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Full scale fire experiments on electronic cabinets II

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ABSTRACT

Three full-scale fire experiments on electronic cabinets have been carried out. In the experiments, one cabinet, the fire cabinet, was fitted with relays, connectors, wiring, cables and circuit boards. A mock-up cabinet made of thin steel sheets was attached to the fire cabinet in order to study the response of an adjoining cabinet to the fire. Another cabinet was placed at a distance of 1 m opposite the fire cabinet to represent a neighbouring row of cabinets. The fire cabinet was ignited with a small propane burner either at the bottom of the cabinet beneath a vertical cable bundle or beneath a wiring bundle.

The rate of heat release by means of oxygen consumption calorimetry, mass change, CO_2, CO and smoke production rate, and gas and wall temperatures in all three cabinets were measured as a function of time. The key role of the ventilation conditions in the cabinet was clearly shown by determining the rate of heat release.

The ignition power and energy sufficient for sustained burning leading to flashover in the cabinet was determined. The ignition power and energy levels seem to be fairly near the ignition/no ignition limit of the cabinet. The fire growth rate after ignition was estimated to be slow.

PREFACE

This study was carried out as a part of the Fire Safety project (PALOTU) which is one of the projects in the Research Programme on the Structural Integrity of Nuclear Power Plants (RATU 2).

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1 INTRODUCTION

Published, documented data on fires in electronic cabinets is scarce in open literature. The present study is a continuation of the fire experiment series on electronic cabinets previously made at VTT (Mangs & Keski-Rahkonen 1994). The particular aim of the present study was to investigate the minimum ignition power and energy needed to reach established burning which could lead to flashover inside the cabinet. From the tests, differing in the location of ignition, ignited material, ignition power and total ignition energy, data was collected which could be used for source terms in numerical modelling of fires in rooms containing electronic cabinets. Additionally, these experiments were used to obtain data to validate a model for maximum heat release (Mangs & Keski-Rahkonen 1994, Keski-Rahkonen 1994) and a model for minimum heat release needed for flashover (Keski-Rahkonen and Mangs 1995). This report concentrates only on describing and recording the data obtained.

2 EXPERIMENTAL

2.1 SPECIMEN

2.1.1 General

The fire experiments, the set-up of which is shown in figures 1 to 4, were carried out with the fire cabinet fitted with relays, connectors behind the relays, cables, wiring and circuit boards. A mock-up cabinet, the adjoining cabinet (figure 3), made of 0.5 mm thick steel sheet was fastened to the fire cabinet in order to study the response of an adjoining cabinet to the fire (Appendix 1, figure 2). Another cabinet, the opposite cabinet (figure 2), was placed at a distance of 1 m opposite the fire cabinet to represent a row of neighbouring cabinets. The ventilation in all cabinets was buoyantly driven.

2.1.2 Structure and dimensions

The fire cabinet (figure 3) consisted of a solid steel frame, an elevated ceiling, walls of 1.5 mm thick steel sheets, a hinged rack in the front part and one steel door 1.5 mm thick in the front (Appendix 1, figures 1 and 2). The height of the fire cabinet was 2250 mm, width 630 mm, and depth 488 mm. To the depth of the cabinet should be added 15 mm for the rear plate, 15 mm for the front edge of the hinged rack, and 15 mm for the front door (figure 3). The open bottom was closed at VTT with a 0.5 mm thick steel plate welded to the frame of the cabinet.

The hinged rack could be locked with three horizontal bolts at the upper right corner, halfway up the right side and at the lower right corner. The steel bolts had aluminium flanges at their ends which closed the rack to the frame of the cabinet when the bolts were turned clockwise. The aluminium flanges melted in experiment 1 and were replaced with corresponding steel plates welded to the locking bolts. The door was closed to the hinged rack with three screws and washers located near the locking bolts. The door was tightened to the hinged frame with a rubber packing.

The height of the hinged rack (figure 3) was 1830 mm, width 490 mm, and depth 270 mm. The rack was separated from the rear part of the cabinet by a 1750 mm high and 50 mm wide vertical steel plate (Appendix 1, figure 1). The relays in the rack were divided into 5 groups containing 10 relays each, and another group had 5 relays. The circuit boards were grouped in the upper part of the rack (figure 1). The uppermost groups in the rack were partly separated from each other in the vertical direction by 430 mm x 180 mm steel sheets.

The adjoining cabinet with the same height, width and depth as the fire cabinet was a light mock-up construction made of 0.5 mm thick steel sheets (figure 3). A 90 mm x 90 mm ventilation opening was made in the front side, 20 mm above the bottom level. This gave a door ventilation area of 0.0081 m^2, corresponding to that of the fire cabinet. An elevated ceiling was attached to the adjoining cabinet with ventilation openings corresponding to the fire cabinet. The adjoining cabinet was attached to the right hand side of the fire cabinet leaving only the original wall of the fire cabinet between them.

The width of the cabinet opposite was 800 mm, depth 800 mm, and height 2260 mm (figures 2 and 4). The door of the opposite cabinet had 27 horizontal ventilation openings in three vertical rows between 80 mm and 280 mm above the bottom level of the cabinet. The free area of each opening was 5 mm x 130 mm which gave a total door ventilation area of 0.0176 m^2. The ceiling was elevated 50 mm above the walls of the cabinet leaving a total ventilation area of 0.16 m^2 at the top of the cabinet.

2.1.3 Ventilation conditions in the fire cabinet

The fire cabinet had 14 vertical ventilation openings in one row below the door, 20 mm above the bottom level of the cabinet. The free area of one opening was 585 mm^2 which gave a total ventilation area of 0.0082 m^2 in the lower part of the cabinet. The ceiling of the cabinet was elevated 27 mm, leaving openings of width 550 mm at the left and right sides and 440 mm at the rear and front sides. The total ventilation area in the ceiling was thus 0.0535 m^2.

In addition to these openings there were three elliptical 18 mm x 22 mm openings in the rear wall with a total area of 0.0011 m^2 and 12 circular openings in the left side wall, 6-8 mm in diameter, with a total opening area of 0.0004 m^2. In experiment 3, there was also one elliptical opening of area 0.0004 m^2 in the door.

During experiment 1, gaps between the steel sheets in the walls, between the rack frame and the cabinet and between the door and the rack occurred because of thermal expansion. Before experiment 2, all gaps in the rear and left side wall were sealed by welding and the steel frame of the hinged rack fixed to the frame of the cabinet with short welding seams. The door was closed to the frame of the hinged rack with two additional bolts in the upper and lower right corner besides the three original bolts in the door. Remaining gaps were filled with mineral wool. The rubber packing between the door and the hinged rack was replaced with a corresponding packing before experiments 2 and 3.

During experiment 2, a gap still occurred on the left side of the door between the hinges. Before experiment 3, this gap was closed with two bolts, the steel frame of the hinged rack was again fixed to the frame of the cabinet with short welding seams and the remaining gaps were filled with mineral wool. The cabinet was practically airtight in experiment 3 except for the openings mentioned in the preceding paragraph and the lower edge of the door where the rubber packing melted away during of the experiment. Estimates of the expansion gaps that developed in the experiments are presented in tables 3 to 7.

2.1.4 Contents of the fire cabinet

The cabinet was delivered to VTT with representative contents. It contained 55 relays and 5 cased circuit boards in the hinged rack, plastic connectors and wiring behind the relays, cables in a vertical bundle at the right side wall, and wiring from the cables to the contents of the hinged rack. The wiring was attached to the rear and left side walls in horizontal bundles at different heights, leading to different parts of the hinged rack. Photographs of the original contents are presented in Appendix 1, figure 1.

The total mass of the relays and connectors was estimated to be 45-48 kg and the circuit boards to be 2-3 kg. The total mass of the wiring in the cabinet was estimated to be 8-10 kg and the mass of the cable bundle to be about 10 kg.

The amount of material in experiments 2 and 3 was intended to be the same as in experiment 1 (Appendix 1, figure 3). Equal amounts of similar relays, connectors and circuit boards were placed in the hinged rack. The mass of the relays differed somewhat depending on the components included. Cables representative of the main type present in experiment 1 were used in experiments 2 and 3. The polyvinyl chloride jacketed and insulated cables, with an outer diameter of 10, 11 or 12.5 mm, were attached in a similar manner to the right side wall. The height of the vertical cables varied from about 700 mm to 1850 - 2000 mm as they led to different panels at the rear wall. The thickness of the cable bundle varied from about 50 mm at the bottom to about 20 mm at the top.

Two types of wiring from different manufacturers were used in experiments 2 and 3. Type A had outer diameters of 1.8, 2.2 and 2.8 mm, and type B had an outer diameter of 3.8 mm. Five horizontal wiring bundles were placed at different heights, leading from the right side cable bundle along the rear and left sides, to the relays in the hinged rack. One vertical bundle was placed at the left side of the hinged rack. The diameter of the wiring bundles was 12-22 mm in experiment 1, and 17-18 mm in experiments 2 and 3. In addition, there was some wiring attached to the connectors of the replacing relays in experiments 2 and 3.

The plastic connectors and miscellaneous components on the rear wall were not replaced in experiments 2 and 3 because corresponding items were not available. These components contributed to only a minor part of the total combustible contents of the cabinet.

The contents of the fire cabinet in the experiments are shown in table 1 and a schematic drawing of their location in the fire cabinet is shown in figure 1.

Table 1. Contents of fire cabinet in the experiments.

Experiment no	1[1)]	2	3
Relays and connectors	45 - 48	49.4	45.3
Cables (kg)	~10	9.9	9.8
Wiring total (kg)	8 - 10	9.0	9.1
(added in bundles)		(8.0)	(8.0)
(readily attached to relays)		(1.0) [1)]	(1.1) [1)]
Circuit boards (kg)	2 - 3	2.4	2.2
Total (kg)	66	70.7	66.4

[1)] estimated

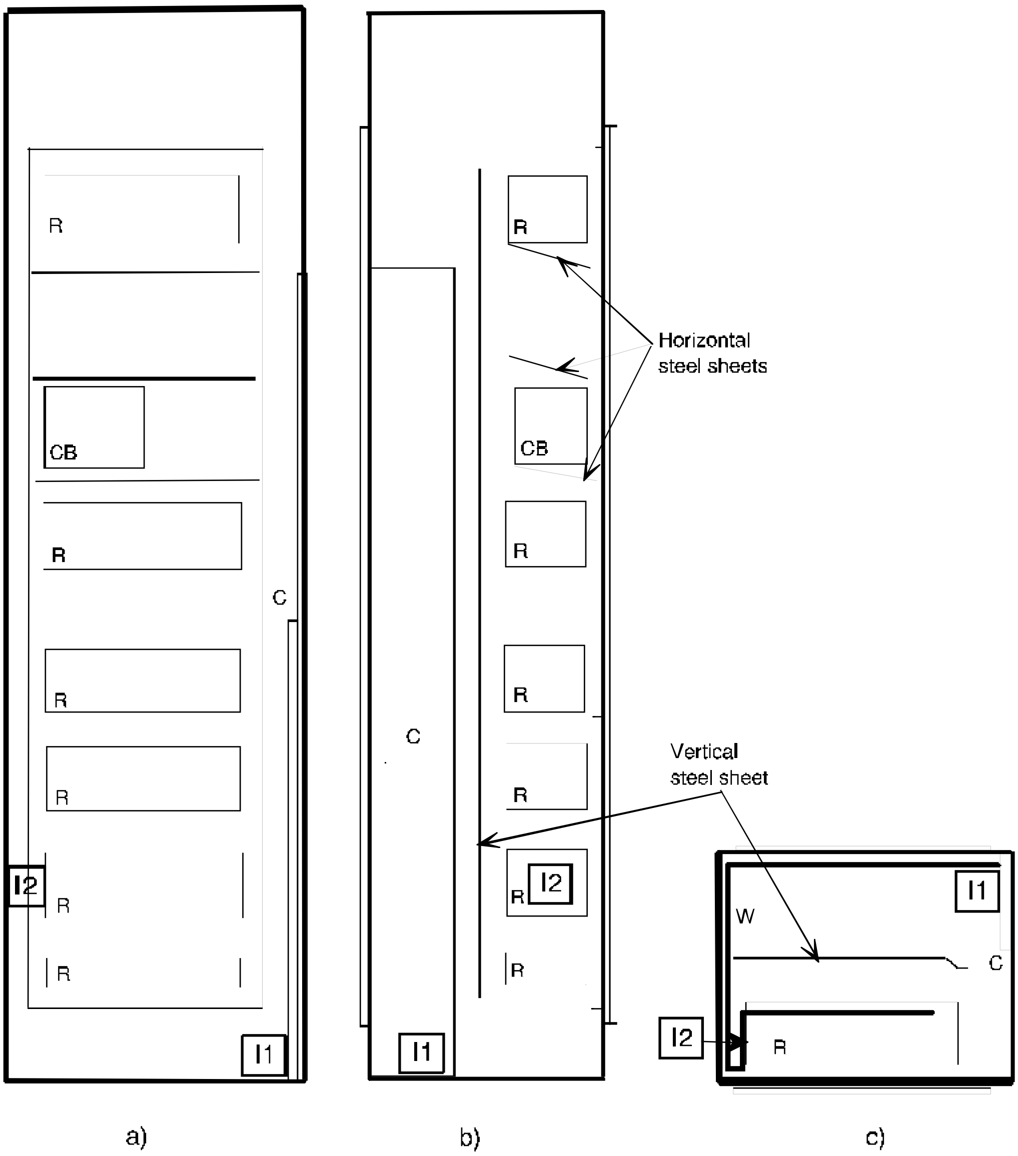

Figure 1. Location of contents of the fire cabinet, a) front, b) side and c) top view. R=Relay group, CB=circuit boards, C=cable bundle, W=wiring, I1=location of ignition with the propane burner in experiments 1 and 3, and I2=location of ignition in experiment 2.

2.2 CONFIGURATION AND INSTRUMENTATION

The experimental configuration is presented in figure 2. The fire cabinet F with the adjoining cabinet A was placed on a weighing device W which registered the mass change during the experiment. The experiment was carried out beneath a hood H which collected all the combustion products.

The concentration of O_2, CO_2 and CO was measured in the exhaust duct E. The O_2 concentration was measured with analysers of the paramagnetic type, Siemens Oxymat 5 E in experiment 1, and Hartmann & Braun Magnos 4 G in experiments 2 and 3. The CO_2 and CO concentrations were measured with a Siemens Ultramat 22 P infrared analyser in all experiments.

The rate of heat released was calculated from the measured O_2 and CO_2 concentration together with the volume flow rate in the exhaust duct using oxygen consumption calorimetry.

The smoke production was measured with a SICK RM 61-01 white light smoke density monitoring equipment in the exhaust duct E.

Gas and wall temperatures were measured with 0.5 mm K-type thermocouples in all three cabinets.

Outer surface temperatures were measured on trial with an Optex HR-1PL non-contact infrared thermometer in experiments 2 and 3.

The location of measurement points in the fire and adjoining cabinets are presented in figure 3, and their location in the opposite cabinet in figure 4.

