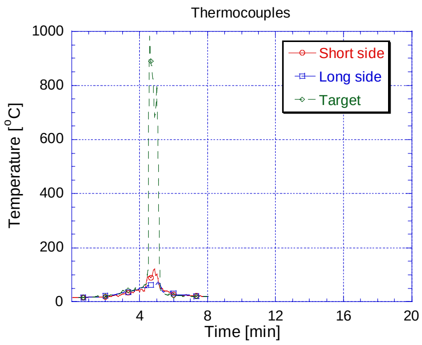




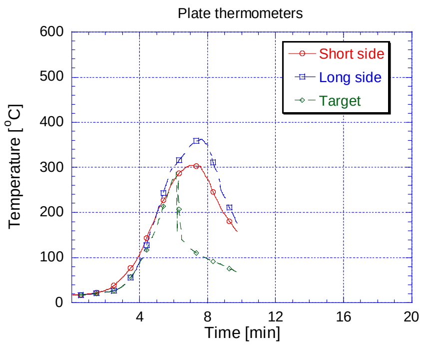
Test id: 6.8 – Low pile goods: 2 pallets, d = 2 m

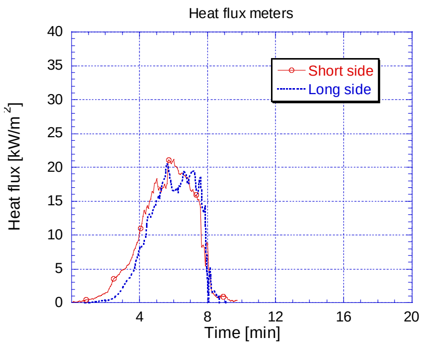


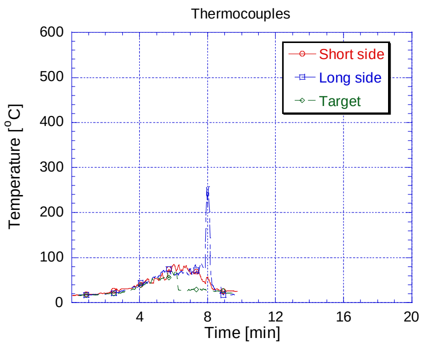




Test id: 6.9 – Low pile goods: 2 pallets, d = 2 m







Appendix 2 Experimental observations

Test id: 3.1 – Four racks free burning

-2:00	Measurement starts
0:00	Ignition
1:23	Fire spreads across flue no. 7 in rack 2.
1:39	Fire spreads across flue no. 5 in rack 2.
2:23	Fire spreads across flue no. 4 in rack 2
2:35	Smoke is coming from the boxes in rack 1.
2:40	Smoke is coming from the boxes in rack 3.
3:40	Fire spreads across flue no. 9 in rack 2.
3:47	Fire spreads to rack 3.
3:49	Fire spreads to rack 1.
4:22	Fire spreads across flue no. 10 in rack 2.
4:24	Fire spreads across flue no. 2 in rack 2.
~4:25	Fire spreads to the second row of cartons in rack 1 and rack 3, respectively.
5:05	Fire spreads across flue no. 1 in rack 2.
5:10	Fire spreads across flue no. 11 in rack 2.
5:15	Smoke is coming from rack 4.
5:40	All of the upper edge of rack 1 towards rack 2 is burning.
5:44	Fire spread to rack 4.
~6:00	All of rack 2 is involved in the fire.
6:30	Fire spread to the second row of cartons in rack 4.
	The flames in a circular region around the point of ignition is decreasing; a large hole in the set-up of boxes has been created by the fire.
~8:00	Almost only rack 4 is burning. In the other racks it is only burning at the ends of the racks.

