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Experiments of Sprinkler Protected Ceiling/Floor Assemblies in a Basement Fire Scenario

IRC-RR-308

Su, J.Z.; Taber, B.C.; Leroux, P.; Bénichou, N.; Loughheed, G.D.; Bwalya, A.C.

May 2011

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Research Report: IRC-RR-308

Date: May 13, 2011

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NRC INSTITUTE FOR RESEARCH IN CONSTRUCTION
Fire Research Program

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EXECUTIVE SUMMARY

The effectiveness of using a single residential sprinkler to protect exposed ceiling/floor assemblies and to provide tenable conditions for occupant evacuation was investigated in full-scale fire experiments simulating basement fire scenarios. This report documents additional experiments that were conducted to test the limitations of the residential sprinkler system with more challenging fires, compared to the primary experiments that are documented in RR-307.

In Phase 1B of the Fire Performance of Houses research project, the residential sprinkler system had been proved to be very effective in suppressing the fire, protecting the exposed ceiling/floor assemblies as egress routes and maintaining tenable conditions in the test house. (The ceiling/floor assemblies above the basement fire room had no finished ceiling – they were exposed in the fire room.) Among the protection measures studied in Phase 1B, the sprinkler protection was the only measure that provided both the structural protection and the tenable conditions for the safety of occupants. Because of this, the sprinkler protection measure was investigated further in the full-scale experiments using more stringent fire scenarios, to which other protection systems were not subjected, in order to test the limitations of the residential sprinkler system. The further investigation involved two challenging fire scenarios.

The first fire scenario involved a more challenging fire location, compared to the experiments conducted in Phase 1 and Phase 1B. The fuel package was essentially the same as that used in Phase 1 and Phase 1B but was moved from the centre to the southeast corner of the fire room, which was at the edges of the sprinkler coverage. The residential sprinkler system successfully controlled the fire, effectively protected the structural integrity of the metal-web wood truss assembly and maintained tenable conditions in the test house. The experiment demonstrated that single-sprinkler arrangement was an effective protection measure to protect the structural integrity of the test assembly and maintain tenable conditions in the test house.

The second fire scenario involved both the more challenging fire location (in the southeast corner of the fire room; at the edges of the sprinkler coverage) and a much more aggressive fire. To test the limit of the residential sprinkler system, a deep-seated test fire was used and two litres of methyl hydrate was used to ignite the stacked large wood cribs of 1.5-m high. This arrangement of the fuel package and ignition source produced a severe fire with an ultra fast growth rate. It is recognized that the ultra-fast fire is an extreme case, which is not a commonly-occurring fire in residential settings and may represent a limited number of fire scenarios including a possible arson scenario. Since the water spray from the pendent sprinkler could not reach the ceiling space where the fire was developing, the exposed CPVC sprinkler piping installed in that space failed due to heat. This led to the interruption of the water spray, the full involvement of the room in fire, and eventually the collapse of the wood I-joint test assembly.

But even under such a scenario, fire events followed the chronological sequence seen in previous experiments: fire initiated and grew, smoke alarms activated, tenability limits were exceeded, and then structural failure of the test assembly occurred. The structural failure of the test assembly occurred after the untenable conditions were reached in the open spaces on the upper storeys. Untenable conditions were not reached, for the duration of the tests, in the second storey bedroom where the door to the bedroom was closed. Tenable conditions on the upper storeys lasted longer, the heat flux measured in the fire room was much lower, and the test assembly remained intact for a longer period of time than in previous non-sprinklered experiments where less severe fires had been used.

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EXPERIMENTS OF SPRINKLER PROTECTED CEILING/FLOOR ASSEMBLIES IN A BASEMENT FIRE SCENARIO

Joseph Z. Su, Bruce C. Taber, Patrice Leroux, Nouredine Bénichou, Gary D. Loughheed, Alex C. Bwalya

1 INTRODUCTION

National Research Council Canada's Institute for Research in Construction (NRC-IRC) is conducting a multiphase research project on the fire performance of houses (FPH) to study the impact of products and systems for use in the construction of single-family houses on life safety of occupants under fire conditions. Phase 1 of the FPH project had investigated the impacts of basement fires on unprotected floor assemblies above the basement and tenability conditions on upper storeys in a test facility representing a typical two-storey detached single-family house (referred to as the test house hereafter) [1-7].

After Phase 1, a further study (Phase 1B) was conducted to investigate the performance of protected ceiling/floor assemblies under a basement fire scenario and the impact of the protection measures on the tenability conditions for occupants on the upper storeys [8]. Among different protection measures, residential sprinkler-protected ceiling/floor assemblies were studied in full-scale fire experiments. For the experiments with sprinkler-protected assemblies, the residential sprinkler systems effectively suppressed the fire and protected the structural integrity of the test assemblies. No ignition, structural failure or damage occurred with the sprinkler-protected test assemblies; tenable conditions were maintained in the test house during the sprinklered primary experiments.

Since the sprinkler was the only protection measure that provided both the structural protection and the tenable conditions in Phase 1B, additional experiments were conducted using a single-sprinkler arrangement with a more challenging fuel package and/or fire location to test the limitations of the residential sprinkler system. Note that other protection systems were not subjected to the additional experiments with these stringent fire scenarios in the test program. This report documents these experiments.

2 EXPERIMENTAL FACILITY



Figure 1. The test facility.

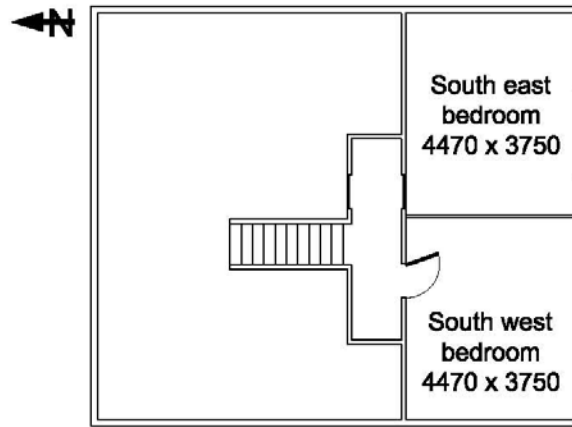
The experimental facility used represented a typical two-storey detached single-family house with a basement. Figure 1 and Figure 2 show an elevation view and a plan view, respectively, of the facility with basement, first storey and second storey. Each storey had a floor area of 95 m² and a ceiling height of 2.4 m. There was no heating, ventilating and air-conditioning or plumbing system installed in the test house, i.e., no associated mechanical openings.

The basement was partitioned to create a fire room representing a 27.6 m² basement living area (the remaining area was not used during the experiments). The walls of the fire room were lined with 12.7-mm-thick regular gypsum board. A rectangular exterior opening measuring 2.0 m wide x 0.5 m high and located 1.8 m above the floor was provided in the south wall of the fire room. The size of the opening is equivalent to the area of two typical basement windows (1.0 x 0.5 m). A removable noncombustible panel was used to cover the opening at the beginning of each experiment. The noncombustible panel was manually removed if and when the temperature at the centre of the opening reached 300°C, which would provide the ventilation for combustion and simulate the fire-induced breakage and complete fall-out of the window glass.

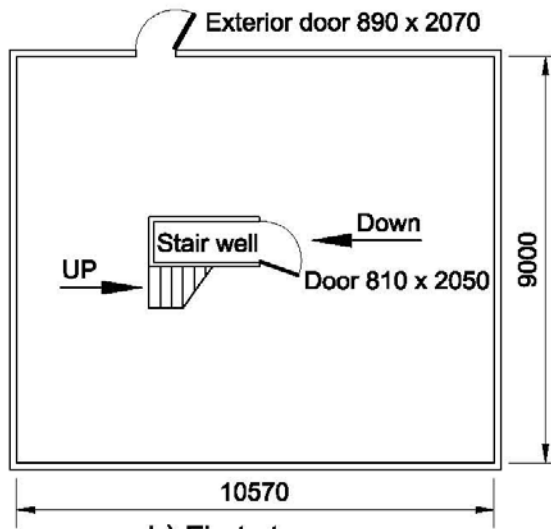
A 0.91-m-wide x 2.05-m-high doorway opening located on the north wall of the fire room led into an empty stairwell enclosure (without a staircase). At the top of this stairwell, a 0.81-m-wide x 2.05-m-high doorway led into the first storey. This doorway leading to the first storey had no door (open basement doorway) in this series of experiments (there is no requirement for a basement door in the National Building Code of Canada (NBCC) [9]).

The first storey had an open-plan layout. A test ceiling/floor assembly was constructed directly above the fire room for each experiment (more details are provided in Sections 4.2 - 4.9). The remainder of the floor on the first storey was constructed out of noncombustible materials. A 0.89-m-wide x 2.07-m-high doorway led to the exterior. The exterior door was initially in the closed position and was then opened at 180 s after ignition and left open to simulate occupants evacuating the test house. The staircase to the second storey was not enclosed. There were no window openings on the first storey.

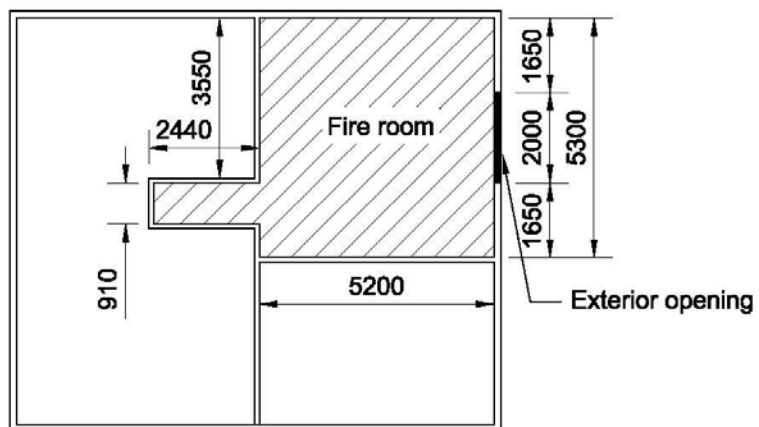
The second storey was partitioned to contain bedrooms, which were connected by a corridor (measuring 4.45 m long x 1.10 m wide). The experiments involved two target bedrooms of the same size. The door of the southeast bedroom was kept closed whereas the door on the southwest bedroom was kept open. Each bedroom doorway was 0.81 m wide x 2.05 m high. There were no window openings on the second storey.



a) Second storey



b) First storey



c) Basement

Figure 2. Facility plan view (all dimensions in mm).

2.1 Protected Ceiling/Floor Assemblies Used

Two test assemblies were used in the full-scale fire experiments: a metal-web wood truss assembly and a wood I-joist assembly, directly above the basement fire room. Both assemblies had no finished ceiling in the basement – they were exposed in the fire room. A single layer of oriented strandboard (OSB) was used for the subfloor of both assemblies without additional floor finishing materials.

The overall dimension of the wood I-joist assembly was 5250 mm x 5150 mm. The wood I-joists were 302 mm deep, with an OSB web of 9.5 mm thickness and flanges of laminated veneer lumber (32 mm x 59 mm). The wood I-joists were spaced at 400 mm on centre and spanned across the entire length of the fire room. Laminated strand lumber (LSL) rim boards (headers) 32 mm thick x 302 mm deep (grade 1.3E), were placed around the perimeter of the assembly.

The overall dimension of the metal-web wood truss assembly was 5079 mm x 5150 mm. The metal-web wood trusses were 302 mm deep, with chords of dimensions 38 mm x 64 mm. The metal webs (20 gauge) had teeth 9.5 mm long and had 0.0171 teeth per square millimeter. The trusses were spaced at 400 mm on centre. The bottom chords of the trusses were reinforced with 2 strongbacks 38 mm x 140 mm located toward the centre of the span. Rim boards (headers) 9.5 mm thick x 302 mm deep, were placed around the assembly. In addition, a solid wood 38 mm x 89 mm x 5150 mm member as part of the header was added at the top ends of the trusses to provide lateral support.

These two test assemblies were reused in these experiments after they had already survived previous fire experiments, which are documented in another report [8]. More specific details on the design and construction of the test assemblies are also provided in that report [8].