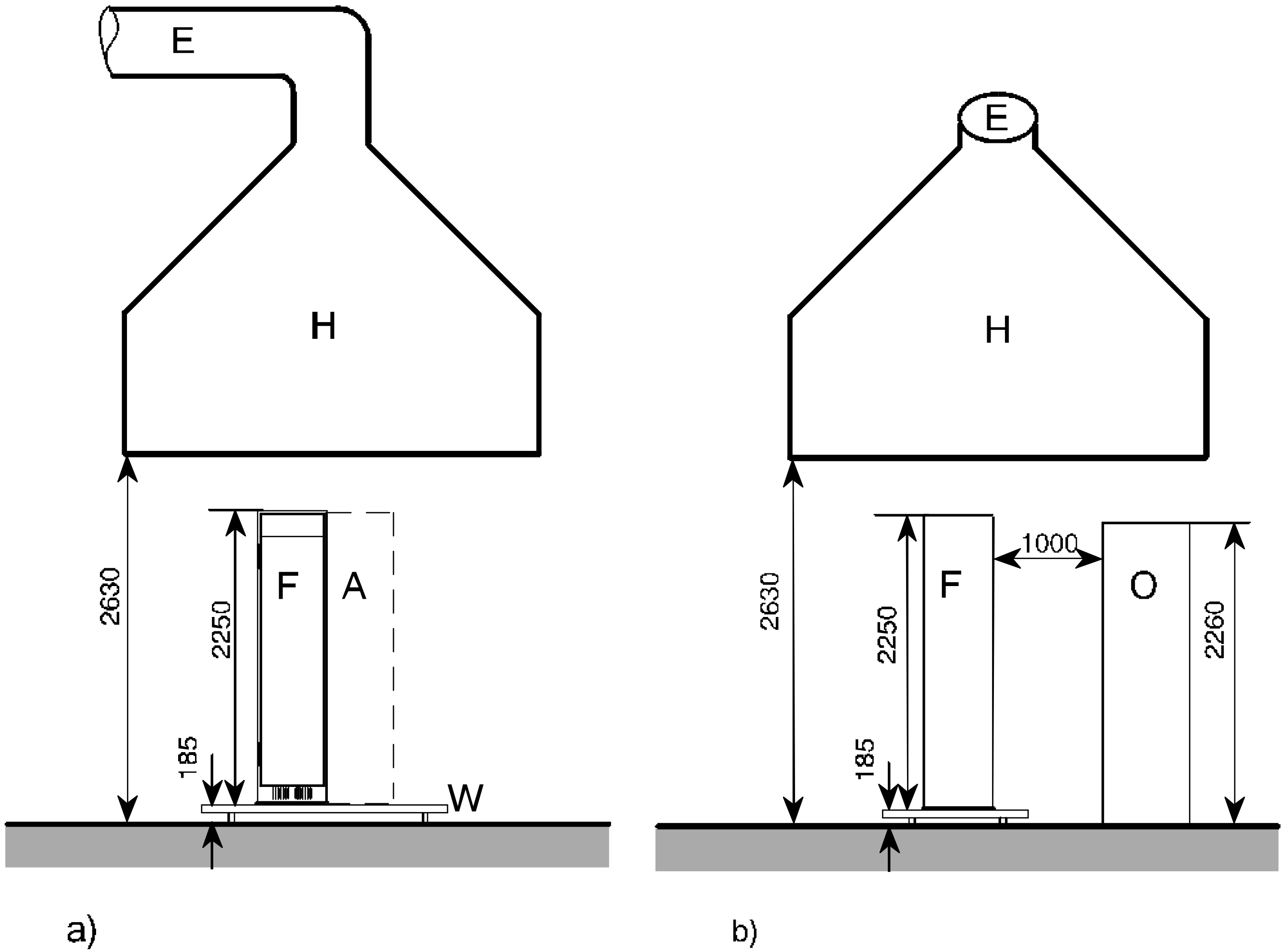

Figure 2. The experimental configuration, a) front view without opposite cabinet, b) side view. F=fire cabinet, A=adjoining cabinet, O=opposite cabinet, W=weighing device, H=hood and = exhaust duct. Dimensions are in mm.

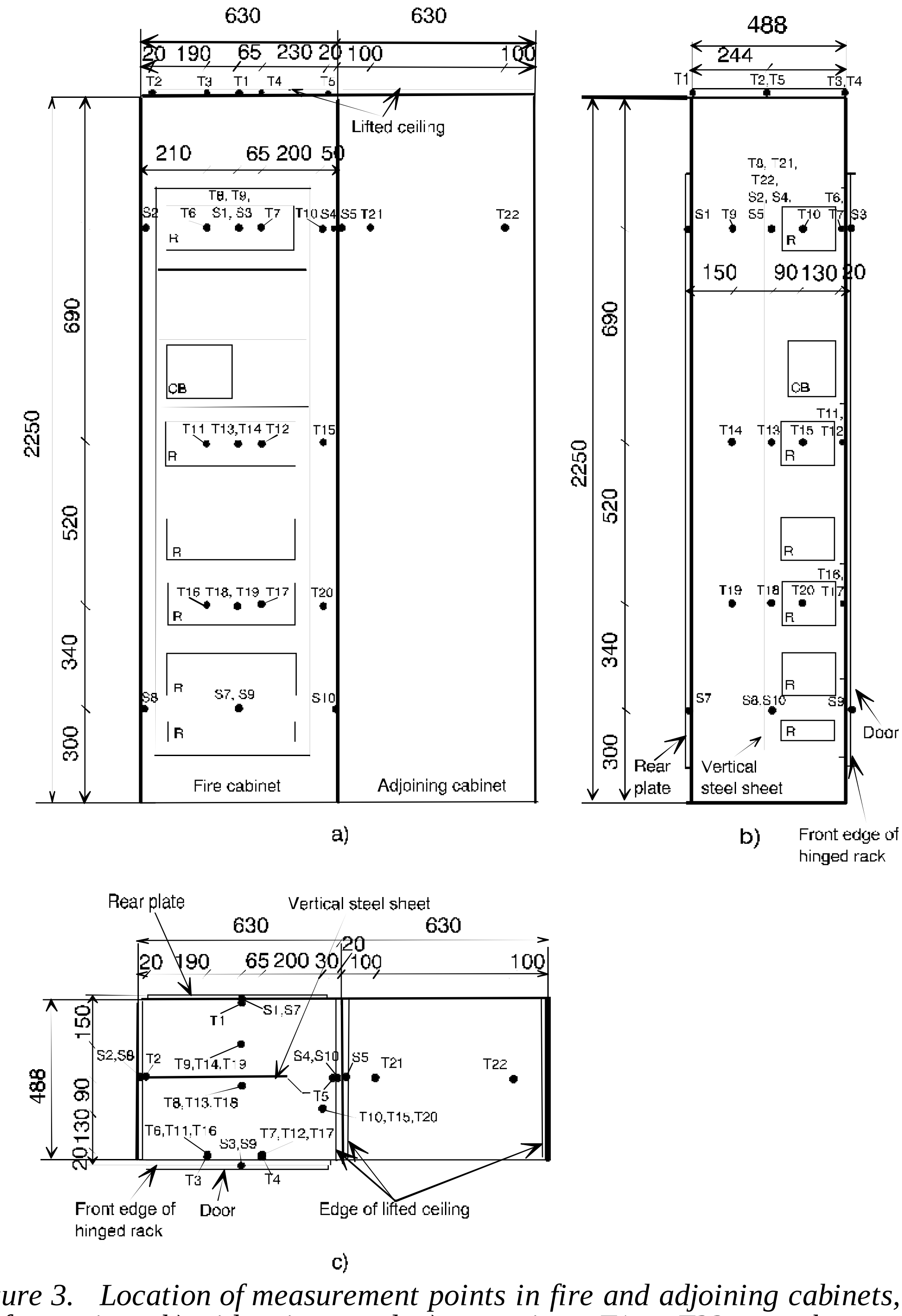

Figure 3. Location of measurement points in fire and adjoining cabinets, a) front view, b) side view, and c) top view. T1 - T22 are the gas temperature measurement points S1 - S5 and S7 - S10 the wall temperature measurement points. S7 - S10 were present only in experiments 2 and 3. Dimensions are in mm.

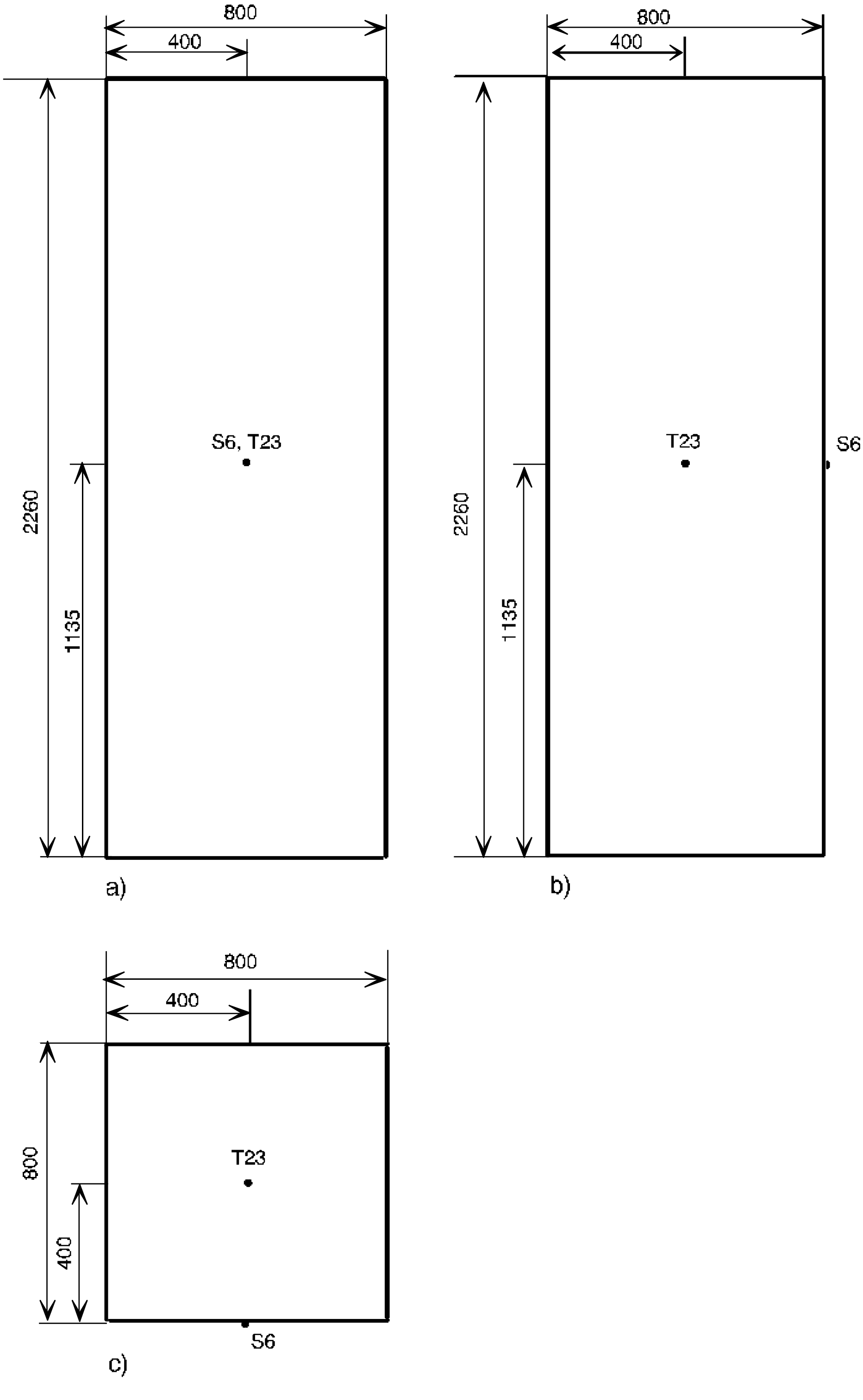

Figure 4. Location of measurement points in the opposite cabinet, a) front view, b) side view, and c) top view. T23 gas temperature and S6 wall temperature measurement points. Dimensions are in mm.

2.3 PROCEDURE

The fire cabinet was ignited with propane gas using a 100 mm long line burner with holes 1 mm in diameter. The burner was located at the bottom of the cabinet below the cable bundle at the right side in experiments 1 and 3 (I1 in figure 1). In experiment 2 the burner was located near the left side of the next-lowest relay group, below one horizontal and one vertical cable bundle (I2 in figure 1). The burner was located so that the flame was in contact with the cables or wiring above. The burner was ignited with a gas flame from the outside of the cabinet and the door was closed immediately after gas burner ignition.

The burner power output was chosen on the basis of small scale tests on cable and wiring (Keski-Rahkonen & Mangs to be published) in order to study the lowest ignition power needed to ensure established burning in the fire cabinet. The propane burner was turned off when the fire in the cable or wiring bundle was estimated to be large enough to sustain burning by itself.

In experiment 2, the first two attempts 2A and 2B did not lead to sustained burning. The fire decreased immediately after turning the propane burner off and went out in a few minutes. The door was then opened and wiring was added above the burner to an amount estimated by the burned area of wiring. The propane burner was then ignited again.

The average burner power output, the duration of burner operation, energy released and the result of burner operation are presented in table 2.

The fire was allowed to develop freely after ignition and data logging continued until the fire went out. The experiments were recorded on videotape with one videocamera. Photographs before, during and after the experiments are presented in Appendix 1.

Table 2. The average burner power output, the duration of burner operation, energy released and the result of burner operation in the experiments.

Experiment	Average burner power (W)	Duration (s)	Energy released (kJ)	Result
1	700	303	210	Ignition which led to flashover
2A	740	300	220	The fire went out after turning the propane burner off
2B	1540	303	470	- " -
2C	3200	601	1920	Ignition which led to flashover
3[1)]	500	301	150	Ignition which led to flashover

[1)] In the first attempt in experiment 3, the flame, about 2 - 3 cm high, was positioned so that the cables did not have flame contact. No damage to the cables from the propane flame was observed. The cable bundle ignited after rearranging cables so that they were in contact with the flames.

3 RESULTS

3.1 GENERAL

Observations from the experiments are presented in tables 3 to 7.

Different ventilation conditions occurred in the experiments because of the gaps between the steel sheets caused by thermal expansion as explained in section 2.1. Estimates of the ventilation areas through these gaps are presented in the observations. The gaps were minimized before experiments 2 and 3 as much as possible, as presented in chapter 2.1.

Table 3. Observations made during experiment 1.

Time (h:min:s)	Event
0:0:0	Ignition of the propane burner, average power output 700 W
0:0:34	The door is closed
0:1:32	The door is secured with bolts
0:4:13	Only the cables directly above the burner are burning
0:5:03	The propane burner is turned off
0:9:50	About 10 mm wide gap between rear plate and cabinet frame, gap area about 0.005 m^2
0:11:00	Flames emerge from the rear ceiling ventilation opening
0:12:00	Paint is burning on the upper side of the rear plate
0:13:30	Gaps on both sides of the rear plate, gap area about 0.004 m^2
0:24:15	The rubber packing has burned away from the bottom part of the door, corresponding gap area about 0.004 m^2
0:26:35	Gap on the left side wall, gap area about 0.001 m^2
0:30:00	The upper part of the door is darkening
0:31:15	Increasing smoke production
0:32:05	First flames out of the front ceiling ventilation openings
0:32:40	The rubber packing is burning on the upper part of the door
0:34:10	Fire on the bottom of the cabinet, paint ignites on the upper part of the left side wall
0:37:20	Large gaps on the upper part of the door, gap area about 0.01 m^2
0:45:10	Burning plastic material is slowly flowing out through the bottom ventilation openings
0:48:05	The bottom part of the rear plate is red-hot
0:53:00	Burning plastic material outside the bottom ventilation openings, the bottom part of the left side wall is red-hot
0:56:35	Decreasing smoke production
1:46:00	Some glow on the bottom of the cabinet
After experiment	The combustible material in the cabinet is completely consumed Gaps occurred at the rear and left walls, between the hinged rack and the cabinet frame, and between the door and the hinged frame

Table 4. Observations made during experiment 2A.