Test id: 3.2 – Four racks free burning

-2:00	Measurement starts
0:00	Ignition
1:24	Fire spreads across flue no. 4 in rack 2.
1:35	Fire spreads across flue no. 2 in rack 2.
2:09	Fire spreads across flue no. 5 in rack 2.
2:10	Fire spreads across flue no. 1 in rack 2.
2:20	Smoke is coming from the boxes in rack 1.
2:25	Smoke is coming from the boxes in rack 3.
2:40	Fire spreads across flue no. 6 in rack 2.
3:17	Fire spreads to rack 1.
3:29	Fire spreads to rack 3.
3:30	Fire spreads across flue no. 6 in rack 2.
4:07	Fire spreads to the second row of cartons in rack 1.
4:25	Fire spreads to the second row of cartons in rack 3. The height of the flames in rack 1 and 3 is about twice the height of the storage racks while the height of the flames in rack 2 is about three times the height the storage racks.
4:32	Fire spreads across flue no. 8 in rack 2.
4:45	Smoke is coming from the boxes in rack 4.
5:05	Fire spreads across flue no. 8 in rack 1.
5:22	Fire spreads across flue no. 9 in rack 1.
5:30	Fire spreads across flue no. 9 in rack 2.
5:32	Fire spreads to rack 3.
5:50	Fire spreads across flue no. 10 in rack 2.

6:00 Fire spreads across flue no. 10 in rack 1.
6:17 Fire spreads to the second row of cartons in rack 4.
6:20 Fire spreads across flue no. 11 in rack 2.
6:28 Fire spreads across flue no. 11 in rack 1.
7:00 Columns 1 to 4 in rack 2 consumed.
7:30 Columns 1 to 4 in rack 1 consumed.
~9:00 Columns 1 to 8 in rack 1 consumed.
10:40 Flames almost only in the far end of rack 2 and rack 4.
~11:00 Columns 1 to 8 in rack 2 consumed.
11:40 All of rack 1 and 3 consumed.
~13:00 All of rack 2 consumed.
~13:30 All of rack 4 consumed.

In test series 4 it was difficult to observe the processes inside the enclosure and therefore no protocols are presented for that test series.

Test id: 5.1 – rack storage 1.2 m beneath ceiling

-2:00 Measurement starts
0:00 Ignition
0:48 Flames reach the top of level three in rack 2
0:55 Flames reach the top of level four in rack 2
1:00 Flames reach the top of level five in rack 2
1:10 The flames reach about 1 m above the rack
1:15 The flames touch the ceiling now and then
1:40 Flames touch the ceiling almost continuously
2:40 The plume is about as wide as the rack, also near the ceiling, but occasionally the flames near the ceiling reaches out about 1 m at both sides of the centre of the rack.
2:50 Smoke from rack 1 and rack 3
3:37 Fire spreads to rack 3.
3:39 Fire spreads to rack 1.
3:45 The flames from rack 1 and 3 reach about 0.5 m above the racks.
4:14 The flames from rack 1 and 3 reach the ceiling.
4:30 Smoke from rack 4.
4:50 Fire spreads to rack 4.
5:00 Flames reach the front edge of the ceiling
5:15 The fire in rack 4 reaches the outer edge of the top level
6:30 The intensity of the fire has decreased and four separate plumes can identified instead of one single large one.
7:00 The flames in rack 3 reach only the top of level 5
7:30 The flames in rack 1 reach only the top of level 5. Almost no flames in rack 3.
8:00 The commodities in rack 3 are consumed
8:30 The flames in rack 2 and 4 reach only the top of level 5, no flames from rack 1.
9:30 The commodities in rack 1 are consumed; almost no flames from rack 2.
10:30 No flames from rack 4.