2.2 Sprinkler Design

The residential sprinkler system was the same single-sprinkler arrangement in the fire room as in the Phase 1B primary Tests PF-03B and PF-06 [8]. A Reliable F1 Residential 49° pendent sprinkler, which had a K factor of 4.9 and a temperature rating of 68°C (155°F), was located 3.05 m (10 ft) from both the south and east walls of the fire room. The deflector of the sprinkler was approximately 25.4 mm (1") below the bottom of the I-joist or truss and 330 mm (13") below the subfloor. The sprinkler and CPVC plastic piping (25.4 mm in diameter) were installed as per NFPA 13D and APA Technical Note J745 [10, 11]. The water supply had a static pressure of 3.45×10^5 Pa (50 psi). The residential sprinkler was set to operate at 1.4×10^5 Pa (20.2 psi) with an 83.2 Lpm (22 USgpm) flow rate.

2.3 Fuel Package

The fuel package consisted of a mock-up sofa constructed with approximately 9 kg of exposed polyurethane foam (PUF), the dominant combustible constituent of upholstered furniture, and approximately 190 kg of wood cribs beside and underneath the mock-up sofa.

* Certain commercial products are identified in this report in order to adequately specify the experimental procedure. In no case does such identification imply recommendations or endorsement by the National Research Council of Canada.

The mock-up sofa was constructed with 6 blocks of flexible polyurethane foam (with a density of 32.8 kg/m³) placed on a metal frame. Each block was 610 mm long x 610 mm wide and 100 mm or 150 mm thick. The 150-mm thick foam blocks were used for the backrest and the 100 mm thick foam blocks for the seat cushion. The PUF was used without any upholstery fabric that is used in typical upholstered furniture.

The wood cribs were made with spruce lumber pieces, each piece measuring 38 mm x 89 mm x 800 mm. Two small cribs were located under the mock-up sofa; four layers with six pieces per layer were used. Two large cribs were located beside the mock-up sofa; eight layers with six pieces per layer were used.

The composition of the fuel package was similar to the one used in Phase 1 of the FPH research [12, 13]. The two experiments documented in this report used different placements and arrangements of the fuel package. As well, placement and source of ignition were varied in the basement fire room for the two experiments. Detailed placements and arrangements of the fuel package and source of ignition are provided in the next sections. The fuel quantity used in each experiment is listed in Table 1.

Table 1. Fuel Quantities in Experiments (kg).

Test	Foam	Large Crib 1	Large Crib 2	Small Crib 1 + Small Crib 2	Moisture Content of the Cribs
PF-06B (June. 24, 2010)	9.38	63.8	67.3	65.1	8%
PF-03C (Nov. 19, 2009)	9.39	124.8		63.7	6%

3 EXPERIMENTS AND RESULTS

More specific details on the design and construction of the test assemblies, instrumentation, experimental procedure and methodology for tenability analysis are documented in a separate report [8]. This section provides details of the fuel package arrangement and source of ignition, the results of measurements and data analysis of the experiments.

3.1 Experiment with Metal-Web Wood Truss Assembly – Test PF-06B

In Phase 1B, a primary fire experiment (Test PF-06) was conducted using a metal-web wood truss assembly with sprinkler protection [8]. During the primary fire experiment, the residential sprinkler system successfully suppressed the fire, protected the structural integrity of the test assembly, and maintained tenable conditions in the test house.

After this primary experiment, the metal-web wood truss assembly was structurally sound and the CPVC sprinkler piping system was intact. A secondary Test PF-06B was conducted using the same assembly and the same single-sprinkler system, but the fuel package was placed at a more challenging location to test the limitations of the residential sprinkler system.

3.1.1 Fuel Package Arrangement in Test PF-06B with Metal-Web Wood Truss Assembly

The fuel package was placed in the southeast corner of the fire room. This was a more challenging location, compared to the fire location used in Phase 1 and Phase 1B experiments. Figure 3 illustrates the placement of the fuel package in the basement fire room in Test PF-06B. Figure 4 and Figure 5 show relative locations of the fuel package, trusses and sprinkler in Test PF-06B. One large wood crib was located in the southeast corner (350 mm from the south wall and 180 mm from the east wall). The mock-up sofa with two small wood cribs underneath was located along the east wall (180 mm from the east wall, 200 mm from the corner crib). The other large wood crib was located 500 mm in front of the mock-up sofa. The mock-up sofa was ignited using a gas burner in accordance with the ASTM 1537 test protocol [14].

This fuel package was essentially the same as that used in Phase 1 and Phase 1B [7, 8] but was moved from the centre to the southeast corner of the fire room (the sofa orientation was rotated 180° to face the room) in order to test the limit of the residential sprinkler system.

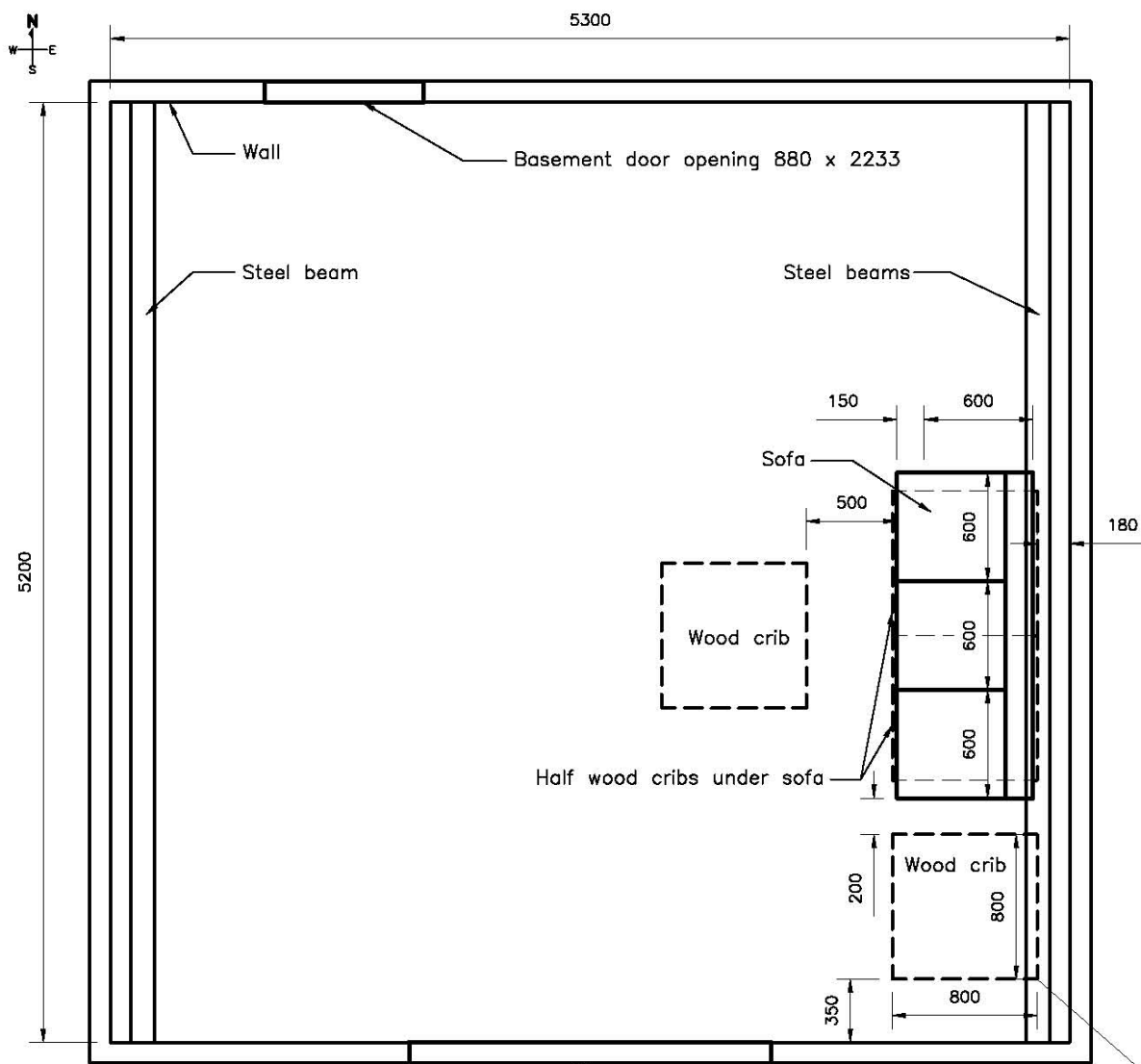
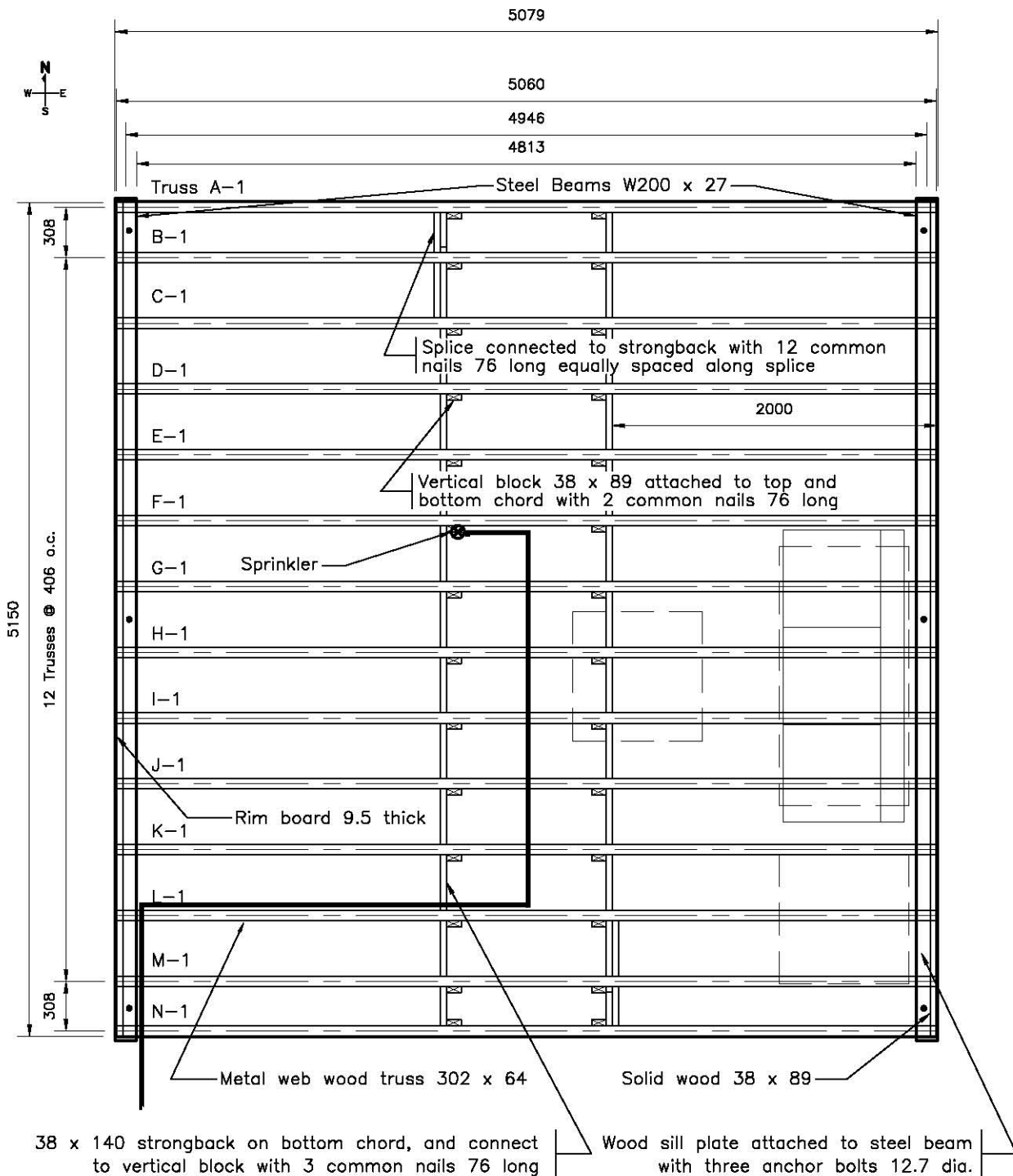


Figure 3. Layout of the fuel package in Test PF-06B (all dimensions in mm).



Note: Truss A-1 and N-1 shall be sheathed with 9.5 thick OSB rim board header nailed at 150 o.c. with 8d common nails

Figure 4. Metal-web wood truss assembly and relative locations for sprinkler and fuel package in Test PF-06B (all dimensions in mm).



Figure 5. Layout of the fuel package in Test PF-06B.