Time (h:min:s)	Event
0:0:0	Ignition of the propane burner, average power output 740 W
0:0:20	The door is closed
0:1:58	The door is secured with bolts
0:2:05	Thin smoke from all ceiling openings
0:5:00	The propane burner is turned off
0:5:10	Decreasing smoke production
0:16:10	Practically no smoke
0:22:00	The door is opened
After experiment	About 250 mm of wiring directly above the burner has burned

Table 5. Observations made during experiment 2B.

Time (h:min:s)	Event
Before experiment	A 500 mm long wiring bundle of weight 119 g is added to the wiring directly above the propane gas burner
0:0:0	Ignition of the propane burner, average power output 1540 W
0:0:18	The door is closed
0:1:36	The door is secured with bolts
0:2:30	Thin smoke from all ceiling openings
0:5:03	The propane burner is turned off
0:5:25	Decreasing smoke production
0:14:00	Practically no smoke
0:18:00	The door is opened
After experiment	About 350 mm of wiring directly above the burner has burned and about 70 mm of wiring above the third relay group from the bottom

Table 6. Observations made during experiment 2C.

Time (h:min:s)	Event
Before experiment	A 500 mm long wiring bundle of weight 462 g is added to the wiring directly above the propane gas burner
0:0:0	Ignition of the propane burner, average power output 3200 W
0:0:18	The door is closed
0:1:35	The door is secured with bolts
0:2:10	More smoke than in 2A and 2B from all ceiling openings
0:7:15	Increasing smoke production
0:10:01	The propane burner is turned off
0:12:45	Decreasing smoke production
0:14:15	Increasing smoke production
0:17:55	Gap between the left side of the door and the hinged frame, gap area about 0.0009 m^2
0:28:40	Flames from the left ceiling ventilation opening
0:31:25	Gap area about 0.004 m^2 on the left side of the door
0:35:55	Flames in the rear part of the cabinet
0:39:25	Intense fire at the bottom of the cabinet
0:41:45	Black smoke
0:42.00	The bottom part of the rear plate is red-hot
0:44:15	The rubber packing at the bottom edge of the door ignites
0:44:40	Burning plastic material is slowly flowing out through the bottom ventilation openings
0:53:25	Soot flakes out through the ceiling ventilation openings
0:54:00	The bottom part of the left side wall is red-hot
0:58:15	Fire at the bottom of the cabinet, the cables at the right side of the cabinet are burning
1:04:55	Decreasing smoke production
1:33:00	The front part of the cables on the right side are burning
1:45:00	No flames are observed through the gaps
After experiment	The combustible material in the cabinet is completely consumed Gaps occurred between the door and the hinged rack at a 650 mm long distance at the left side between the hinges and at a 800 long distance between two locking bolts at the right side

Table 7. Observations made during experiment 3.

Time (h:min:s)	Event
0:0:0	Ignition of the propane burner, average power output 500 W
0:0:16	The door is closed
0:1:36	The door is secured with bolts
0:5:01	The propane burner is turned off
0:10:18	Flames at the ceiling ventilation openings
0:13:50	Flames out of all ceiling ventilation openings
0:19:00	Flames out of the rear ceiling ventilation opening
0:20:50	Decreasing smoke production
0:21:50	Flames out of the rear ceiling ventilation opening
0:26:50	Flames out of the front and rear ceiling ventilation openings
0:28:05	Increasing smoke production
0:45:00	The rubber packing softens at the upper left side of the door
0:46:00	Considerable amounts of soot accumulation in the ceiling ventilation openings (Appendix 1, figure 5)
0:58:00	Smoke jet out of the small elliptical opening in the door at 1.24 m above bottom level
1:00:00	All ceiling ventilation openings are blocked up with soot
1:23:45	Soot falls from the front and left ceiling ventilation openings
1:33:53	Soot particles are falling from the front and left ceiling ventilation openings leaving soot-free openings
1:35:30	Increasing smoke production
1:55:0	The front ceiling ventilation opening is nearly completely blocked up with soot
2:11:0	Some melted plastic material is slowly flowing out through the bottom ventilation openings
2:32:0	The rubber packing between the lower edge of the door and the hinged rack melts away from the door
After experiment	Part of the combustible material was incompletely consumed: about 1.6 kg of the lowest vertical wiring bundle was unburned or partly melted, 0.6 kg of cable was unburned and part of the plastics in relay covers, connectors, etc. had melted, flowed down and formed a 10 kg heavy and 30 - 45 mm thick slab covering the bottom of the cabinet (Appendix 1, figure 6) No gaps occurred except where the rubber packing had melted at the lower edge of the door at 2:32:0 Soot layers had deposited on the inside surfaces of the upper part of the cabinet Part of this soot was ignited by sparks when cutting up the welding seams and smouldered for about ten minutes (Appendix 1, figure 5)

3.2 RESULTS FROM MEASUREMENTS

The plotted curves of the acquired data are denoted by 1, 2 and 3 in the figures which correspond to experiments 1, 2C and 3, respectively. The zero of the time axis corresponds to the time of ignition in all figures. The curves from experiment 2A and 2B are not shown because of the small changes in the measured quantities. Maximum values for the measured quantities in experiment 2A and 2B are given in the text.

3.2.1 Rate of heat release and mass

The total energy released, the initial mass of the contents of the fire cabinet, the total mass loss, the mass of the contents of the fire cabinet after each experiment, and the effective heat of combustion in the experiments are presented in table 8. The total rate of heat release, mass and rate of mass change curves from experiments 1, 2C and 3 are presented in figures 5, 6 and 7 respectively.

The oxygen analyser failed in experiment 1 at about 72 min after ignition and, therefore, the RHR curve shows the data only up to that moment. The total energy released is correspondingly calculated up to the 72 min.

During experiment 3, the CO_2 analyser showed extremely low concentrations, (practically zero). The influence of a zero CO_2 signal upon the rate of heat release obtained from oxygen consumption calorimetry is estimated to be an overstatement of about 10 per cent at 100 kW level. A possible overstatement is not compensated in the results presented here.

The oxygen depletion in experiments 2A and 2B was at, or below, the resolution level of the oxygen analyser and no reliable RHR curve was obtained.

The signal transmission from the weighing device to the data logger failed in experiment 1 at time 58.7 min. The total mass loss during the experiment could, however, be obtained from the visual display of the weighing device. The effective heat of combustion in experiment 1 is calculated from data obtained up to the 58.7 min.

Table 8. Total energy released, initial mass of contents of fire cabinet, total mass loss, mass of contents of fire cabinet after the experiment and effective heat of combustion in the experiments.

Experiment	1	2A	2B	2C	3
Total energy (MJ)	442[1)]			270	288
Initial mass (kg)	66.5[2)]	70.7	70.4	70.7	66.4
Total mass loss (kg)	22.0	0.4	0.2	23.6	14.6
Total mass loss (%)	33			33	22
Mass after experiment (kg)	44.5			47.4	51.2
Effective heat of combustion (MJ/kg)	19.6[3)]			11.4	19.7

[1)] integrated from time of ignition up to 72 min
[2)] estimated from the sum of total burned mass and mass of contents after experiment
[3)] total energy release up to 58.7 min divided by the corresponding mass loss

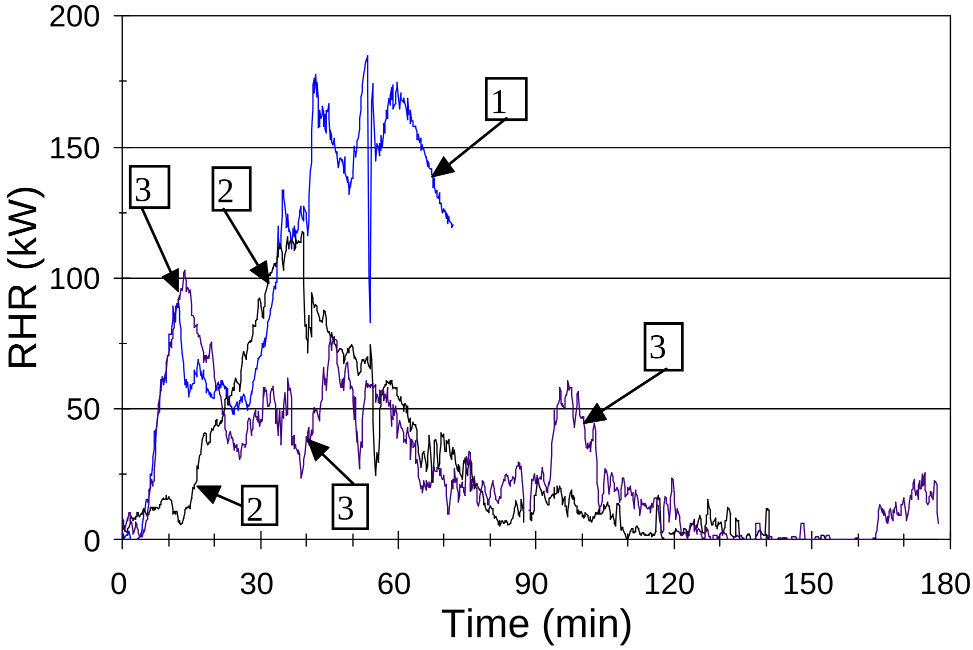

Figure 5. Total rate of heat release in experiments 1, 2C and 3. The RHR measurement in experiment 1 failed at about 72 min.

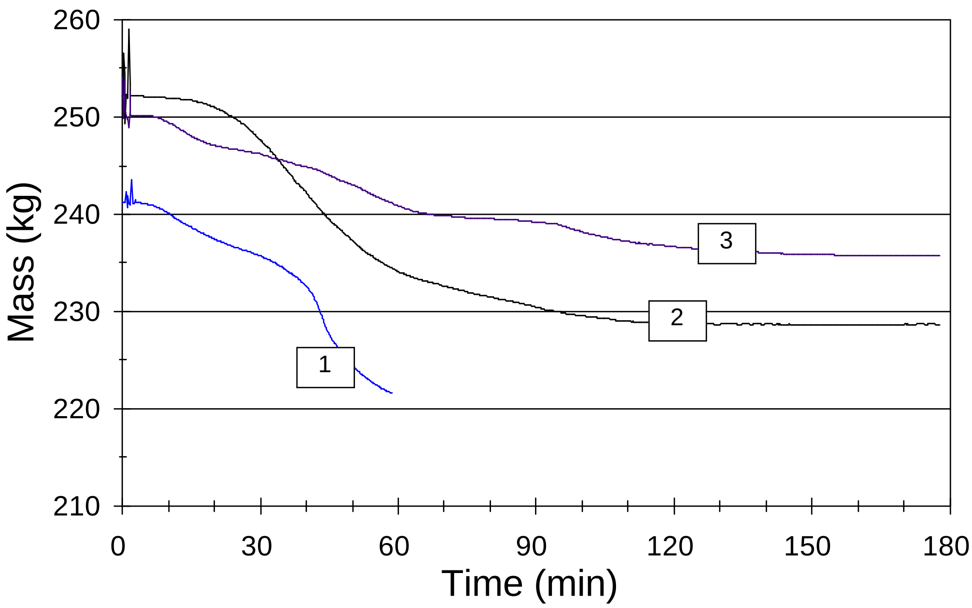

Figure 6. Mass of the fire and adjoining cabinets in experiments 1, 2C and 3. The mass signal was not registered after 58.7 min in experiment 1.

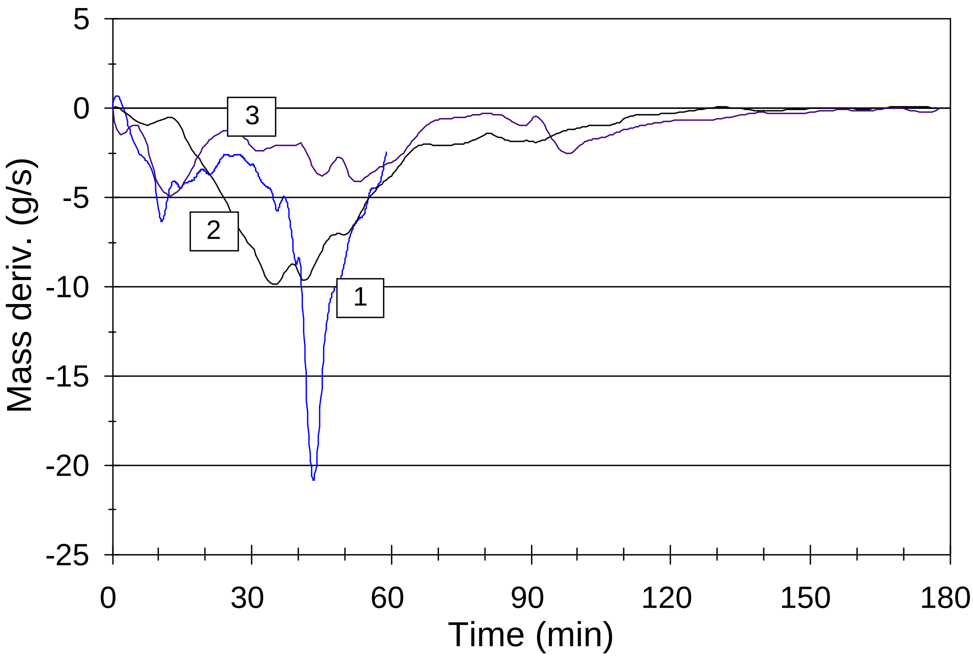

Figure 7. Rate of mass change in experiments 1, 2C and 3. The mass signal was not registered after 58.7 min in experiment 1.

3.2.2 CO_2, CO and smoke production and mass flow rate in the exhaust duct

The CO_2, CO and smoke production rate and mass flow rate in the exhaust duct in experiments 1, 2C and 3 are presented in figures 8, 9, 10 and 11 respectively.

The CO_2 and CO production in experiments 2A and 2B was below the resolution limits for the analysers.

The CO_2 concentration measurement showed nearly zero throughout experiment 3. The reason for this is not fully clear, but one source may be the very large production of soot in this experiment leading to a sooty gas sample which may have led to an obstruction in the gas lines in the CO_2 analyser.

Maximum smoke production was 0.05 m^2/s at 1 min in experiment 2A and 0.35 m^2/s at 5 min in experiment 2B.

The smoke production rate R is here defined as

$$R = D\dot{V} \tag{1}$$

where

- D is $(10/L)\log_{10}(I_0/I)$
- I_0 is the light intensity for a beam of parallel light rays measured in a smoke free environment
- I is the light intensity for a beam of parallel light rays having traversed a certain length L of smoky environment
- L is length of beam through smoky environment
- $\dot{V}$ is volume flow in exhaust duct at actual duct gas temperature.