Test id: 5.2 – rack storage 0.2 m beneath ceiling

-2:00	Measurement starts
0:00	Ignition
0:27	Flames reach the top of level two in rack 2
0:45	Flames reach the top of level three in rack 2
0:51	Flames reach the top of level four in rack 2
0:55	Flames reach the top of level five in rack 2
0:57	The flames reach the ceiling
1:17	The flames in the ceiling reach about 0.5 m from centreline of rack 2. Black smoke down stream the tip of the ceiling plume.
1:50	The flames in the ceiling reach about 1.5 m from centreline of rack 2.
2:38	Fire spreads to rack 3.
2:40	Fire spreads to rack 1.
2:58	Fire spreads to rack 4.
3:30	The fire in rack 4 is spreading from the top and down and has now reached to the top of level 4.
3:40	Flames reach now and then the front edge of the ceiling.
4:30	Flames constantly reach the front edge of the ceiling.
6:00	Not much flames from rack 1 and 3.
6:40	Large flames only from rack 2.
8:00	Almost all commodities in rack 1, 3 and 4 are consumed.
9:00	No flames reaches the ceiling.
11:45	Almost everything has self extinguished.

Test id: 5.3 – rack storage 0.6 m beneath ceiling

-2:00	Measurement starts
0:00	Ignition
0:24	Flames reach the top of level two in rack 2
0:32	Flames reach the top of level three in rack 2
0:38	Flames reach the top of level four in rack 2
0:40	Flames reach the top of level five in rack 2
0:48	The flames reach the ceiling
1:15	The flames in the ceiling reach about 0.75 m from centreline of rack 2.
1:30	Some smoke from rack 1 and 3. The flames in the ceiling reach about 1 m from centreline of rack 2.
1:45	The flames in the ceiling reach about 1.5 m from centreline of rack 2.
2:00	Much smoke from rack 1 and 3.
2:15	Fire spreads to rack 3.
2:17	Fire spreads to rack 1.
2:40	Smoke from rack 4.
2:50	Fire spreads to rack 4.
3:20	Flames reach now and then the front edge of the ceiling.
4:00	Flames constantly reach the front edge of the ceiling. Most of the commodities are involved in the fire.
5:00	The intensity of the fire has decreased, not much flames from rack 3.
5:20	No flames above the top level of rack 4.
6:00	No flames above the top level of rack 1.
7:15	No flames reaches the ceiling. Rack 1, 3 and 4 have self extinguished.
8:00	No flames above the top level of rack 2.
10:30	Rack 2 has self extinguished.

Test id: 5.4 – rack storage 0.6 m beneath ceiling with beams

-2:00	Measurement starts
0:00	Ignition
0:34	Flames reach the top of level two in rack 2
0:37	Flames reach the top of level three in rack 2
0:51	Flames reach the top of level four in rack 2
0:55	Flames reach the top of level five in rack 2
1:03	The flames reach the ceiling
1:45	Smoke from rack 1 and 3.
2:17	Fire spreads to rack 3.
2:22	Fire spreads to rack 1.
2:45	Smoke from rack 4.
2:53	Flames passes the outer beams
2:56	Fire spreads to rack 4.
3:45	Almost all commodities involved in the fire.
5:10	The intensity has decreased; not much flames from rack 3.
5:20	Not much flames from rack 3.
5:50	Not much flames from rack 4. Still ember in rack 1 and 3.
7:00	The flames from rack 2 reach the lower edge of the beams.
7:45	No flames outside rack 2. The racks 1, 3 and 4 are self-extinguished.
10:30	Rack 2 is self-extinguished.

Test id: 5.5 – rack storage sloped ceiling with beams

-2:00	Measurement starts
0:00	Ignition
0:30	Flames reach the top of level two in rack 2
0:55	Flames reach the top of level three in rack 2
1:00	Flames reach the top of level four in rack 2
1:05	Flames reach the top of level five in rack 2
1:12	The flames reach the ceiling
1:50	Smoke from rack 1 and 3.
2:23	Fire spreads to rack 3.
2:30	Fire spreads to rack 1.
2:40	Smoke from rack 4.
2:56	Fire spreads to rack 4. About at the same time, flames pass the outer beam.
5:00	Not much flames from rack 1 and 3, some flames in rack 4, but still much flames in rack 2.
5:50	Not much flames from rack 4.
6:30	Ember only at the bottom of the racks 1, 3, and 4. Rack 2 is still burning.
8:35	Not much flames from rack 2.
10:00	Ember only at level 1 and 2 of rack 2.