3.1.2 Fire Development in Basement

Figure 6 shows the temperature measured beside the sprinkler in the basement fire room after the mock-up sofa was ignited. The sprinkler was activated by the heat at 115 s and quickly controlled the fire. At 210 s and afterward, based on observation and video records, small visible flame was limited to two of the three foam blocks that were used as the backrest of the mock-up sofa. The sprinkler discharge continued for 1800 s (30 min).

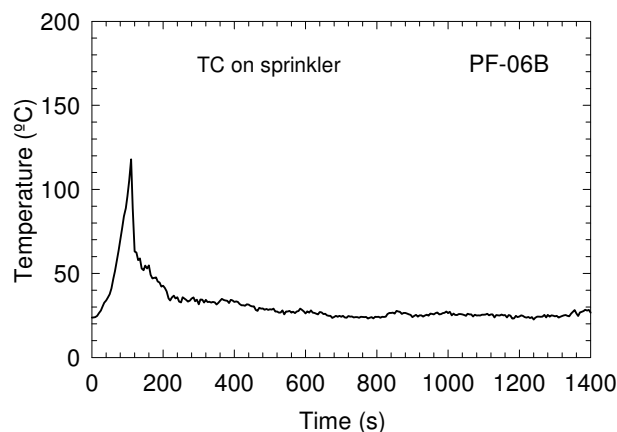


Figure 6. Temperature beside sprinkler in the basement fire room in Test PF-06B.

Figure 7 shows the temperature profiles measured in the basement fire room. Prior to sprinkler activation, the peak temperatures at the 2.4 m height were 69°C at the NW quadrant, 74°C at the NE quadrant, 87°C at the SW quadrant, and 158°C at the SE quadrant. The peak temperatures at the window were 234°C. Upon sprinkler activation, the temperatures in the fire room quickly declined to almost as low as ambient temperature. Figure 7 also shows the heat flux measured at the west wall (near the centre, 2.05 m above the floor). The maximum heat flux was 1.2 kW·m⁻² prior to the sprinkler activation. The sprinkler discharge was able to control the fire and keep the temperature in the fire room close to the ambient level. Because the temperature at the window did not reach 300°C, the noncombustible window covering panel was not removed during the experiment.

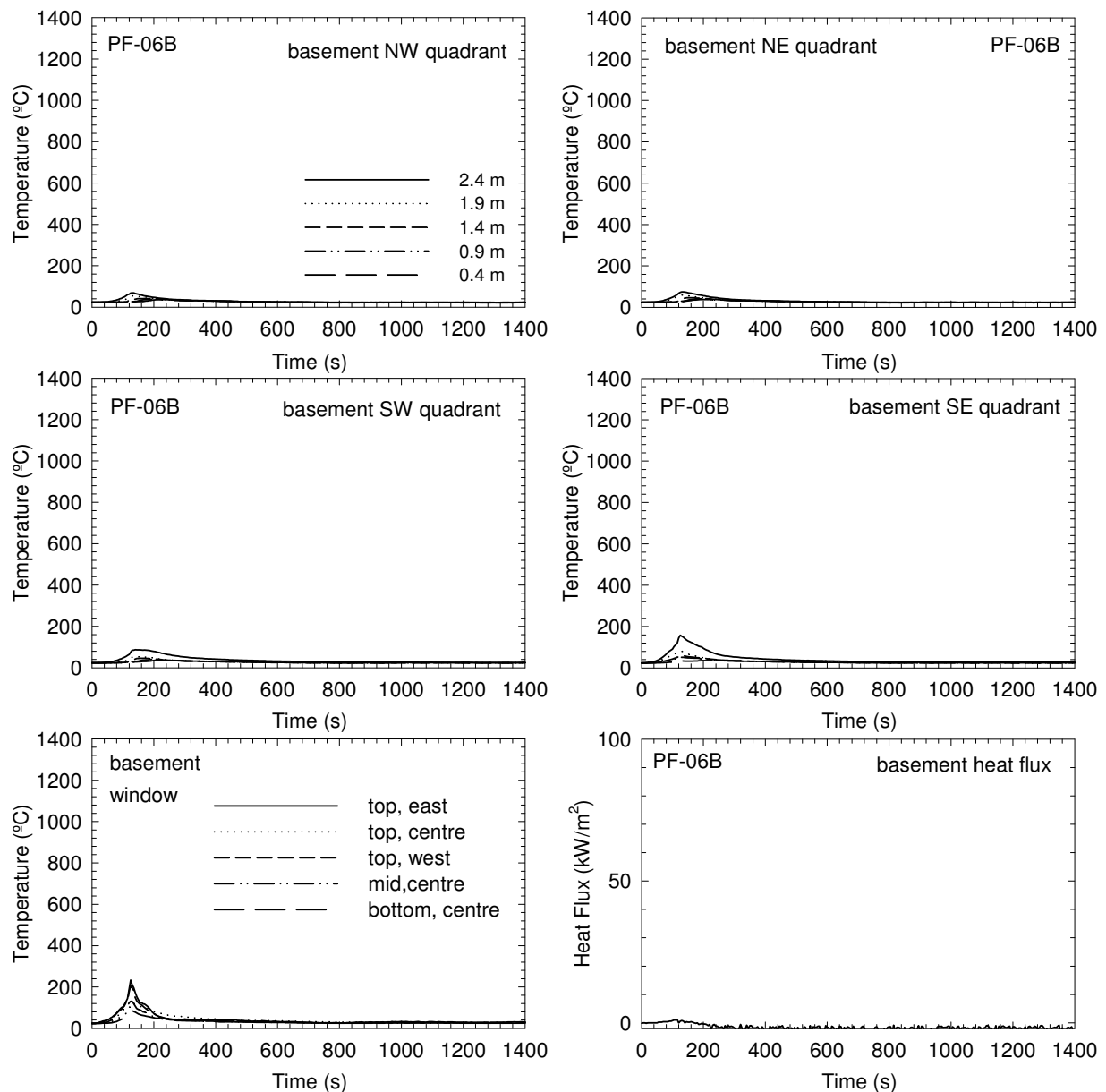


Figure 7. Temperatures and heat flux in the basement fire room in Test PF-06B.

3.1.3 Smoke Alarm Response

Table 2 shows the activation times of the smoke alarms installed in the test facility. There was significant delay for the smoke alarms in the second storey to activate, compared to the smoke alarm in the basement fire room.

Table 2. Smoke Alarm Activation Times (in seconds) after Ignition in Test PF-06B.

Location	Basement fire room	1 st storey		2 nd storey corridor		2 nd storey SW bedroom (door open)		2 nd storey SE bedroom (door closed)	
Smoke alarm type	P	I	P	I	P	I	P	I	P
Test PF-06B	75	100	110	185	185	240	na	na	na

Note:

1. I: Ionization P: Photoelectric na: no activation.

3.1.4 Visual Obscuration

The optical density was measured at 0.9 and 1.5 m heights (simulating the height of the nose/mouth of an average height individual crawling and standing, respectively) above the floor on the first and second storeys. Figure 8 shows the optical density-time profiles; OD remained under 0.15 m^{-1} throughout the upper storeys during the experiment. At this smoke level, a normal person should still be able to see their surroundings.

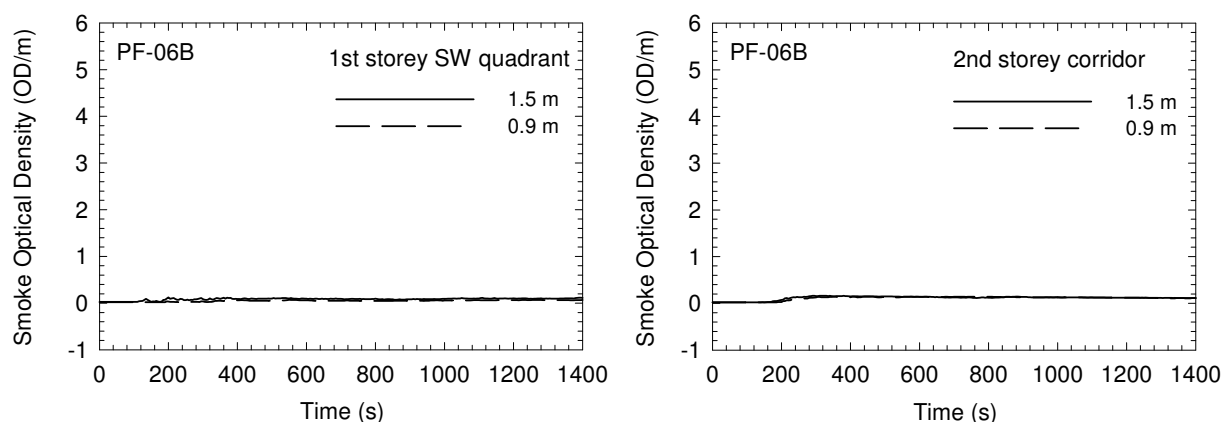


Figure 8. Smoke optical density measurements in Test PF-06B.

3.1.5 Gas Measurements and Analysis (CO, CO₂ and O₂)

Figure 9 shows the CO, CO₂ and O₂ concentration-time profiles measured at the southwest quarter point on the first storey and at the centre of the corridor on the second storey during the experiment. The oxygen concentrations remained above 20.5%. The CO₂ concentrations remained below 0.35%, and CO below 0.01%. These conditions would not cause incapacitation or any reduction in tenable conditions.

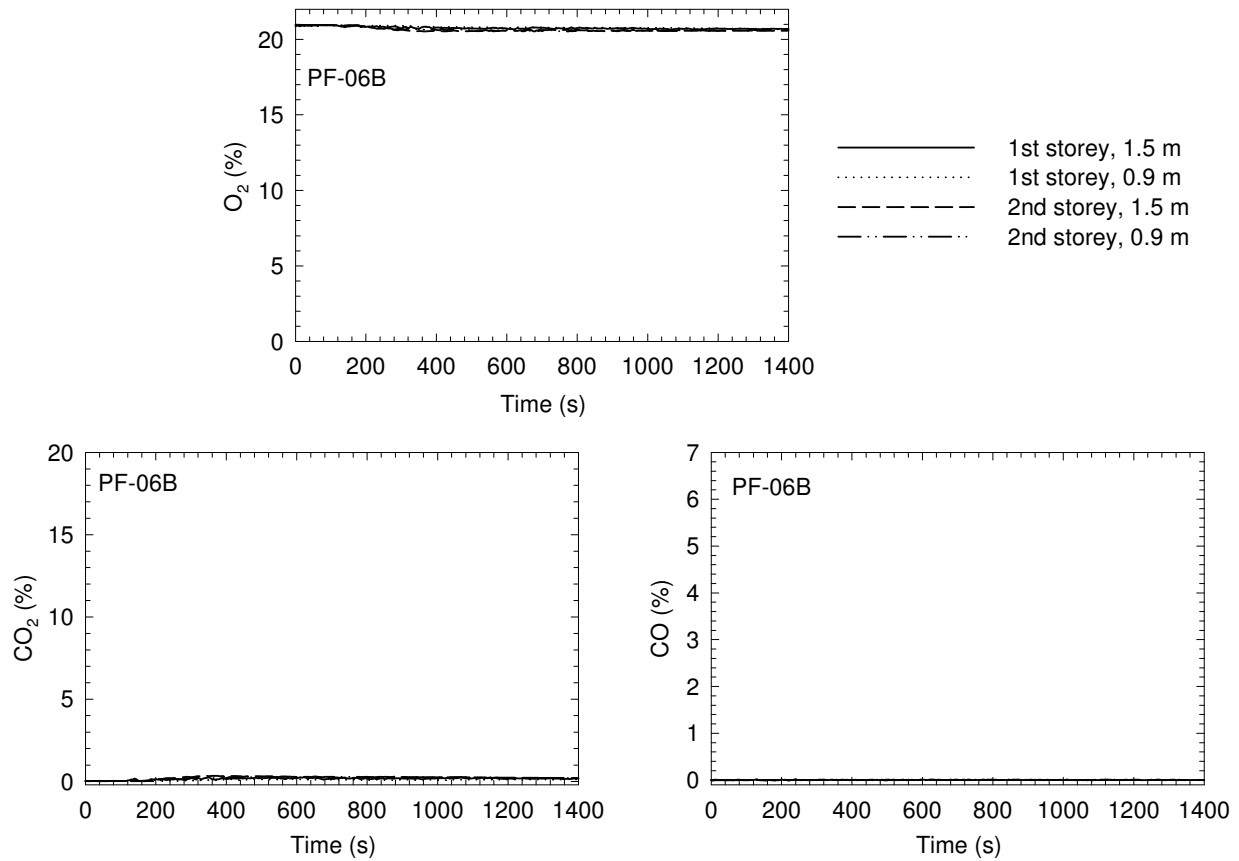


Figure 9. CO, CO₂ and O₂ concentrations in Test PF-06B.