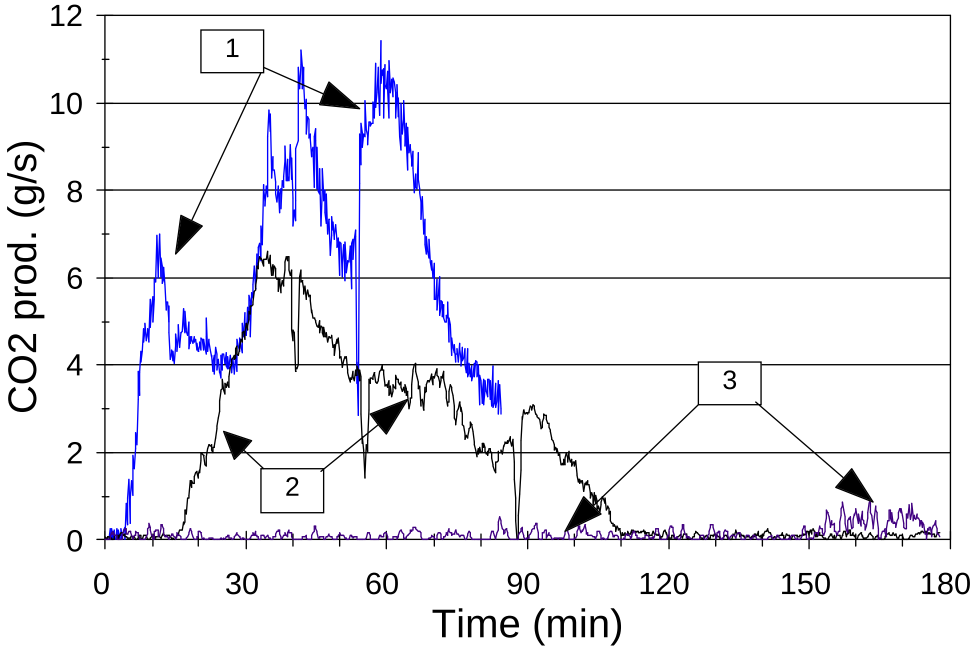

Figure 8. CO_2 production rate in experiments 1, 2C and 3. The CO_2 analyser showed abnormally low values in experiment 3.

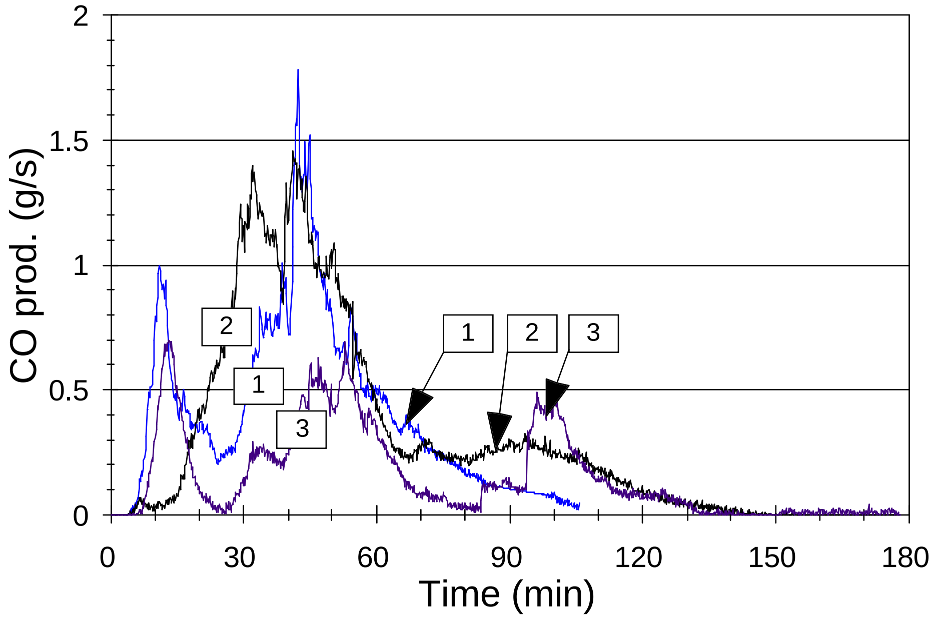

Figure 9. CO production rate in experiments 1, 2C and 3.

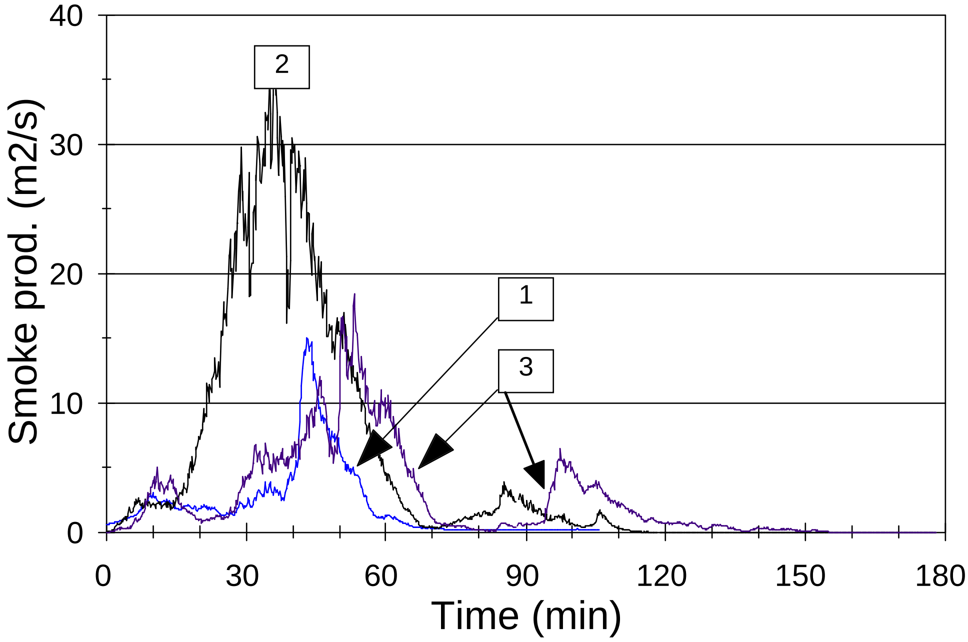

Figure 10. Smoke production rate in experiments 1, 2C and 3.

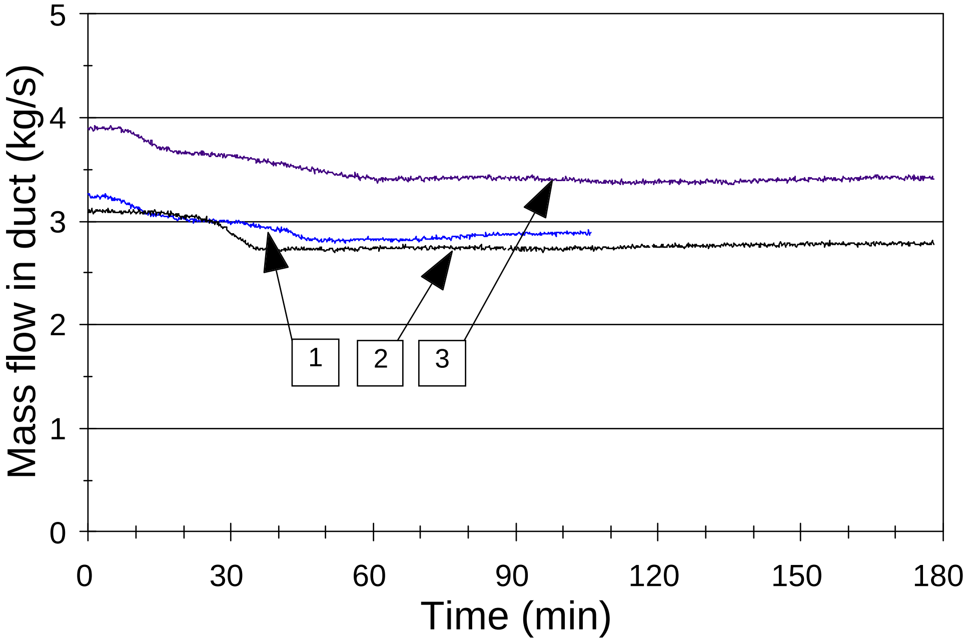

Figure 11. Mass flow rate in exhaust duct in experiments 1, 2C and 3.

3.2.3 Temperatures

Thermocouple locations are indicated in the upper right corner of each temperature curve figure.

Maximum outer surface temperatures measured with the infrared thermometer did not exceed maximum temperatures measured with wall thermocouples. The measured wall temperatures seems to be applicable for dimensioning purposes.

Considerable uncertainty is associated with temperatures measured with the infrared thermometer because of the difficulty in determining the emissivity of the wall. Outer surface temperatures measured with the infrared thermometer are, therefore, not reported here.

Experiment 1

Gas temperatures in the fire cabinet are presented as follows: T1 - T5 in figure 12, T6 - T10 in figure 13, T11 - T15 in figure 14 and T16 - T20 in figure 15. Wall temperatures S1 - S4 in the fire cabinet are presented in figure 16. Gas temperatures T21 - T22 and wall temperature S5 in the adjoining cabinet are presented in figure 17. Wall temperature S6 and gas temperature T23 in the opposite cabinet are presented in figure 18.

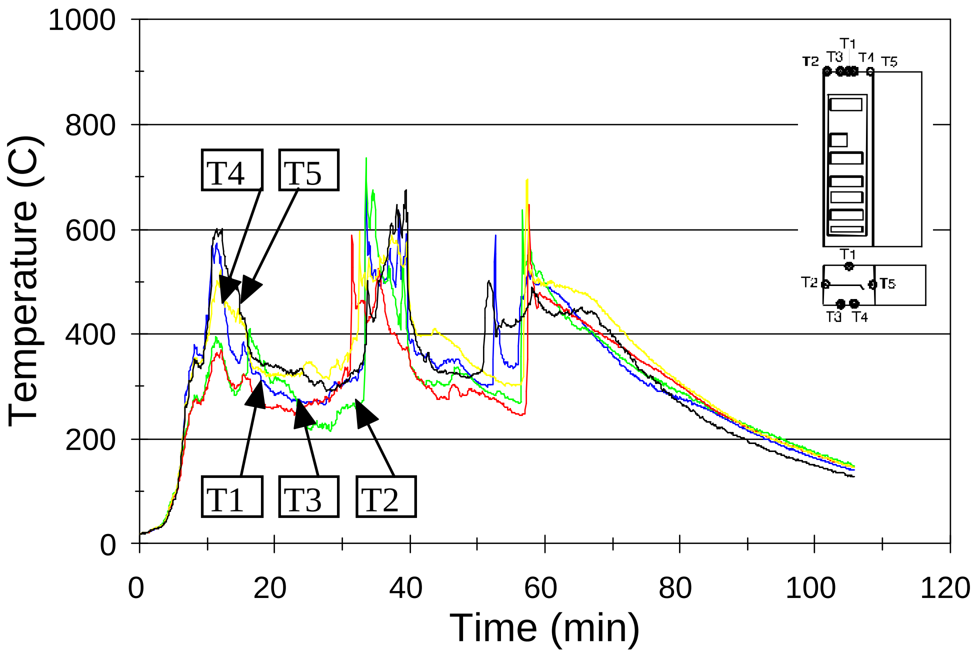

Figure 12. Gas temperatures T1 - T5 in the fire cabinet in experiment 1.

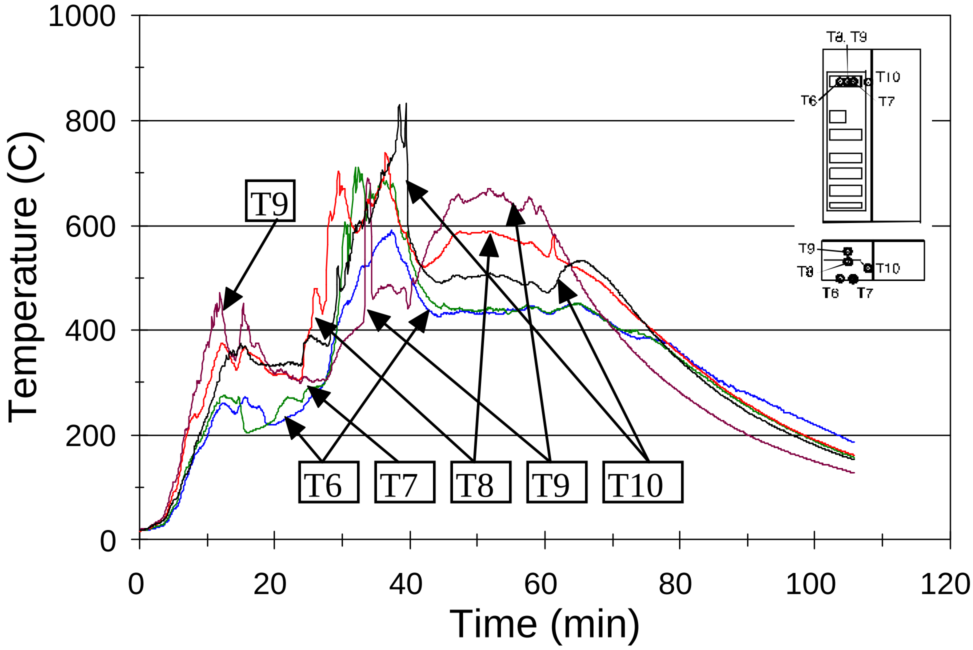

Figure 13. Gas temperatures T6 - T10 in the fire cabinet in experiment 1.

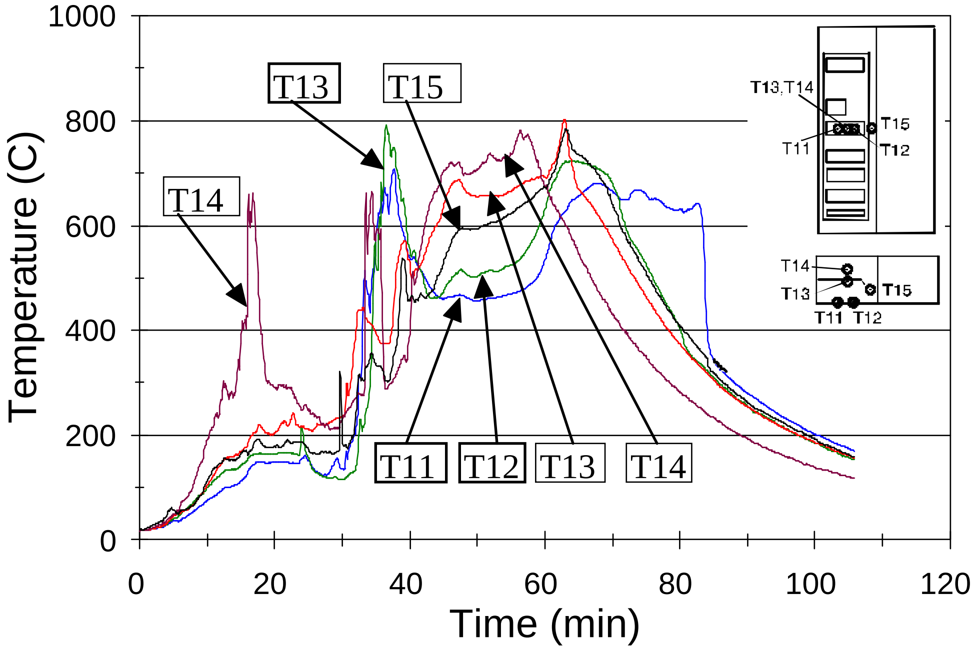

Figure 14. Gas temperatures T11 - T15 in the fire cabinet in experiment 1.