Test id: 5.6 – rack storage sloped ceiling without beams

-2:00	Measurement starts.
0:00	Ignition.
0:30	Flames reach the top of level two in rack 2.
0:54	Flames reach the top of level three in rack 2.
1:00	Flames reach the top of level four in rack 2.
1:02	Flames reach the top of level five in rack 2.
1:11	The flames reach the ceiling.
1:30	The flames in the ceiling reach about 0.75 m from centreline of rack 2.
1:45	The flames in the ceiling reach about 1.25 m from centreline of rack 2. Smoke from rack 1 and 3.

2:24	Fire spreads to rack 1 and 3.
2:30	The flames in the ceiling reach about 1.75 m up the slope and 1 to 1.25 m down the slope from centreline of rack 2. The flames from rack 1 and rack 2 are flowing somewhat towards rack 2 before they reach the outwards flow near the ceiling.
2:45	Smoke from rack 4.
2:54	Fire spreads to rack 4.
4:00	Almost all commodities involved in the fire.
5:00	The fire in rack 1 and 3 has decreased and there are only some small flames.
6:00	Only small flames in rack 4; rack 2 is still burning.
7:00	Only ember at the bottom of the racks 1, 3, and 4. Rack 2 is still burning even if the flames do not reach the ceiling.
8:00	Only small flames in rack 2.
9:00	Only ember in rack 2, at the levels 1 to 3.
10:00	Rack 2 almost extinguished, only some ember at the bottom of the rack.

Test id: 5.7 – rack storage 0.6 m beneath ceiling

-2:00	Measurement starts.
0:00	Ignition.
0:44	Flames reach the top of level two in rack 2.
0:53	Flames reach the top of level three in rack 2.
1:00	Flames reach the top of level four in rack 2.
1:04	Flames reach the top of level five in rack 2.
1:09	The flames reach the ceiling.
1:50	The flames in the ceiling reach about 1 m from centreline of rack 2. Smoke from rack 1 and 3.
2:32	Fire spreads to rack 3.
2:34	Fire spreads to rack 1.
2:55	Smoke from rack 4.
3:04	Fire spreads to rack 4.
4:15	Flames reach the edge of the ceiling.
4:30	Almost all commodities involved in the fire.
5:00	The intensity has decreased in rack 1 and 3, especially in rack 3.
5:30	Almost no flames in rack 1 and 3, some flames in rack 4. Flames from rack 2 still reach the ceiling.
6:30	Some ember at the level 2 to 4 in the racks 1, 3, and 4, but most ember at the bottom of the racks. The flames from rack 2 have decreased, but they still reach the ceiling.
7:15	The racks 1, 3, and 4 are almost extinguished. The flames from rack 2 reach above the top level of the rack.
9:00	Almost only ember in rack 2.
10:00	Extinguished

Test id: 5.8 – rack storage inside room

-2:00	Measurement starts.
0:00	Ignition.
0:50	Flames reach the top of level two in rack 2.
1:07	Flames reach the top of level three in rack 2.
1:15	Flames reach the top of level four in rack 2.
1:23	Flames reach the top of level five in rack 2.
1:30	The flames reach the ceiling.
2:00	The flames in the ceiling reach about 0.5 m from centreline of rack 2