3.1.6 Temperature-Time Profiles on the Upper Storeys

Figure 10 and Figure 11 show temperature profiles measured on the first and second storeys during the experiment. On the first storey, the maximum temperature of 53°C was measured at the doorway to the basement prior to the sprinkler activation; the maximum temperatures at the four quadrants were less than 37°C. Upon sprinkler activation, the temperatures on the first storey quickly reduced to the ambient temperature. On the second storey, there was only a 2°C temperature rise throughout the experiment. These conditions would not cause incapacitation or any reduction in tenable conditions.

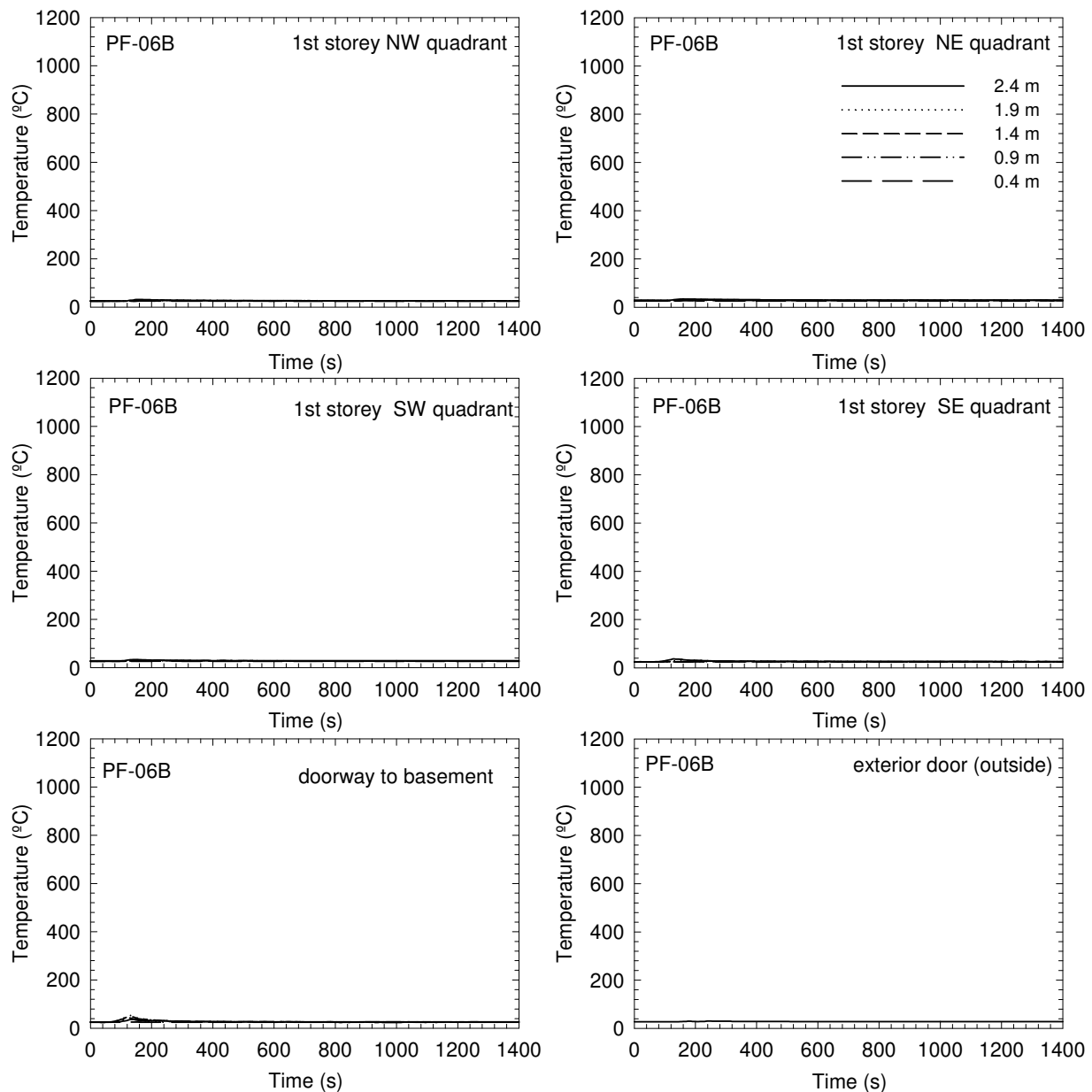


Figure 10. Temperatures on the first storey in Test PF-06B.

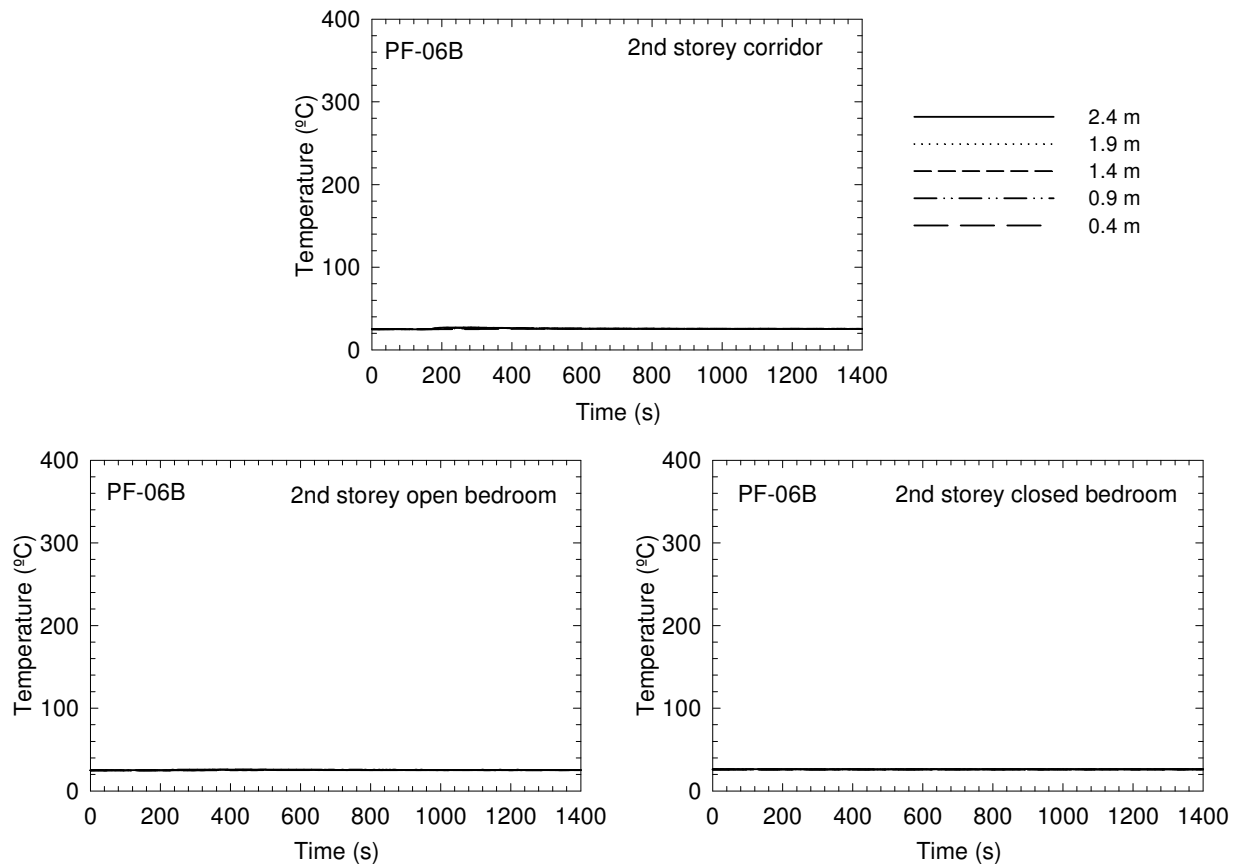


Figure 11. Temperatures on the second storey in Test PF-06B.

3.1.7 Performance of Test Assembly

A floor system provides an egress route for occupants and its structural integrity directly impacts their ability to evacuate safely from the house during a fire emergency. During the fire experiment, the conditions of the test assembly were monitored.

The ceiling/floor assembly was instrumented with sixty-one Type K (20-gauge) chromel-alumel thermocouples to measure temperatures on the unexposed side and in the exposed cavities of the assembly, as shown in Figure 12 and Figure 13.

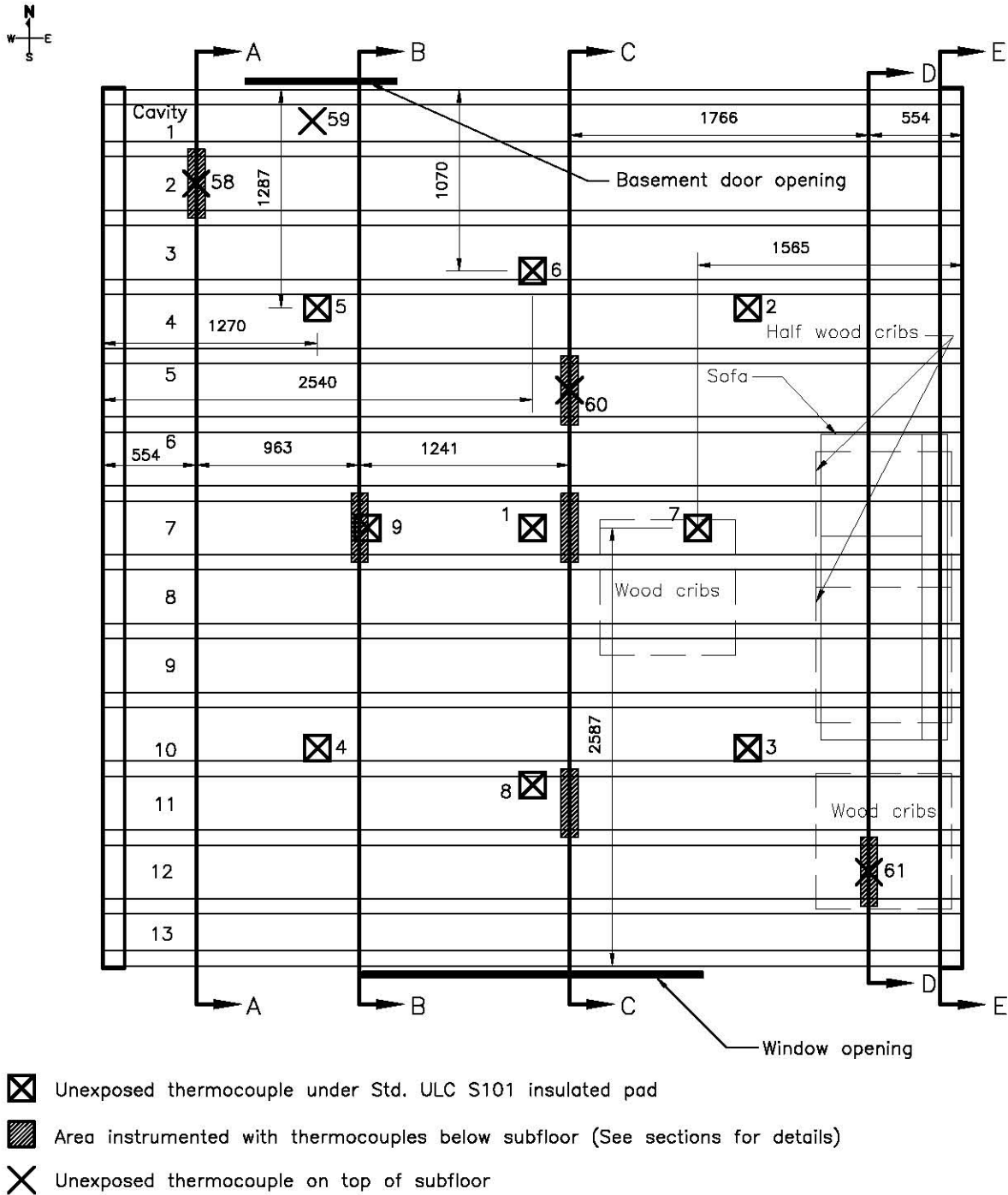
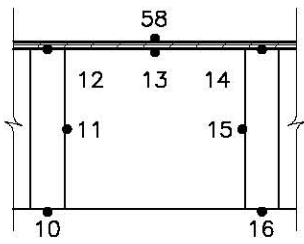
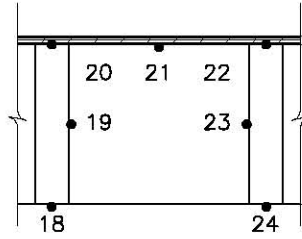


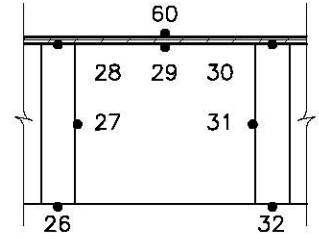
Figure 12. Thermocouples locations in the test assembly (Test PF-06B, all dimensions in mm).