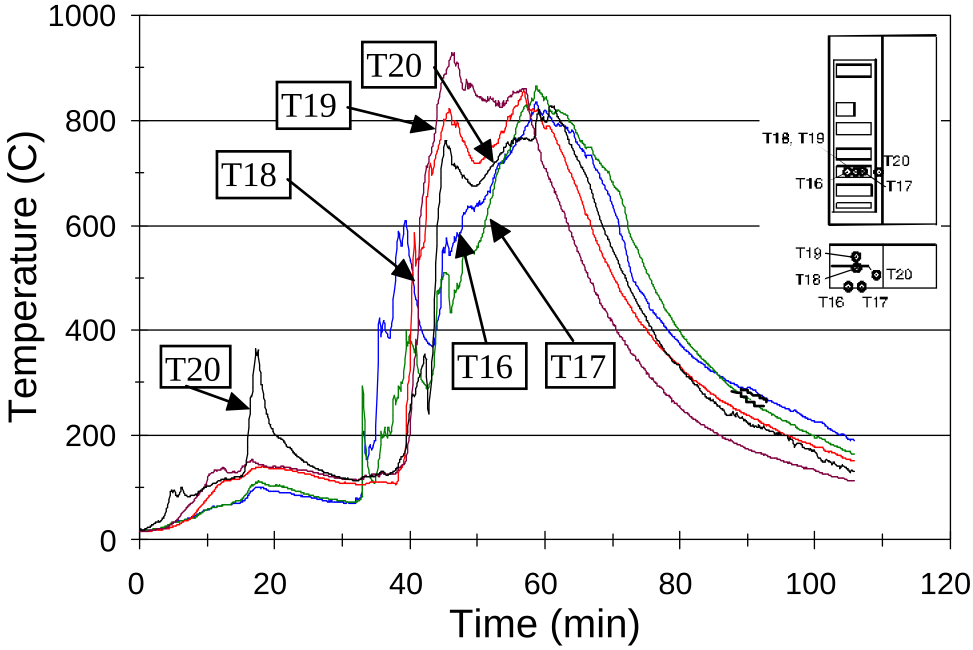

Figure 15. Gas temperatures T16 - T20 in the fire cabinet in experiment 1.

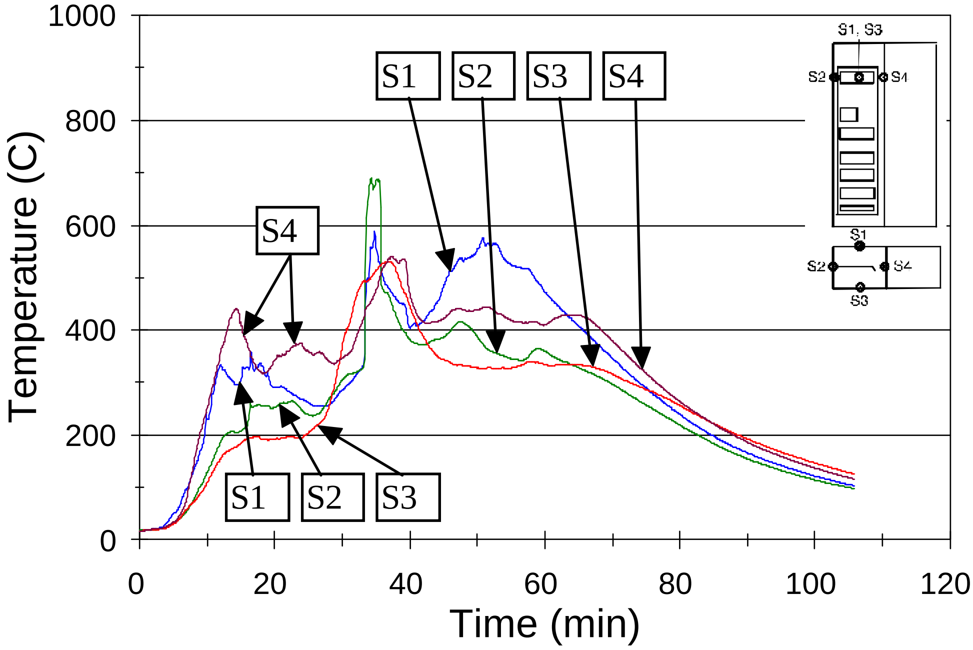

Figure 16. Wall temperatures S1 - S4 in the fire cabinet in experiment 1.

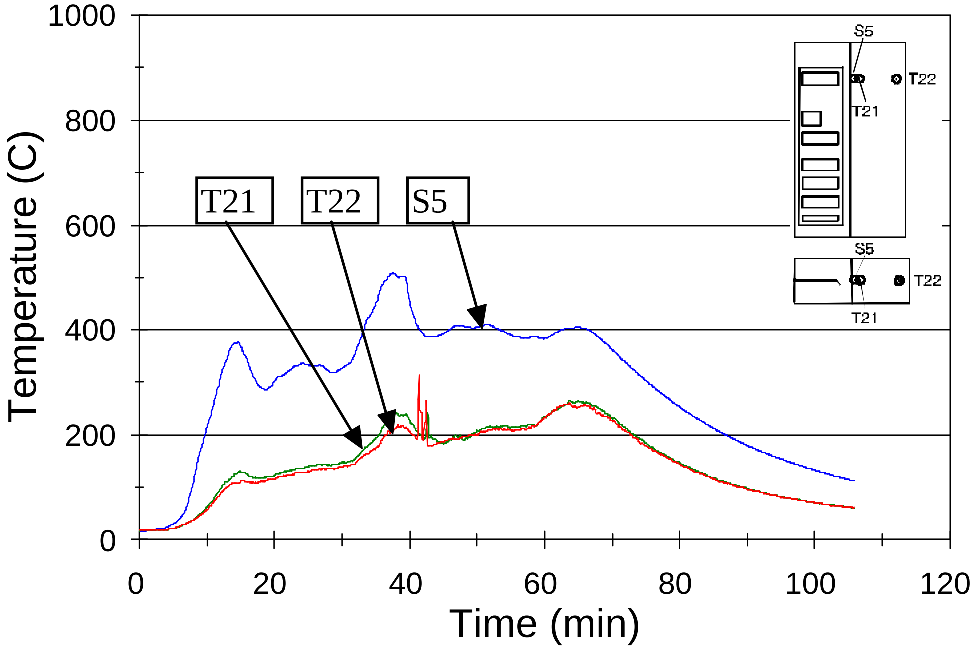

Figure 17. Gas temperatures T21 - T22 and wall temperature S5 in the adjoining cabinet in experiment 1.

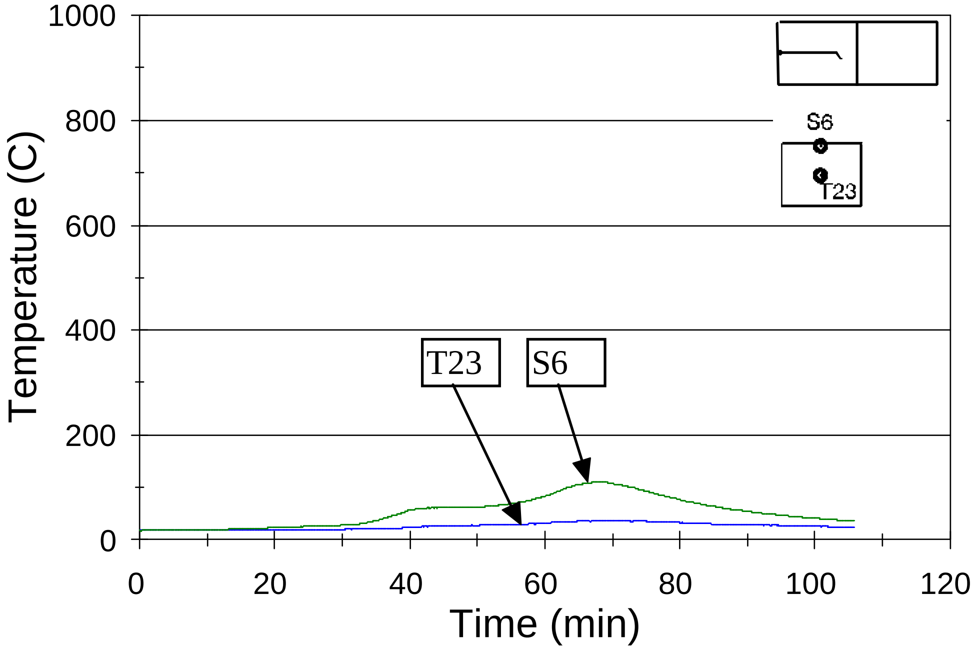

Figure 18. Wall temperature S6 and gas temperature T23 in the opposite cabinet in experiment 1.

Experiment 2

Maximum temperatures in the fire and adjoining cabinets in experiment 2A and 2B are presented in table 9. No temperature rise was detected in the opposite cabinet during experiments 2A and 2B.

Table 9. Maximum temperatures in the fire and adjoining cabinets in experiments 2A and 2B.

	Fire cabinet			Adjoining cabinet		Initial temp.
	Ceiling opening	Within cabinet	Wall	Within cabinet	Wall	
2A: Temperature (°C)	23	26	22	18	18	17-18
Location	T2	T11	S8	T21,T22	S5	
Time (min)	4.7	5.0	6.6	1.6	8.7	
2B: Temperature (°C)	39	32	26	18	21	18-19
Location	T2	T11	S8	T21	S5	
Time (min)	5.0	4.8	6.5	1.6	8.7	

Temperature curves from experiment 2C are presented as follows: Gas temperatures in the fire cabinet T1 - T5 in figure 19, T6 - T10 in figure 20, T11 - T15 in figure 21 and T16 - T20 in figure 22. Wall temperatures in the fire cabinet S1 - S4 are presented in figure 23, and S7 - S10 in figure 24. Gas temperatures T21 - T22 and wall temperature S5 in the adjoining cabinet are presented in figure 25. Wall temperature S6 and gas temperature T23 in the opposite cabinet are presented in figure 26.

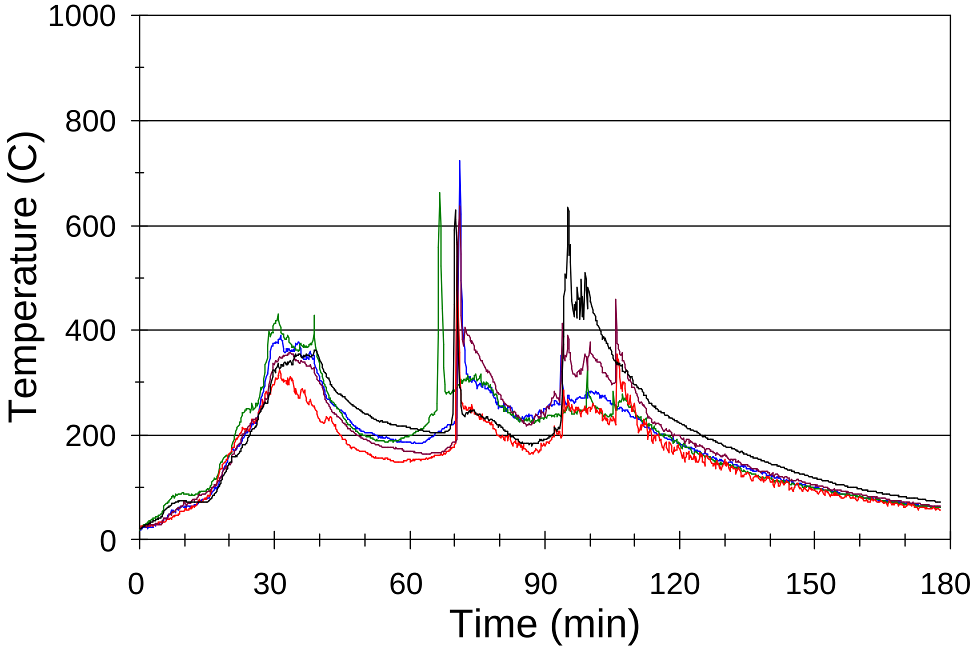

Figure 19. Gas temperatures T1 - T5 in the fire cabinet in experiment 2C.

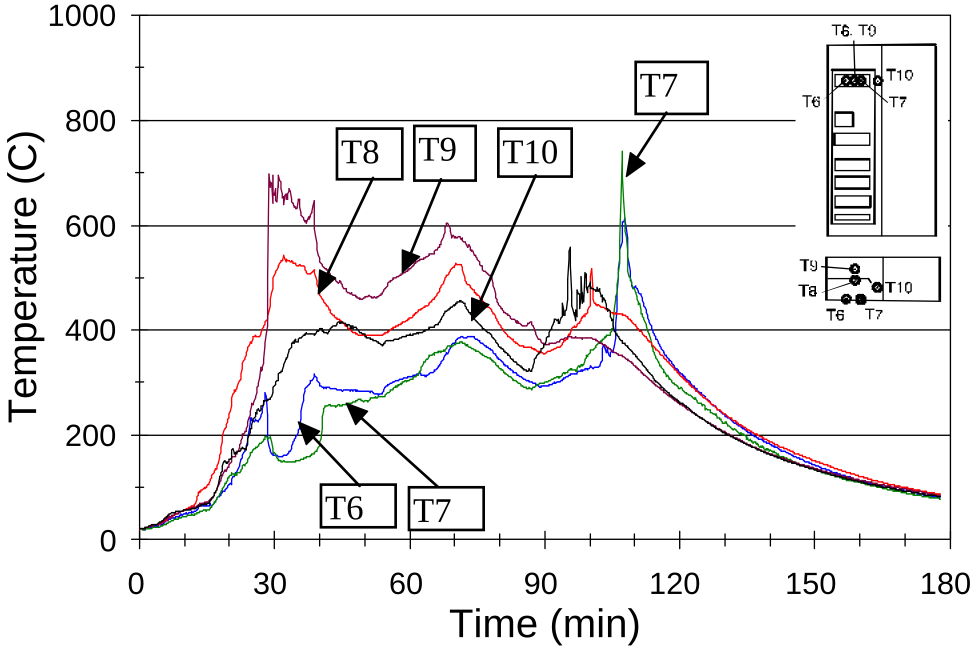

Figure. 20. Gas temperatures T6 - T10 in the fire cabinet in experiment 2C.