2:15	The flames in the ceiling reach about 1 m from centreline of rack 2
2:20	Smoke from rack 1 and 3.
2:30	The flames in the ceiling reach about 1.5 m from centreline of rack 2.
3:03	Fire spreads to rack 3.
3:15	Fire spreads to rack 1.
3:38	Fire spreads to rack 4.
3:50	The smoke layer reach the top of racks and is quickly descending.
3:55	The smoke layer reach the top of level 4.
4:03	The smoke layer reach the top of level 3
4:20	The smoke layer reach the top of level 2.
4:30	Smoke comes out of the door opening.
5:00	The smoke layer reach a few cm below the top of the door opening.
6:30	The smoke layer reach to about 25 cm above the floor.
8:00	The smoke layer reach to about 20 cm above the floor. Flames can be seen through the smoke.
11:00	No visible smoke out through the opening. Near the opening the smoke layer reach to 15 to 20 cm above the floor, further into the room the smoke layer reach the floor.
16:30	Smoke comes out of the door opening.
22:00	The racks become somewhat visible again; it is burning in rack 2 and furthest away in rack 3. Rack 4 seems not to be burning.
24:30	Rather much combustible material left to be consumed, specially in rack 4.
28:00	Rack 4 is burning.
32:00	It is burning at the outer ends of rack 4
32:50	Some ember in rack 2 and 3; rack 1 seems to be extinguished.
34:00	Rack 3 seems to be extinguished. some ember in rack 2.
40:00	Rack 4 is almost extinguished. Still some ember in rack 2.
42:30	Rack 2 is almost extinguished.

Test id 5.9 – rack storage inside room, fire ventilation

-2:00	Measurement starts.
0:00	Ignition.
0:27	Flames reach the top of level two in rack 2.
0:45	Flames reach the top of level three in rack 2.
0:53	Flames reach the top of level four in rack 2.
0:55	Flames reach the top of level five in rack 2.
1:03	The flames reach the ceiling.
1:48	Smoke from rack 1 and 3. The flames in the ceiling reach 1 to 1.25 m from centreline of rack 2.
2:14	The bulbs at the fire ventilations reach the temperature 94 ºC and the fire ventilation is opened.
2:24	Fire spreads to rack 3.
2:26	Fire spreads to rack 1.
2:50	Fire spreads to rack 4.
3:03	The smoke layer reach the top of racks.
3:06	The smoke layer reach the top of level 4.
3:13	The smoke layer reach the top of level 3.
3:22	The smoke layer reach the top of level 2.
4:15	Heavy draft inside the room.
4:20	The smoke layer reach to 20 to 30 cm above the floor.
6:30	The smoke layer reach to 15 to 20 cm above the floor.
7:30	The smoke becomes somewhat less dense and flames can be seen.

10:45	Much flames from rack 4, some flames from rack 3, much ember in rack 2, some ember in rack 1. The flames from rack 4 are several meters long.
13:10	Long flames from one end of rack 4.
14:20	Only small flames in the lower part of rack 4.
14:35	Much ember in rack 4; some ember in the other racks.
20:30	Rack 1 almost extinguished.
21:30	Rack 3 and 4 almost extinguished.
26:00	Extinguished.

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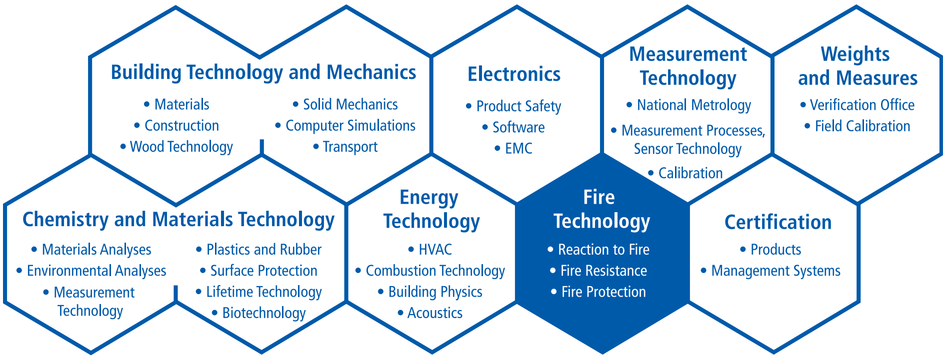

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SP Swedish National Testing and Research Institute
Box 857
SE-501 15 BORÅS, SWEDEN
Telephone: + 46 33 16 50 00, Telefax: +46 33 13 55 02
E-mail: info@sp.se, Internet: www.sp.se

A Member of
United Competence