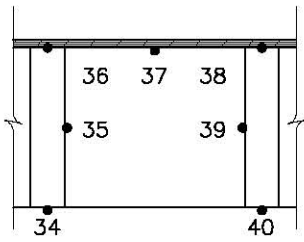
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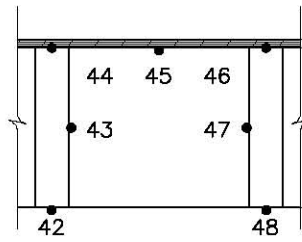
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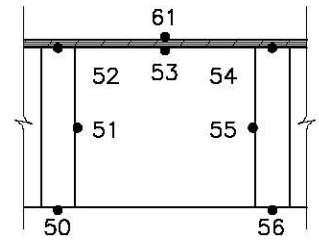
Section C-5



Section C-7



Section C-11



Section D-12

Figure 13. Thermocouples installed in the sections shown in Figure 12 (Test PF-06B).

Figure 14 shows temperatures in the cavities of the test assembly. The thermocouples installed in the six sections of the floor cavities aimed to monitor the temperatures in the cavities and provide an indication of the effectiveness of sprinkler protection for the test assembly. Depending on the position, the maximum temperatures in the floor cavities were in the range of 55–228°C prior to the sprinkler activation. Upon sprinkler activation, the temperatures in the floor cavities quickly reduced to the ambient temperature.

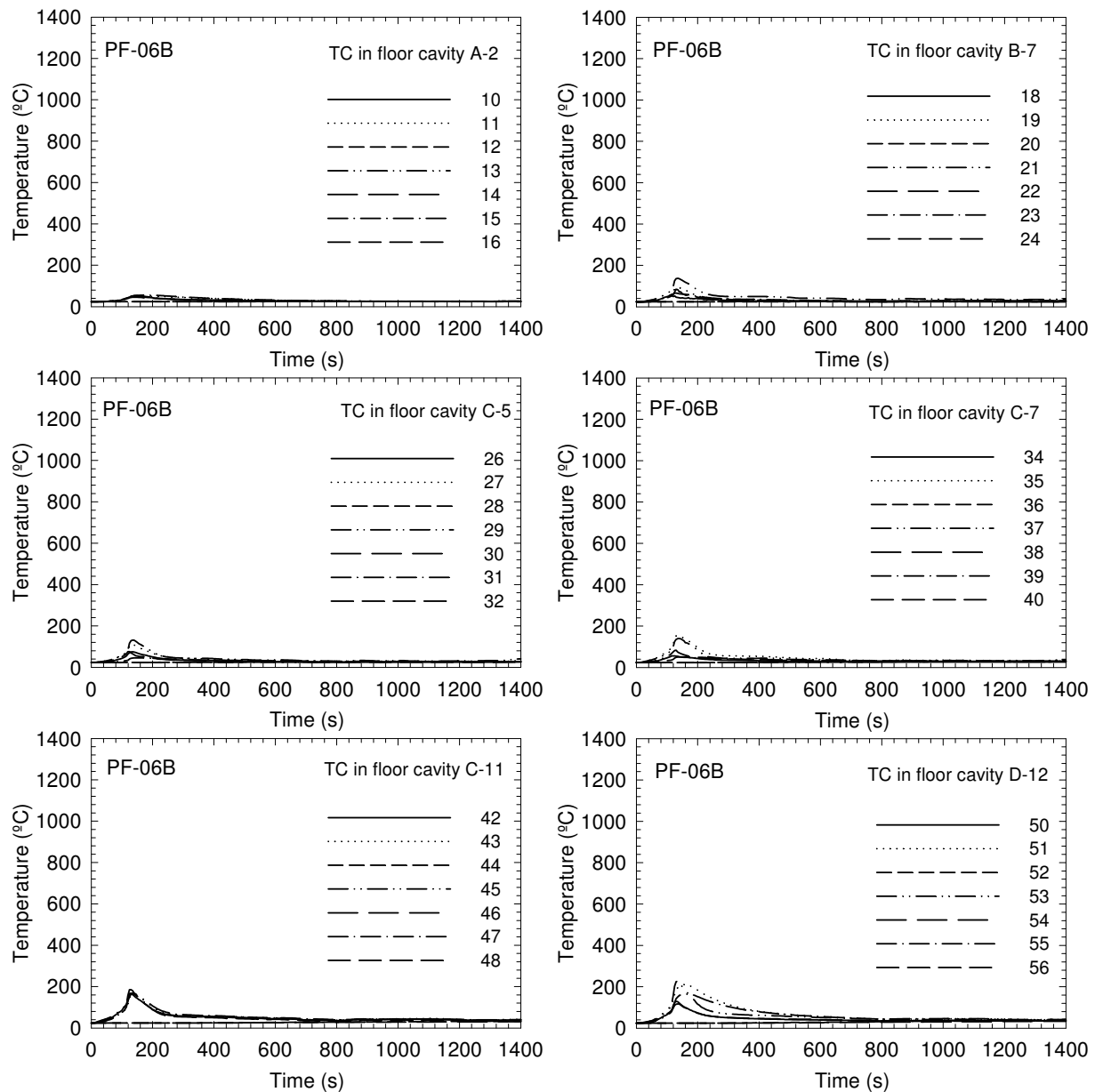


Figure 14. Temperatures in floor cavities in Test PF-06B.

Figure 15 shows results of the measurements using thermocouples, flame-sensing devices and deflection devices on the unexposed side of the test assembly on the first storey. The temperature measurements by nine thermocouples under insulation pads on top of the subfloor (on the first storey) are consistent with the measurements in the standard fire-resistance test with respect to thermocouple type, installation and layout [15]. There were also four bare thermocouples installed on top of the subfloor. The increase in the temperatures measured on the unexposed side of the assembly was less than 15°C during the experiment.

The deflection of the test assembly was measured at nine points located in the central area of the test assembly. There was no deflection of the test assembly during the experiment. The flame-sensing device [16] at the central tongue-and-groove joint on the unexposed side of the OSB subfloor allowed for detection of flame penetration through the ceiling/floor assembly. There was no noticeable change in the voltage signal.

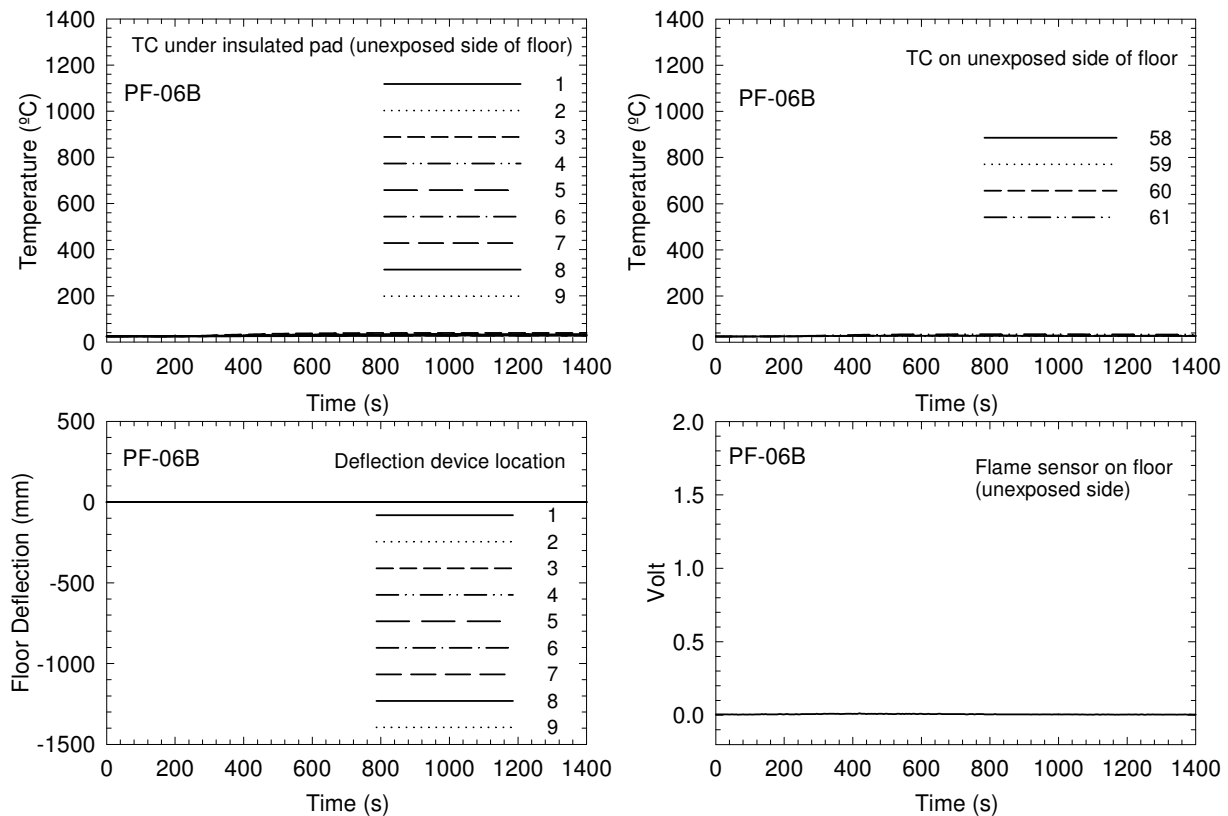


Figure 15. Temperatures, deflections and flame sensor voltage signal on the unexposed side of the test assembly on the first storey in Test PF-06B.

Visual observation after the experiment confirmed that, other than soot deposition from the burning of the fuel package, no ignition or damage occurred with the test assembly and the CPVC piping system.

3.1.8 Summary of Test PF-06B with Metal-Web Wood Truss Assembly

In Test PF-06B, the residential sprinkler system successfully controlled the fire that was located in the southeast corner of the fire room, which was a more challenging location than the centre of the fire room. The residential sprinkler system effectively protected the structural integrity of the metal-web wood truss assembly and maintained tenable conditions in the test house.

3.2 Experiment with Wood I-Joist Assembly – Test PF-03C

In Phase 1B, two fire experiments (Test PF-03 and Test PF-03B) were conducted using a wood I-joist assembly with sprinkler protection [8]. During these fire experiments, the residential sprinkler systems successfully suppressed the fire, protected the structural integrity of the test assembly, and maintained tenable conditions in the test house.

After these two experiments, the wood I-joist was structurally sound and the CPVC sprinkler piping systems were intact. A secondary Test PF-03C was conducted using the test assembly that had survived two previous fire experiments and the single-sprinkler system that had survived the previous fire experiment (Test PF-03B). But Test PF-03C used a much more aggressive fire to test the limitations of the residential sprinkler system.

3.2.1 Fuel Package Arrangement in Test PF-03C with Wood I-Joist Assembly

The components of the fuel package were the same as those used in Phase 1 and Phase 1B experiments. However, different placement and arrangement of the fuel package, and different placement and source of ignition were used in the basement fire room in Test PF-03C.

Figure 16 illustrates the placement and arrangement of the fuel package and ignition source in the basement fire room in Test PF-03C. Figure 17 and Figure 18 show relative locations of the fuel package, wood I-joists and sprinkler in Test PF-03C. The fuel package was located in the southeast corner of the fire room. The mock-up sofa with two small wood cribs underneath was located along the east wall (180 mm from the east wall). The two large wood cribs were stacked on top of each other in the southeast corner (1.42 m high, 150 mm from the mock-up sofa, 350 mm from the south wall and 180 mm from the east wall).