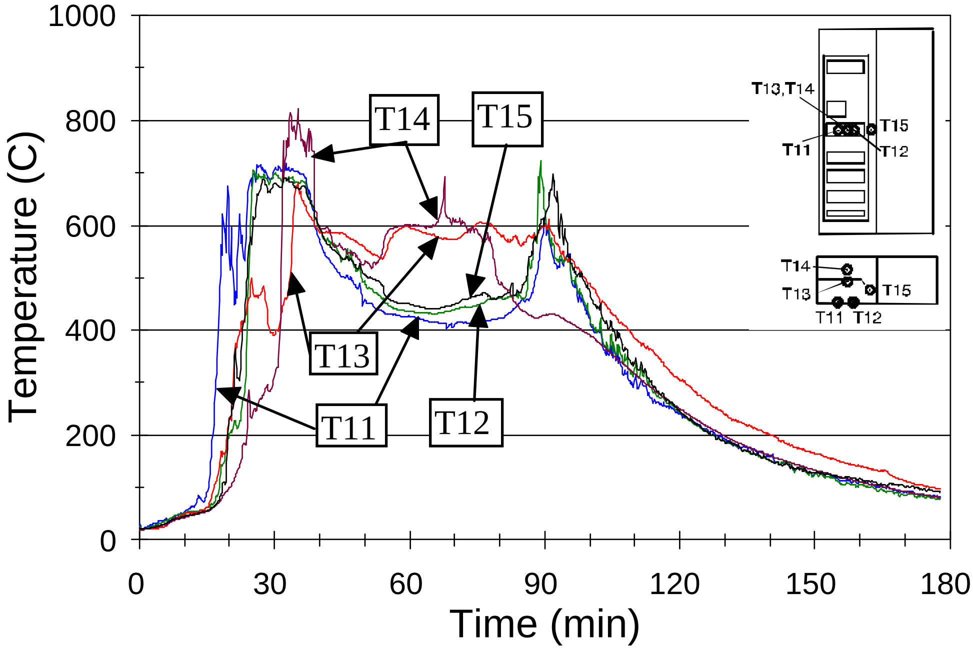

Figure 21. Gas temperatures T11 - T15 in the fire cabinet in experiment 2C.

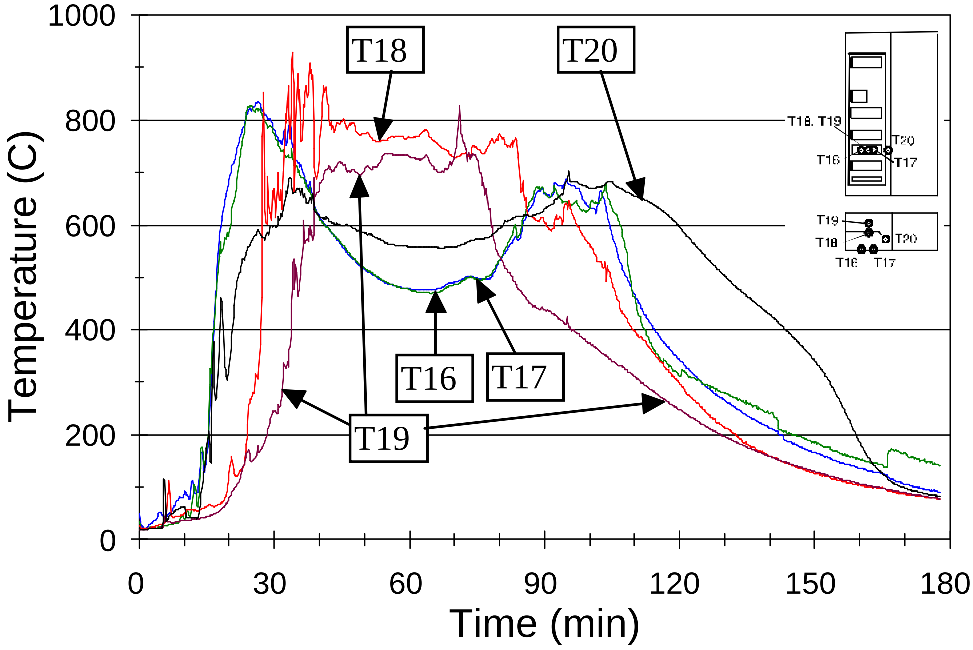

Figure 22. Gas temperatures T16 - T20 in the fire cabinet in experiment 2C.

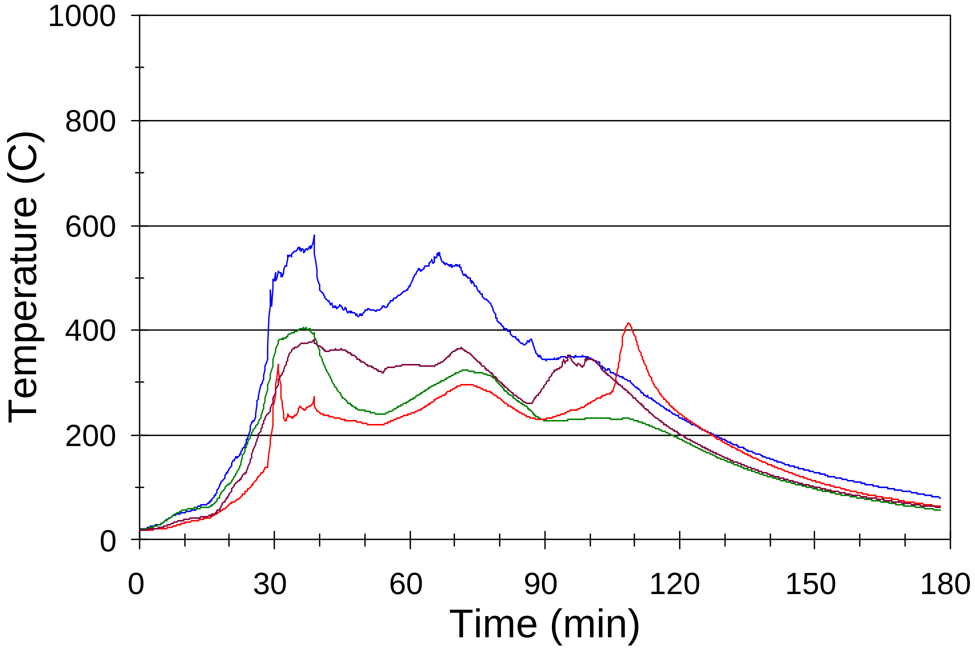

Figure 23. Wall temperatures S1 - S4 in the fire cabinet in experiment 2C.

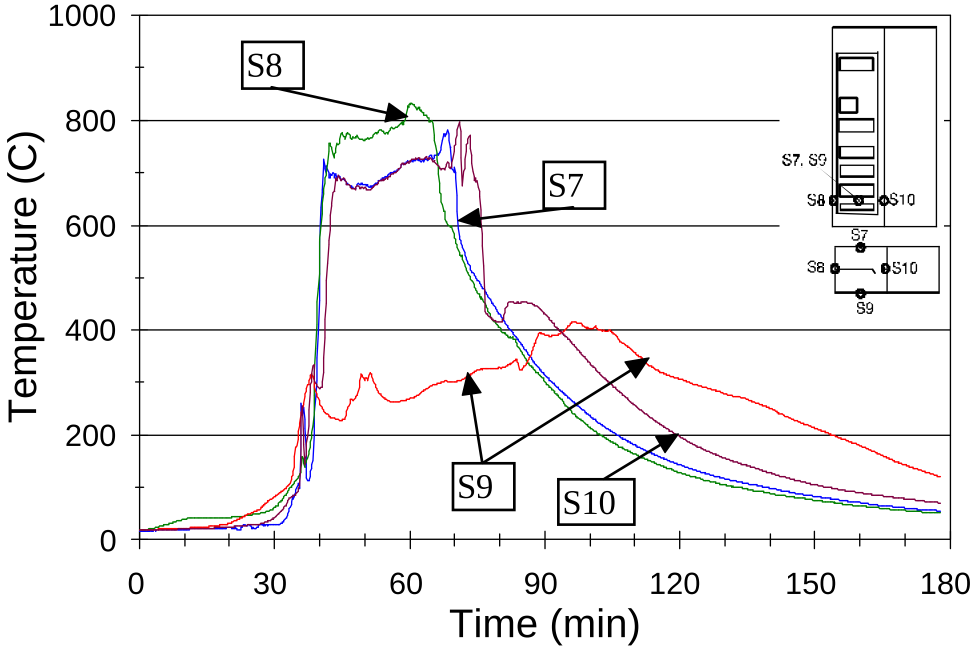

Figure 24. Wall temperatures S7 - S10 in the fire cabinet in experiment 2C.

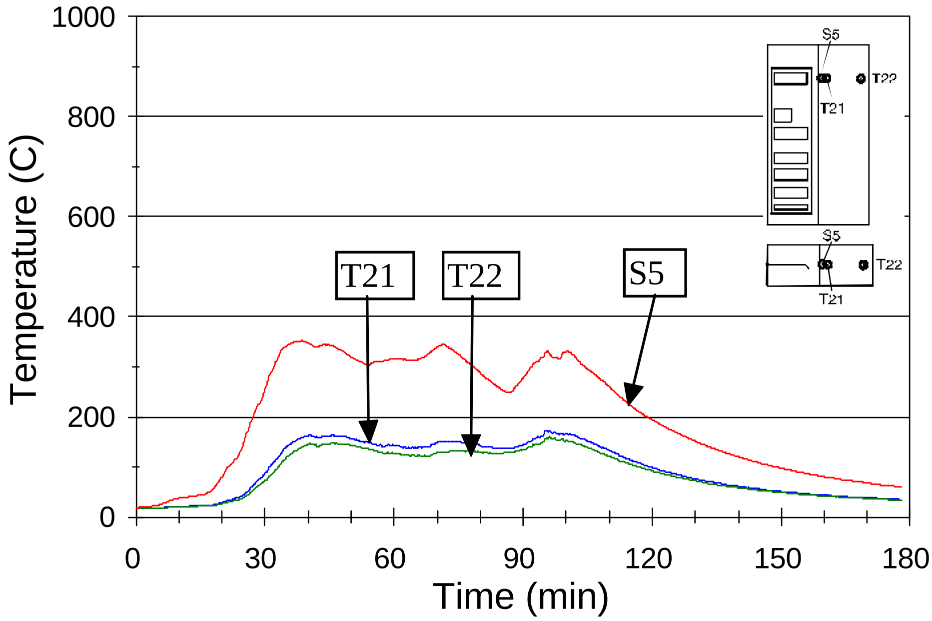

Figure 25. Gas temperatures T21 - T22 and wall temperature S5 in the adjoining cabinet in experiment 2C.

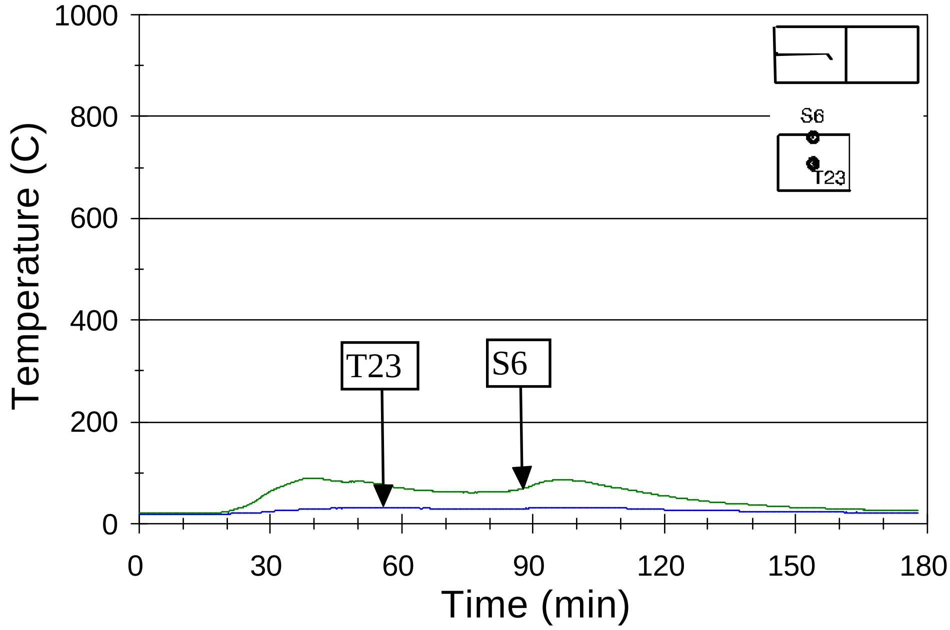

Figure 26. Wall temperature S6 and gas temperature T23 in the opposite cabinet in experiment 2C.

Experiment 3

Temperature curves from experiment 3 are presented as follows: Gas temperatures in the fire cabinet T1 - T5 in figure 27, T6 - T10 in figure 28, T11 - T15 in figure 29 and T16 - T20 in figure 30. Wall temperatures in the fire cabinet S1 - S4 are presented in figure 31 and S7 - S10 in figure 32. Gas temperatures T21 - T22 and wall temperature S5 in the adjoining cabinet are presented in figure 33. Wall temperature S6 and gas temperature T23 in the opposite cabinet are presented in figure 34.

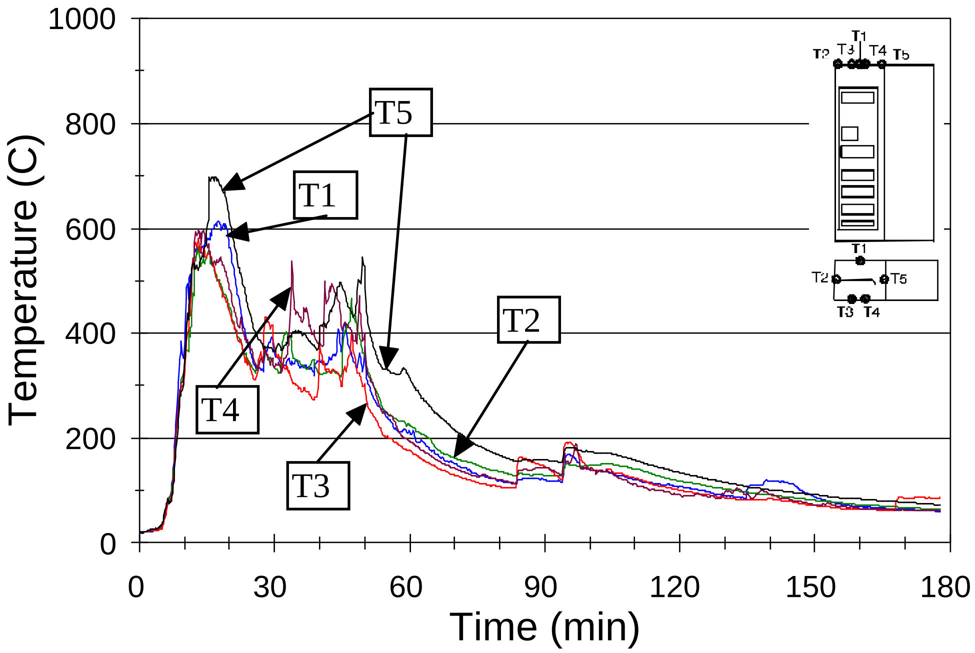

Figure 27. Gas temperatures T1 - T5 in the fire cabinet in experiment 3.

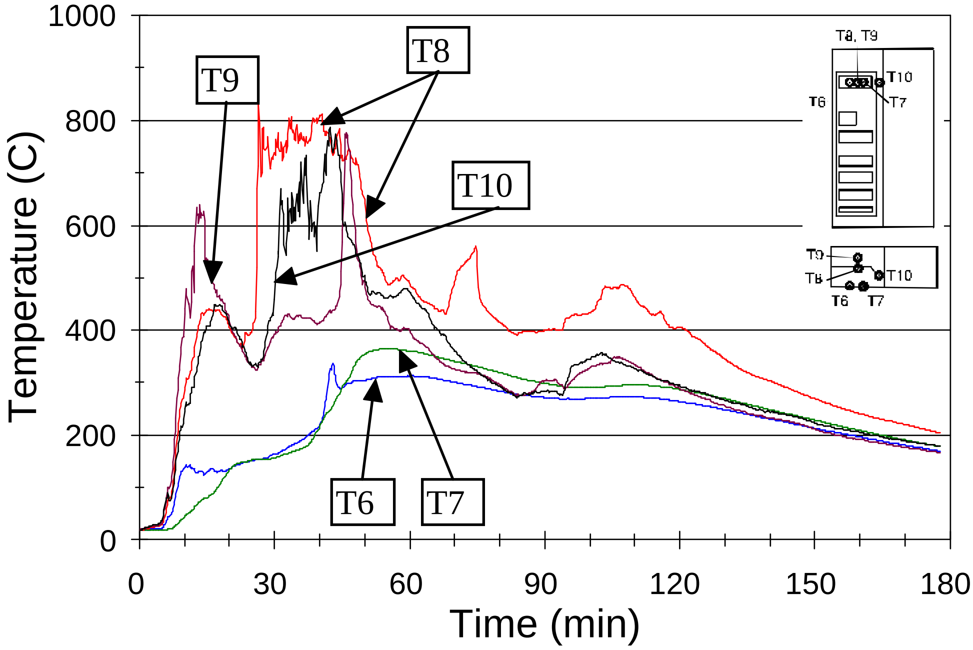

Figure 28. Gas temperatures T6 - T10 in the fire cabinet in experiment 3.

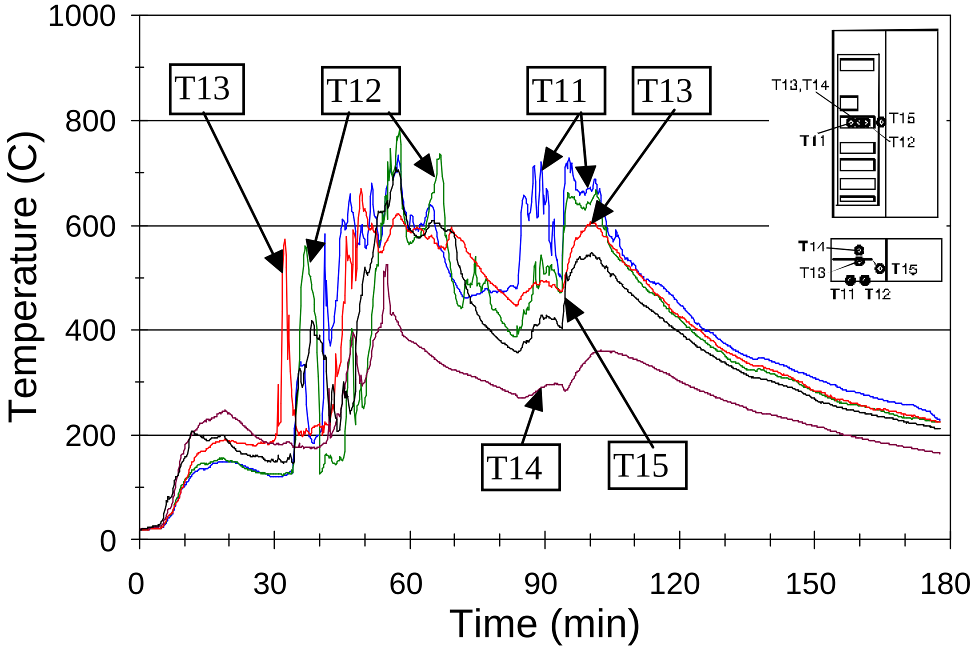

Figure 29. Gas temperatures T11 - T15 in the fire cabinet in experiment 3.

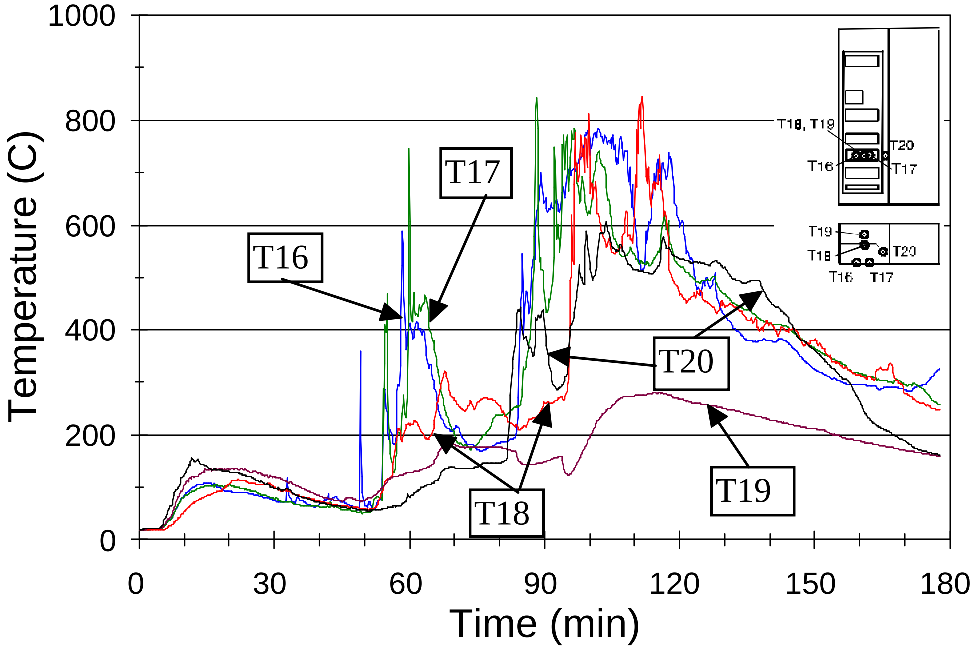

Figure 30. Gas temperatures T16 - T20 in the fire cabinet in experiment 3.

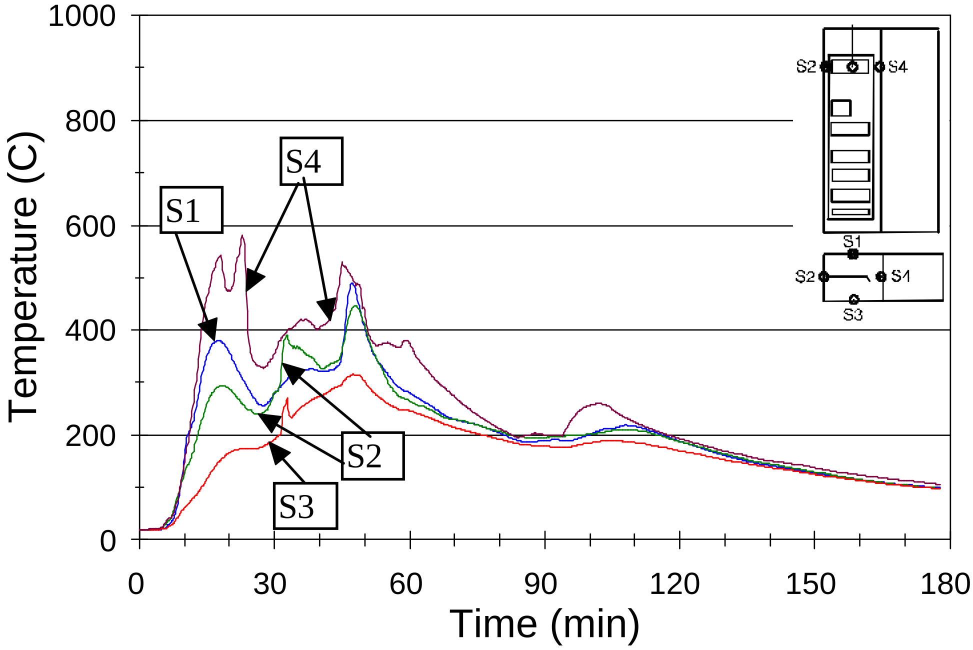

Figure 31. Wall temperatures S1 - S4 in the fire cabinet in experiment 3.

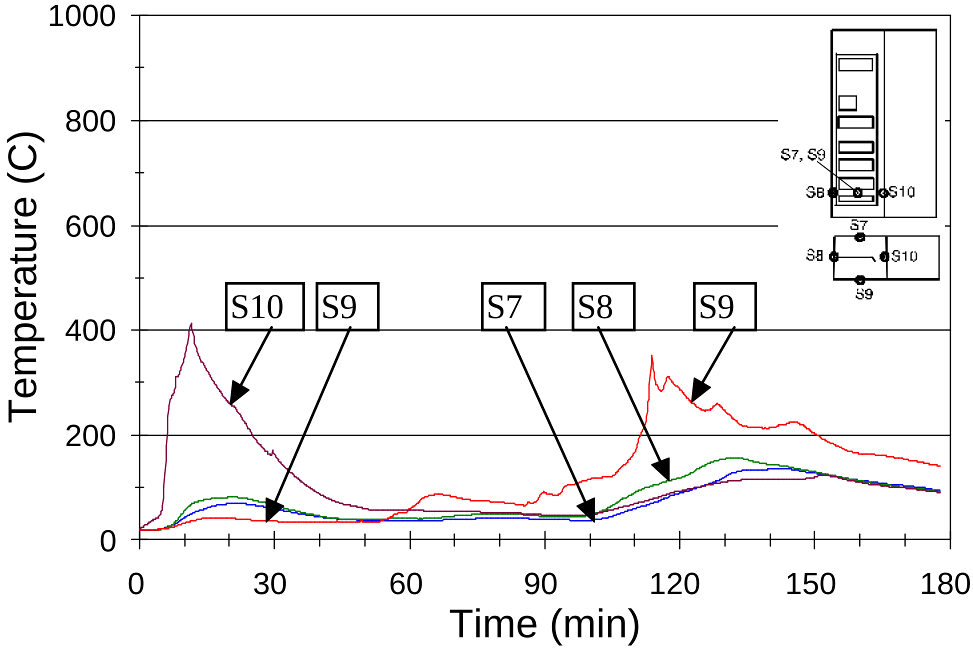

Figure 32. Wall temperatures S7 - S10 in the fire cabinet in experiment 3.

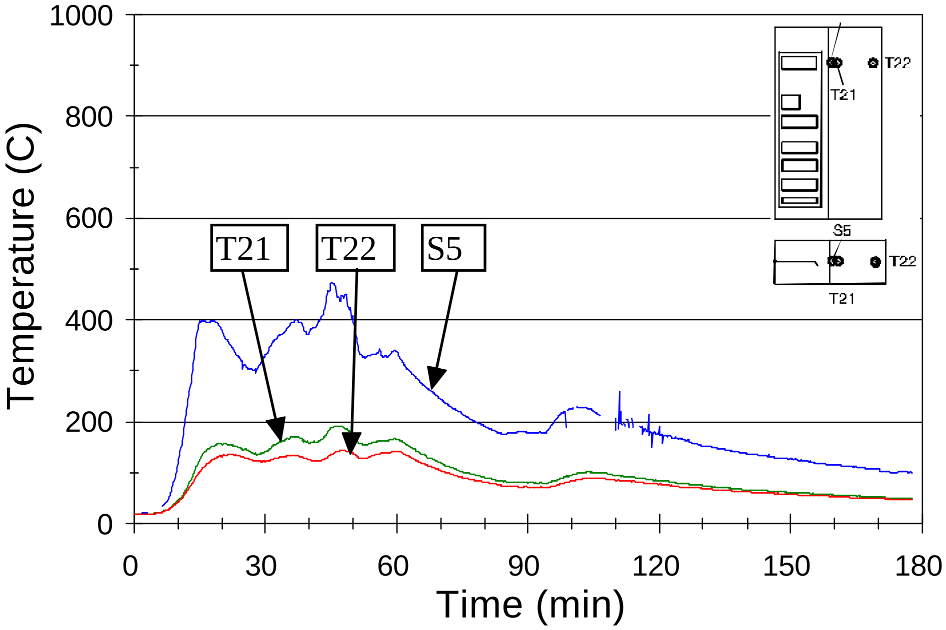

Figure 33. Gas temperatures T21 - T22 and wall temperature S5 in the adjoining cabinet in experiment 3.

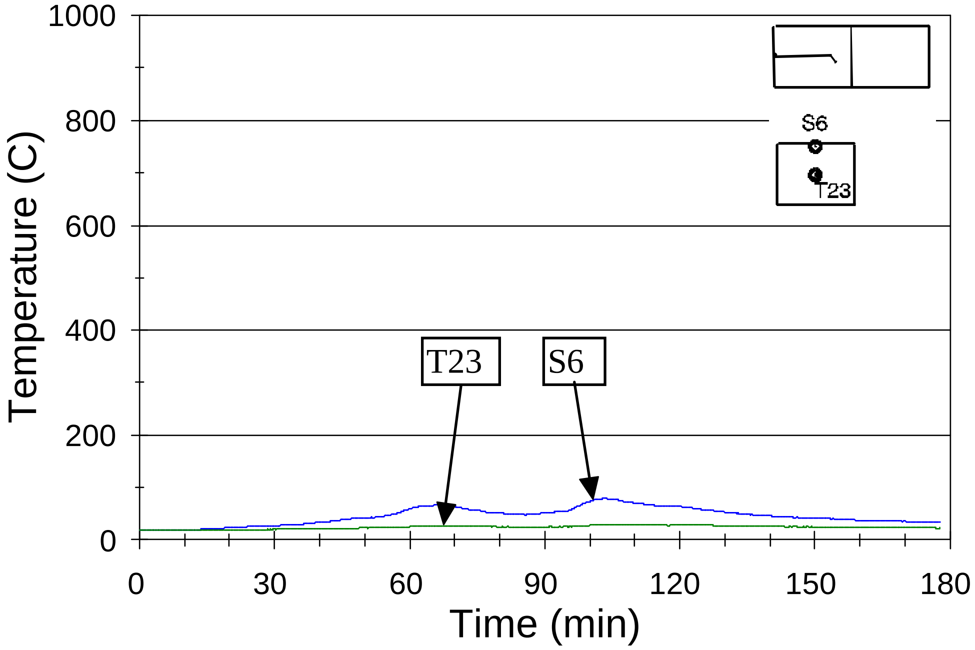

Figure 34. Wall temperature S6 and gas temperature T23 in the opposite cabinet in experiment 3.

4 DISCUSSION

4.1 BOUNDARY CONDITIONS

Inside the cabinet: These experiments were carried out with one type of cabinet furnished in a particular way, i.e. the combustible material consisted mainly of relays with attached connectors. The following distinctions between the present cabinet and the cabinet in the previous fire experiments (Mangs & Keski-Rahkonen 1984) can be made: different ventilation conditions, contents and structure. The most important of these is the ventilation, where the air intake area of the cabinet in the previous series was 5 times, and the air outlet 1.5 times, as large as in the present study. The difference in structure consists mainly in the vertical steel plate dividing the cabinet roughly in two parts. Its influence on the spread of fire is not easy to investigate in detail because direct observations are not possible due to the encapsulated structure of the cabinet. It is probably small in comparison to the effect of different ventilation conditions at least in the later phases of the fire.