In the previous sprinklered fire experiments, with the fast response of the residential sprinkler system, the fire on the mock-up sofa was quickly suppressed and the large wood cribs were hardly involved in the fire. To test the limit of the residential sprinkler system, it was decided to use a deep-seated test fire by igniting the wood cribs directly in Test PF-03C. The ignition source was a 0.5-m square pan with 2 litres of methyl hydrate that was placed on the floor in-between the mock-up sofa and the stacked large wood cribs. The pan was partially (60% in area) under the stacked large cribs. The pan protruded out so as to ignite the edge of the sofa foam.

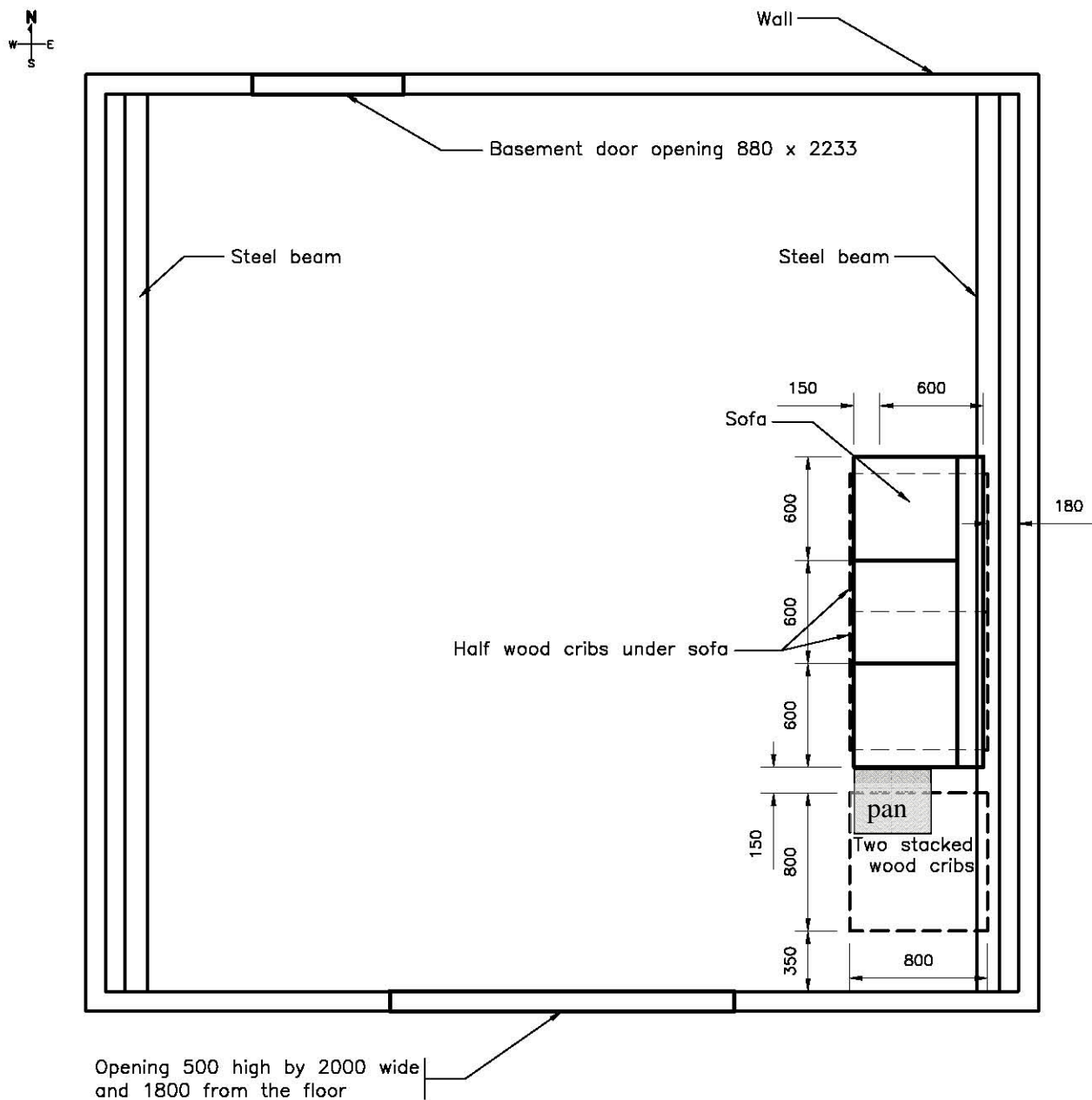


Figure 16. Layout of the fuel package in Test PF-03C (all dimensions in mm).

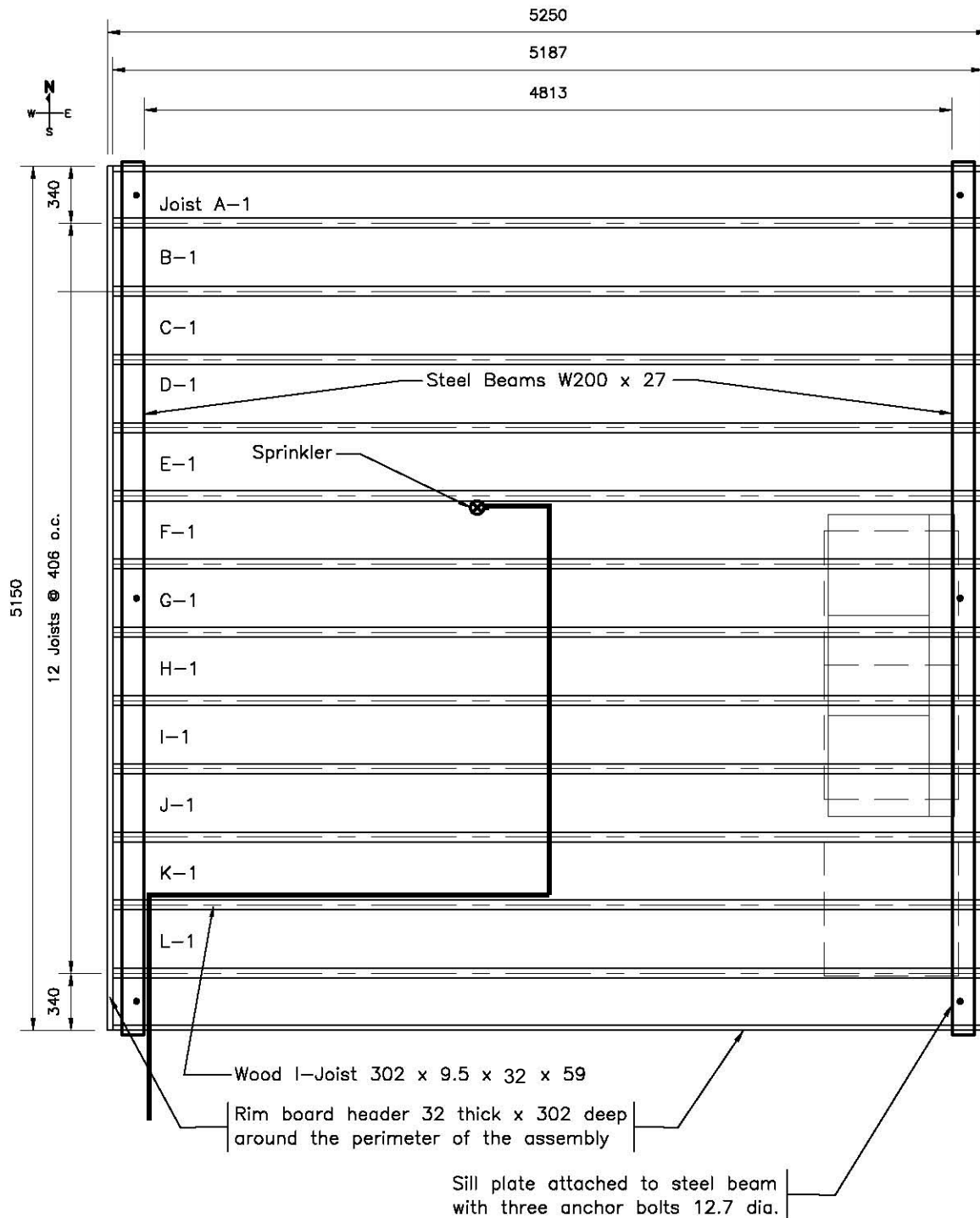


Figure 17. Sprinkler location related to wood I-joists and fuel package in Test PF-03C (all dimensions in mm).



Figure 18. Sprinkler and CPVC piping relative to exposed wood I-joists and fuel package in Test PF-03C.

3.2.2 Fire Development in Basement

The arrangement of the fuel package and ignition source produced a severe fire with an ultra-fast growth rate. Due to the increased height, the stacked wood cribs routed flame upward and resulted in a fire plume that quickly struck the assembly causing flames to spread along the channel between the two joists above the cribs. The flame reached a height of 2.4 m in 45 s from ignition. At 60 s, flame quickly spread along the channel created between the two I-joists J and K (see Figure 17) above the cribs.

Figure 19 shows the temperatures measured beside the sprinkler and on the wood cribs. Figure 20 shows the temperature profiles measured in the basement fire room.

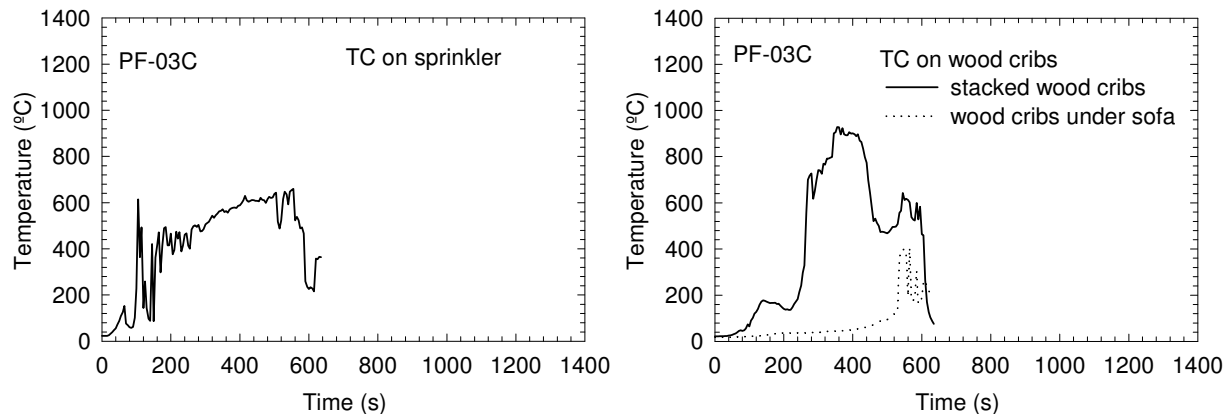


Figure 19. Temperatures on sprinkler and wood cribs in the fire room in Test PF-03C.

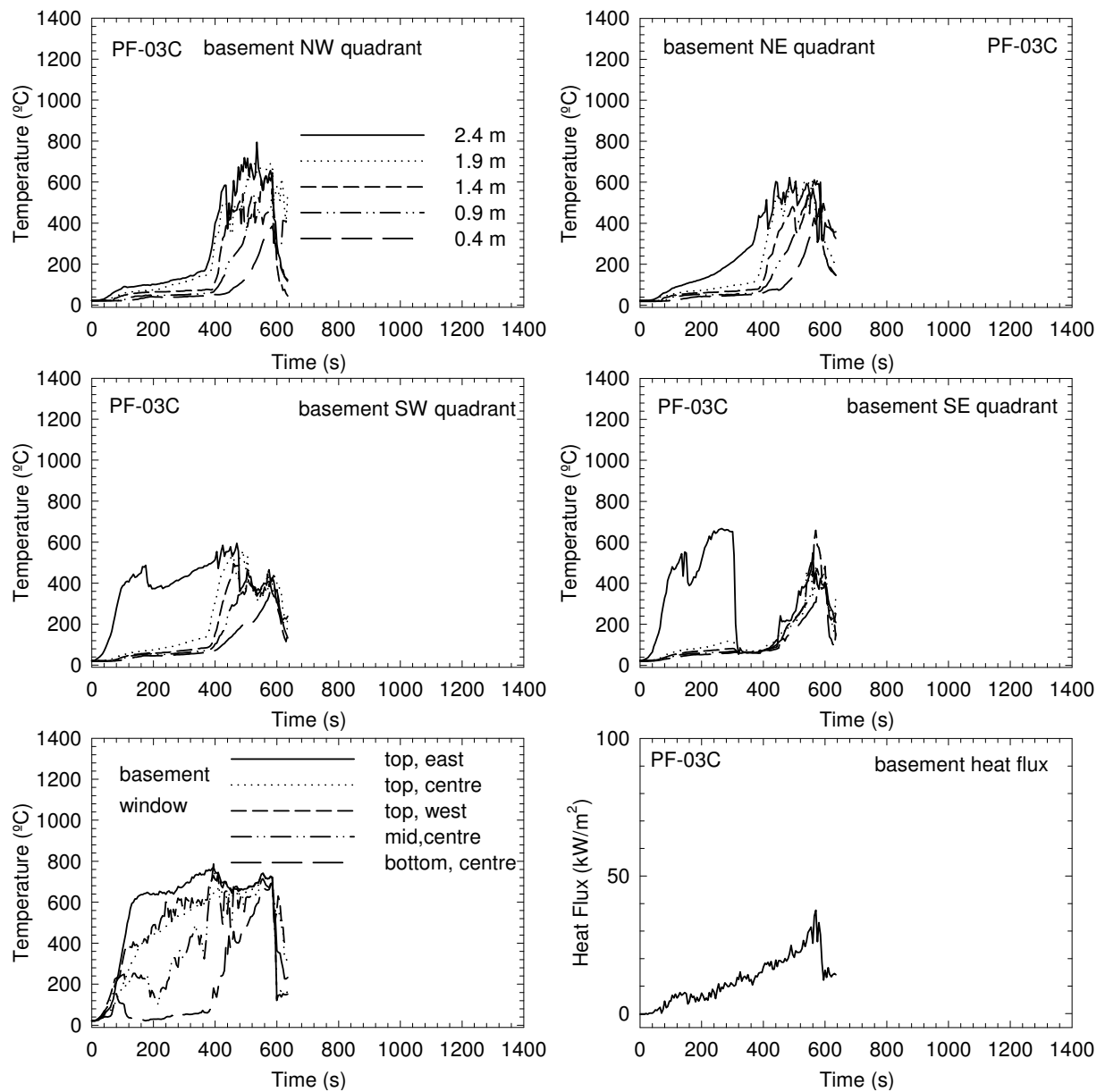


Figure 20. Temperatures and heat flux in the basement fire room in Test PF-03C.

The sprinkler activated at 70 s, kept the northern part of the fire room relatively cool but the water spray from the pendent sprinkler could not reach the ceiling space above the fuel package in the southern part of the room. The temperatures at the 2.4 m height in the southern part of the fire room exceeded 350°C within 90 s from ignition, which is the ignition temperature for wood. The temperatures at the top of the window reached 300°C at 100 s and the noncombustible window covering panel was removed to provide ventilation for combustion and to simulate the fire-induced breakage and complete fall-out of window glass.

At 366 s, it was observed that the exposed CPVC piping along I-joist K (see Figure 17) failed due to the heat at the ceiling, which resulted in the interruption of the water spray to the sprinkler. Then, the temperatures in the fire room increased quickly and exceeded 600°C, indicating flashover. Figure 20 also shows the heat flux measured at the west wall (near the centre, 2.05 m above the floor). The maximum heat flux was 38 kW•m⁻².

It is recognized that the ultra-fast fire used in Test PF-03C is an extreme case and may represent a limited number of fire scenarios including a possible arson scenario.

3.2.3 Smoke Alarm Response

Table 3 shows the activation times of the smoke alarms installed in the test facility. There was significant delay for the smoke alarms in the second storey to activate, compared to the smoke alarm in the basement fire room.

Table 3. Smoke Alarm Activation Times (in seconds) after Ignition in Test PF-03C.

Location	Basement fire room	1 st storey		2 nd storey corridor		2 nd storey SW bedroom (door open)		2 nd storey SE bedroom (door closed)	
Smoke alarm type	P	I	P	I	P	I	P	I	P
Test PF-03C	55	65	90	150	160	175	175	315	275

Notes:

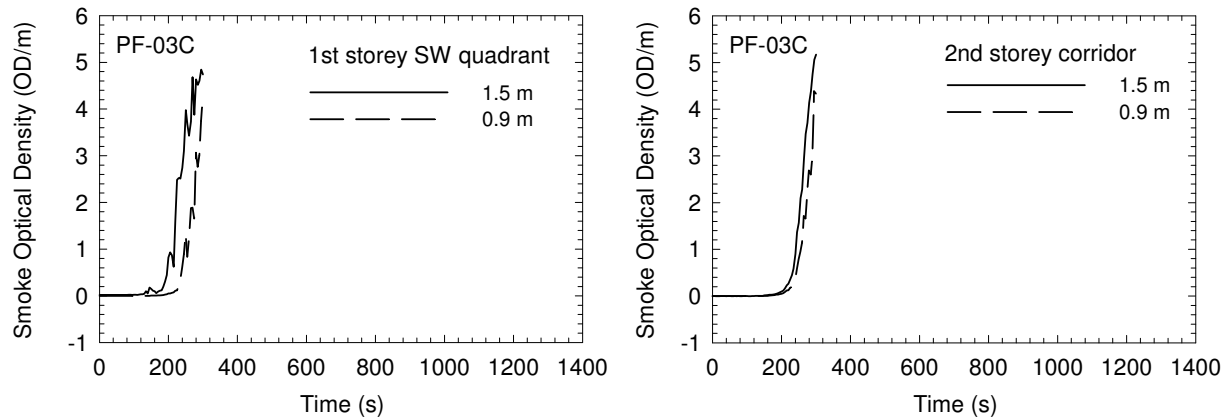
1. I: Ionization
2. P: Photoelectric.

3.2.4 Visual Obscuration

The optical density was measured at 0.9 and 1.5 m heights (simulating the height of the nose/mouth of an average-height individual crawling and standing, respectively) above the floor on the first and second storeys. Table 4 shows the times to reach OD = 2 m⁻¹, which are consistent with the video records, when visibility was lost. Figure 21 shows the optical density-time profiles.

Table 4. Time (in seconds) to the Smoke Optical Density Limit in Test PF-03C.

Test PF-03C	1 st storey SW quadrant	2 nd storey corridor
OD =	2 m⁻¹	2 m⁻¹
1.5 m above floor	225	255
0.9 m above floor	280	275

**Figure 21.** Smoke optical density measurements in Test PF-03C.

3.2.5 Gas Measurements and Analysis (CO, CO₂ and O₂)

Figure 22 shows the CO, CO₂ and O₂ concentration-time profiles measured at the southwest quarter point on the first storey and at the centre of the corridor on the second storey during the experiment. At 470 s, oxygen was diminished to below 10% and CO₂ increased to above 10%, which could cause incapacitation and lead to rapid loss of consciousness due to lack of oxygen alone or due to the CO₂ asphyxiant effect alone [17, 18]. The concentrations were below 5% O₂ and above 14% CO₂ near the end of the experiment. The tenability analysis indicated that the toxic effect of CO would be capable of causing incapacitation at an earlier time than the effect of O₂ vitiation and the asphyxiant effect of CO₂. The times to reach the specified Fractional Effective Dose (FED) for exposure to O₂ vitiation, CO₂ and CO are shown in Table 5.

Table 5. Time (in seconds) to the Specified FED for Exposure to O₂ Vitiation, CO₂ and CO in Test PF-03C.

Fractional Effective Dose	FED = 0.3	FED = 1.0
CO alone – 1 st storey	315	410
CO with CO ₂ hyperventilation – 1 st storey	290±20	355±25
Low O ₂ hypoxia – 1 st storey	500	570
CO alone – 2 nd storey corridor	355	445
CO with CO ₂ hyperventilation – 2 nd storey corridor	330±20	390±25
Low O ₂ hypoxia – 2 nd storey corridor	505	530
High CO ₂ hypercapnia – 1 st storey	485	515
High CO ₂ hypercapnia – 2 nd storey corridor	490	505

Note:

1. Values determined using concentrations at 1.5 m height.

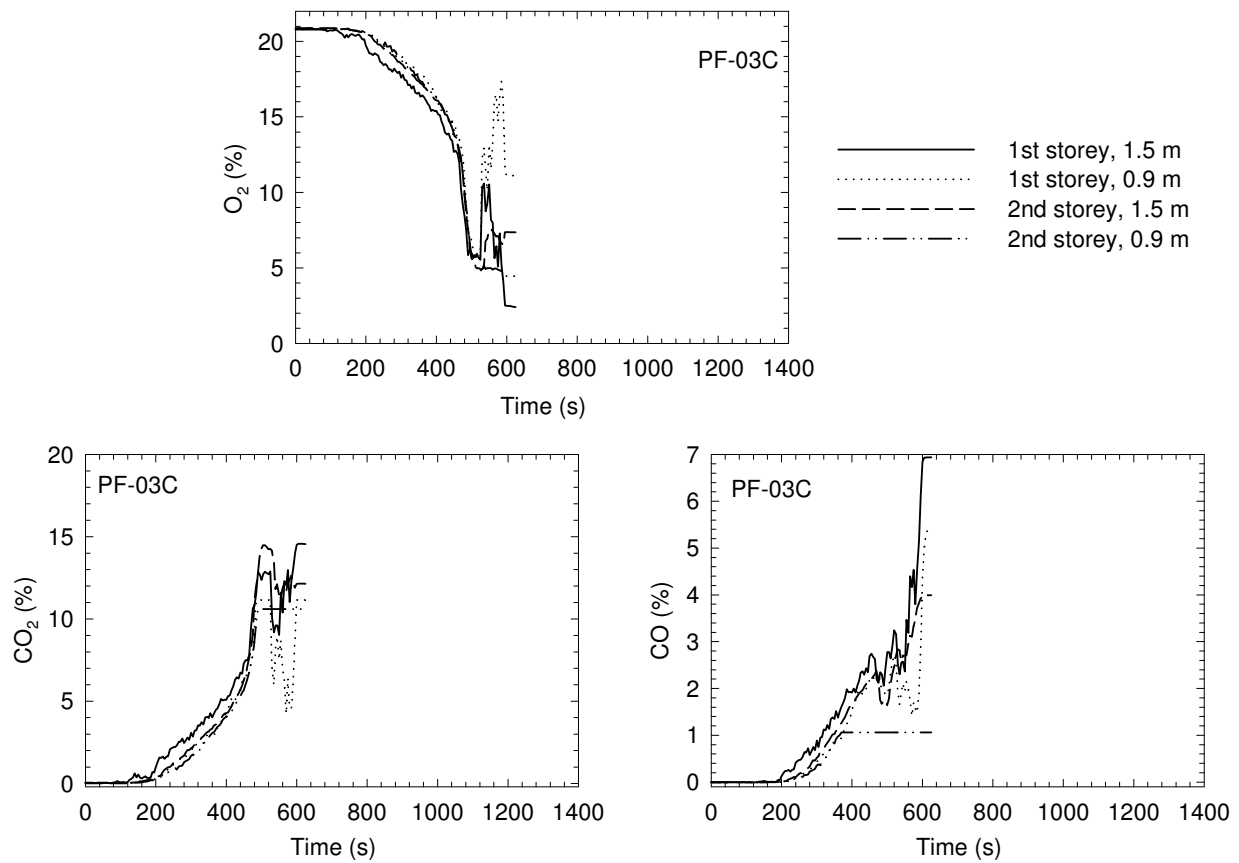


Figure 22. CO, CO₂ and O₂ concentrations in Test PF-03C.

3.2.6 Temperature-Time Profiles on the Upper Storeys

Figure 23 and Figure 24 show temperature profiles measured on the first and second storeys during the experiment. The temperatures did not show significant increase on the upper storeys until after the failure of the sprinkler CPVC piping. In the bedroom with the door closed, the temperatures never exceeded 80°C even at the ceiling height during the experiment.