Outside the cabinet: As in the preceding fire experiment series on electronic cabinets, the experiments in this study were carried out under an exhaust hood which collected the fire products in order to measure the rate of heat release. These conditions are a good approximation for a cabinet fire in free space. The experiments do not describe the situation in which a cabinet is burning in a small room. In a fire in a room, a layer of hot gases accumulates below the ceiling radiating energy to the lower parts of the room. The thickness and temperature of the hot gas layer will increase with time as the fire increases. Finally, if not interrupted, fire growth may result in a full room flashover. The burning conditions inside the primary burning cabinet are not influenced much by the hot layer in the room because the replacement air is taken from the lower oxygen-rich cold layer. Therefore, despite free space approximation during the experiments, the present experiments do still give direct information about a fire inside a cabinet but not about conditions in a room where the fire takes place. The present results can be used as input data for room fire simulations.

4.2 VENTILATION

The important role of ventilation conditions was clearly seen in the experiments. The air intake in experiment 1 changed during the experiment as gaps opened in the walls of the cabinets because of thermal stresses. At about 10 min, gaps with an area of the same order of magnitude as the ordinary intake appeared. At about 37 min, large gaps appeared which increased the intake area thus supplying the fire with more oxygen. This is reflected in the RHR curve (figure 5) with a considerable rise starting at about 35 min, after which the maximum rate of heat release was reached at a level of 150 - 170 kW for about 20 min. The total energy released in experiment 1 is also considerably greater than in experiments 2 and 3 (table 8).

The gaps were closed before experiment 2 thus constraining the air intake possibilities to mainly the ordinary ventilation openings. One gap still appeared at the left side of the door starting from about 18 min. This can again be seen in the RHR curve (figure 5) as a corresponding rise leading to a maximum rate of heat release level of about 115 kW for about 6 min.

No additional gaps were present in experiment 3. This is reflected in the RHR curve which overall shows lower values than in the preceding experiments. The restricted air intake could also be noted visually as notable soot formation during the experiment indicating a high degree of incomplete combustion.

The soot stuffed up the ceiling ventilation openings which further decreased the air exchange possibilities in the cabinet. The peak in the RHR curve rising at 93 min corresponds to improved ventilation conditions when relatively large amounts of soot fell from the blocked ceiling openings which were thus partially cleared. The effect of insufficient air intake in experiment 3 is also seen in the large amount of melted and partly burned material that accumulated on the bottom of the cabinet where the temperatures had been too low to sustain burning (tables 7 and 8, Appendix 1 figure 6).

4.3 SPREAD OF FIRE INSIDE THE CABINET

The cabinet was ignited from two different locations in order to study the influence on spread of the fire inside the cabinet (figure 1). The fire spread in each case to the rest of the cabinet igniting all combustible material after established burning was achieved around the point of ignition.

The spread of fire in the cabinet was rather slow in all experiments. No visual observations about the spread of fire in the cabinet could be made because of its closed structure. Some indications are given by the temperature measurements, e.g. the spread of fire in experiment 1 (figures 13 - 15). The fire was ignited at the right rear corner and correspondingly, the temperatures measured at points T6 - T7, T11 - T12 and T16 - T17 in the front part of the cabinet rose later than at the other measurement points. The overall heating of the cabinet, with a hot upper layer increasing in temperature and thickness with time, can also be deduced from the temperatures measured at different heights.

4.4 IGNITION

The cabinet was ignited with a propane gas burner in all experiments. A gas burner was chosen because it provided the most reliable method to bring a well defined energy output to a fixed point inside the cabinet.

An alternative ignition procedure would have been a deliberate electric fault such as a short circuit, ground contact or overloading representing a ‘real’ source of ignition. Several attempts were made to obtain a reliable electrical source filling the following requirements: to be capable of igniting the cables or wiring, to have an easily measurable energy output, to fit into the rather limited space in the cabinet and to be easy to operate from outside the closed cabinet. Despite an extensive search and testing, no electrical device which would even approximately have fulfilled these requirements was found.

The burner power was chosen to gain knowledge about the lowest ignition power needed to ensure established burning in the cabinet. Two different types of material were ignited, the cable bundle in experiment 1 and 3 and the wiring near the relays in experiment 2.

The cable bundle ignited and the fire developed to flashover in both experiments 1 and 3. The rising RHR curves indicate the spread of fire at about 4 min in experiment 1 and at about 4.5 min in experiment 3. In both experiments, the propane burner was turned off at 5 min. It is difficult to make certain conclusions about how far the 500 W power and 150 kJ energy levels in experiment 3 are from the ignition/no ignition limit but they are possibly fairly close.

The fire went out in experiments 2A and 2B after turning the propane burner off (with power 1540 W and energy output 470 kJ in 2B). The burner power 3200 W and total energy release 1920 kJ in experiment 2C led to ignition and flashover. Here, the decreasing RHR curve after turning the burner off reveals a decrease in the fire intensity. The RHR curve then distinctly rises showing that the fire is after all able to sustain itself. This may indicate that the used ignition power and energy are just above the ignition/no ignition limit.

It is to be noted in this context that the statistical scatter in experimentally determining the limits where a cabinet may ignite or not can be considerable and that a large series of experiments are needed in order to obtain high accuracy.

4.5 FIRE GROWTH RATE

The fire growth rate of the first ignited cable or wiring bundle was determined by fitting a parabola

$$\dot{Q} = \alpha (t - t_i)^2 \qquad (2)$$

on the RHR-curve (figure 5) according to the procedure used for a burning foam sofa by Schifilliti as referred to in Evans (1988). The obtained growth parameters α and ignition reference times t_i are given in table 10. NFPA 72E, Standard on Automatic Fire Detectors, classifies fire growth according to the growth parameter α as follows (Evans 1988)

Growth parameter	Fire development
2.93	Slow
11.72	Medium
46.9	Fast
187.6	Ultrafast

The fitting of the curves is not unique, because a parabola does not reproduce the salient features of the general fire growth curve. Therefore, the margin of error of the growth parameter is large (of the order of a factor two). Despite these inaccuracies, the fire development in all the cabinet fire experiments was slow according to the NFPA classification. The reference ignition time t_i is only a fitting parameter and does not refer, despite its name, to any time relevant to ignition.

Table 10. Growth parameters and reference ignitions times for the cabinet fire tests.

Experiment	Growth parameter α (W/s^2)	Reference ignition time t_i (s)
1	0.6	170
2C	0.2	615
3	0.7	200

5 CONCLUSIONS

The present experiments with electronic cabinets give information about the total rate of heat release, mass change, CO_2, CO and smoke production rate and gas and wall temperatures in all three cabinets as a function of time. Maximum rate of heat release measured in the experiments were 180 kW in experiment 1, 120 kW in experiment 2C and 100 kW in experiment 3.

These measurements can be used as input data in different types of fire simulation programs that are used to calculate the fire spread in rooms containing electronic cabinets. However, the present results should be applied with care to the evaluation of the fire behaviour of other cabinets because there are significant differences in ventilation conditions, cabinet structure, amounts of and location of contents, which have an effect particularly on the ignition and spread of a fire.

The key role of the ventilation conditions in the cabinet when determining the rate of heat release was clearly shown. To reduce the intensity of the fire causing additional ventilation openings, such as gaps in the walls due to thermal stresses if the mechanical structure of the cabinet is weak, seemed to be important.

The spread of fire to neighbouring cabinets is possible due to the heating of the separating walls. Fire spreading across the corridor is unlikely as a direct heat transfer process. It becomes possible via the hot gas layer that accumulates in the upper part of the room when the fire has grown big enough. Another spreading mechanism is through molten plastic which could flow across a corridor.

The importance of the tight bottom of the cabinet became also clear. Burning melt or dripping components could quickly spread the fire under a false floor in a cable spreading area.

The power and energy needed for igniting the cable bundle were 0.5 kW and 150 kJ, and corresponding power and energy for igniting the wiring bundle, 3.2 kW and 1.9 MJ. In both cases, these power and energy levels were sufficient to achieve established burning which led to flashover in the cabinet. The power and energy levels for igniting the cable bundle in experiment 3 are possibly fairly close to the ignition/no ignition limit. The power and energy levels for igniting the wiring bundle in experiment 2C seem to be just above the ignition/no ignition limit.

After ignition, the fire development was slow according to NFPA classification.

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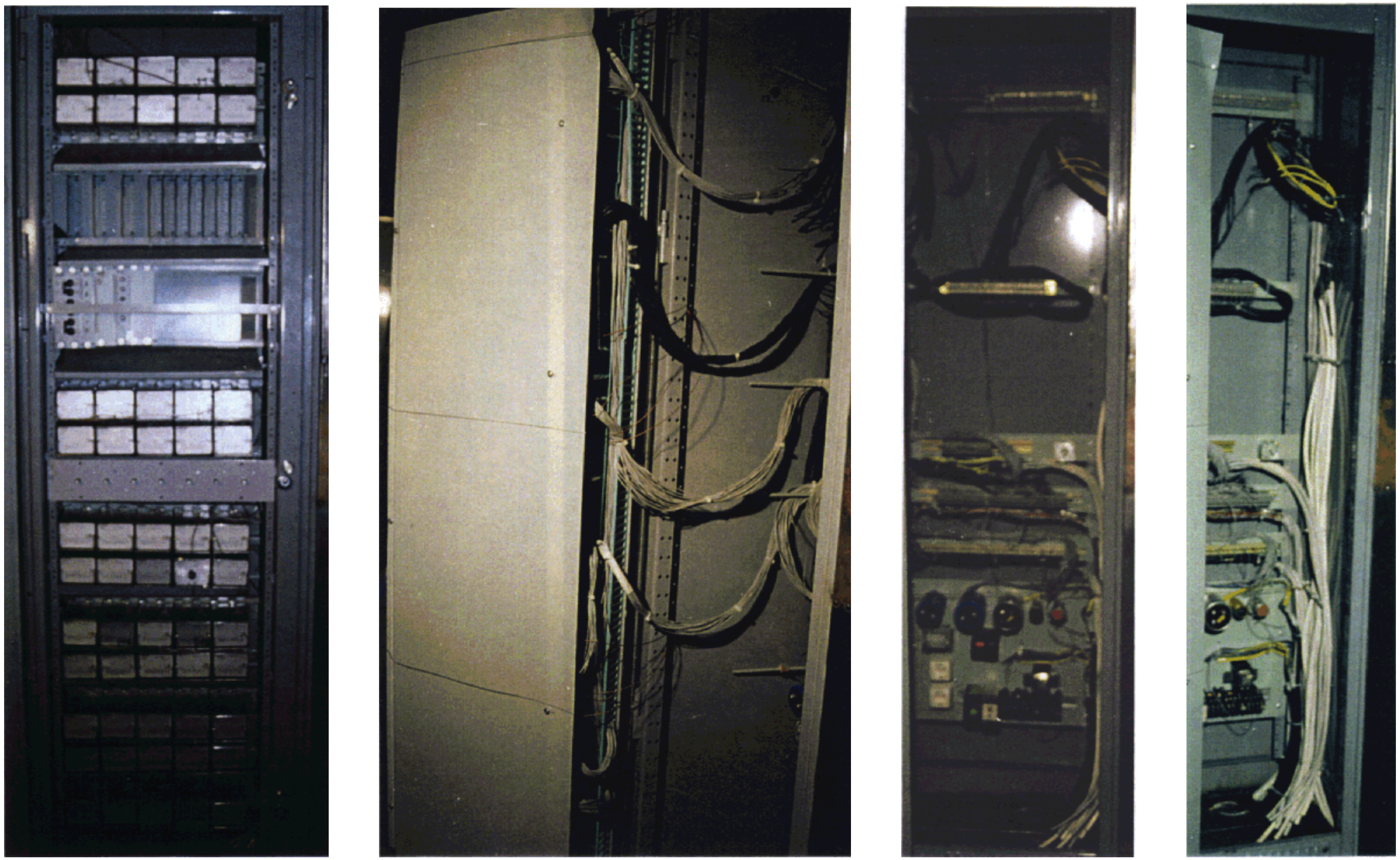
PHOTOGRAPHS FROM THE EXPERIMENTS



a) b) c) d)

Figure 1. The fire cabinet before experiment 1. A) relays and circuit boards in the hinged rack, b) wiring on the left side wall leading into the hinged rack with vertical steel plate separating the rack from the rest of the cabinet, c) wiring at the rear, d) vertical cablebundle on the right side wall. The hinged rack is swilled out from the cabinet in b), c) and d).

Figure 2. The fire cabinet after experiment 1. A) relays and circuit boards in the hinged rack, adjoining cabinet on the right, b) wiring on the left side wall, c) wiring on the rear, d) vertical cable bundle on the left side wall.

a) *b)* *c)*

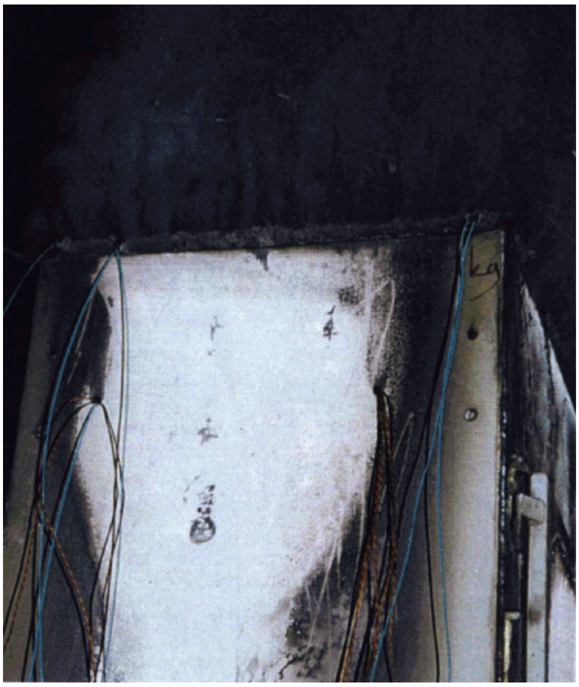
Figure 3. The fire cabinet before experiment 2. A) relays and circuit boards in the hinged rack, b) wiring on the left side wall leading to the relays in the hinged rack, c) wiring on the rear and vertical cable bundle on the left side wall.

a)

b)

c)

Figure 4. The fire cabinet after experiment 2. A) relays and circuit boards in the hinged rack, b) wiring on the left side wall leading to the relays in the hinged rack, c)wiring on the rear and vertical cable bundle on the left side wall.



a) *b)*

c)

Figure 5. Experiment 3. A)fire cabinet, time after ignition 29.5 min, b) fire cabinet with ceiling ventilation openings blocked with soot, time after ignition 46.5 min, c) 3 days after the experiment, soot in the upper part of the cabinet was ignited by sparks when cutting open the welding seams between the rack and the cabinet frame.

a) b) c)

Figure 6. The fire cabinet after experiment 3. a) relays and circuit boards in the hinged rack, b) wiring at the rear and vertical cable bundle on the left side of the wall, c) the slab composedof melted plastics on the bottom of the fire cabinet has been broken while emptying the cabinet. Note the soot depositions in the upper part of the cabinet in a) and b).