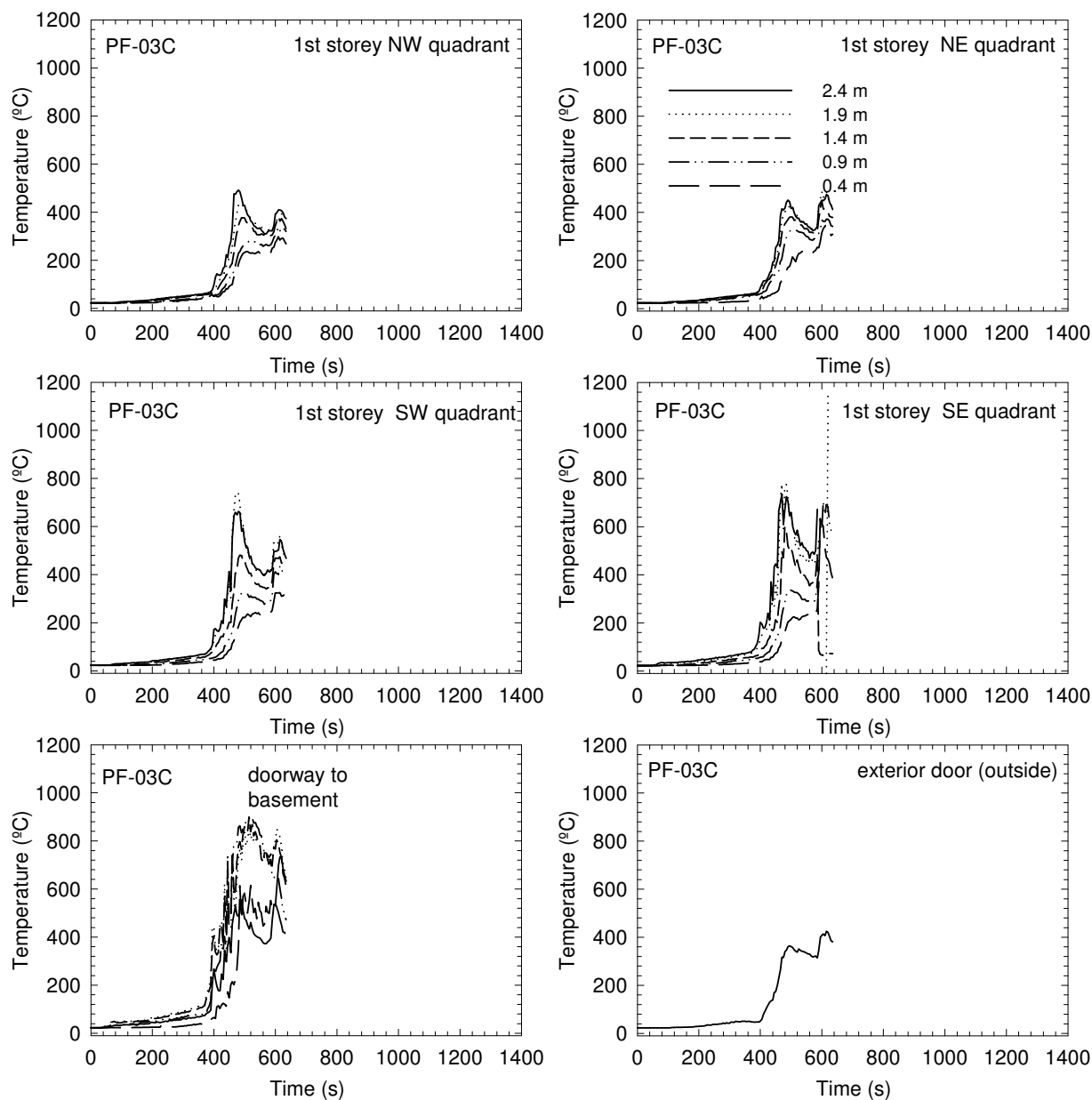


Figure 23. Temperatures on the first storey in Test PF-03C.

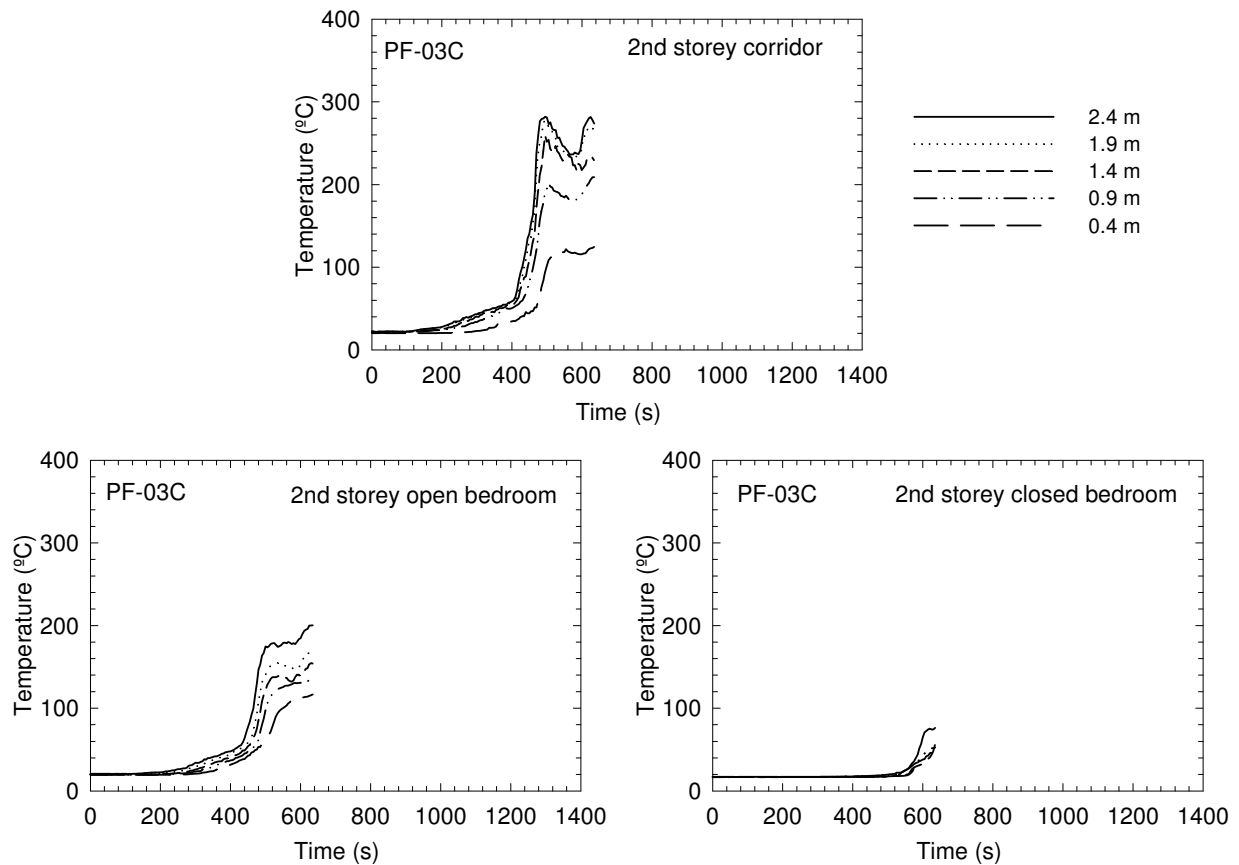


Figure 24. Temperatures on the second storey in Test PF-03C.

The convective heat exposure depended on the location in the test house. In the closed bedroom, heat exposure would not cause incapacitation. On the first storey and in the corridor and open bedroom on the second storey, the calculated times to incapacitation due to exposure to the convected heat are given in Table 6 for FED = 0.3 and 1. The calculated times to reach the heat incapacitation doses were longer than those for CO exposure; but the time difference for FED to change from 0.3 to 1.0 due to the heat exposure was shorter than that for CO exposure.

Table 6. Time (in seconds) to the Specified FED for Convected Heat in Test PF-03C.

Fractional Effective Dose	FED = 0.3	FED = 1.0
1 st storey SE quadrant	445	465
1 st storey SW quadrant	440±5	460±5
1 st storey NE quadrant	450	470
1 st storey NW quadrant	455	475
2 nd storey corridor	475	495
2 nd storey open bedroom	535	635*
2 nd storey closed bedroom	not reached (FED < 0.01)	not reached (FED < 0.01)

Notes:

1. Values determined using temperatures at 1.4 m height;
2. *after assembly collapse.

3.2.7 Estimation of Time to Incapacitation

Table 7 summarizes the results of tenability analysis with the estimated times to the onset of various conditions for Test PF-03C. Smoke obscuration was the first hazard to arise. The calculated time for reaching the specific FED either due to heat exposure or due to CO exposure (exacerbated by CO₂-induced hyperventilation), whichever occurred first, is listed in Table 7. In Test PF-03C, CO exposure reached the specific FED at times earlier than for heat exposure on both the first storey and the corridor of the second storey. Note that for the closed bedroom on the second storey, based on the temperatures and the heat exposure calculation, the conditions in the closed bedroom would not reach untenable conditions.

Table 7. Summary of Time to Specified FED and OD (in seconds) for Test PF-03C.

Test	OD = 2 m ⁻¹		FED = 0.3		FED = 1	
	1 st storey	2 nd storey	1 st storey	2 nd storey	1 st storey	2 nd storey
PF-03C	225±5	255±5	<i>290±20</i>	<i>330±20</i>	<i>355±25</i>	<i>390±25</i>

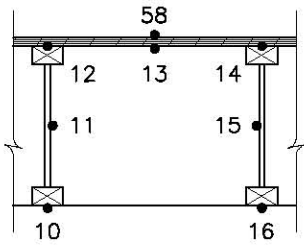
Notes:

1. Values determined using the measurements at 1.5 m height (for gas concentrations and OD) or 1.4 m height (for temperatures);
2. The number with the *Italic* font represents the calculated time for reaching the CO incapacitation dose, while the number in **bold** represents the calculated time for reaching the heat incapacitation dose, whichever occurred first.

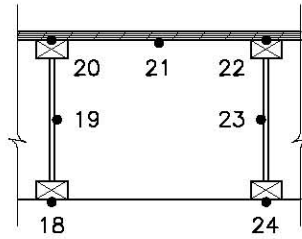
3.2.8 Performance of Test Assembly

A floor system provides an egress route for occupants and its structural integrity directly impacts their ability to evacuate safely from the house during a fire emergency. During the fire experiment, the conditions of the test assembly were monitored.

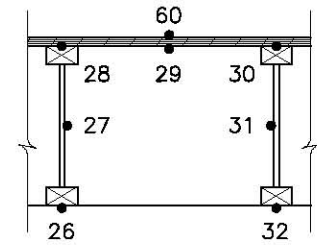
The test assembly was instrumented with sixty-one Type K (20-gauge) chromel-alumel thermocouples to measure temperatures on the unexposed side and in the exposed cavities of the assembly, as shown in Figure 25 and Figure 26.



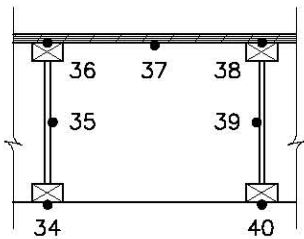
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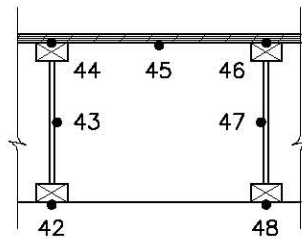
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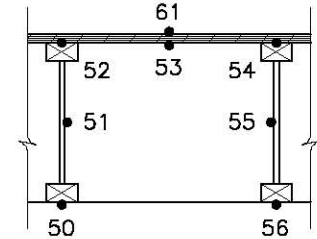
Section C-5



Section C-7



Section C-11



Section D-12

Figure 26. Thermocouples in the sections shown in Figure 25 (Test PF-03C).

Figure 27 shows temperatures in the cavities of the test assembly. The temperatures in the cavities provide an indication of the effectiveness of sprinkler protection for the test assembly. Prior to the sprinkler activation and depending on the position, the maximum temperatures were varied from 50–110°C in cavities A-2, B-7, C-5 and C7 but 350–400°C in cavities C-11 and D-12.

Cavity section C-11 was in the channel created between the two I-joists J and K (see Figure 17) along which the flame spread across the room ceiling, and cavity section D-12 was just above the fuel package. The temperature measurements at these locations indicate that the I-joists and OSB subfloor already started to burn before sprinkler activation. The water spray from the pendent sprinkler could not cover the space above it. The flames continued to spread in the ceiling space near the vicinity of the fire, and temperatures in cavities C-11 and D-12 exceeded 600°C at 120 s.

The sprinkler discharge kept other areas of the test assembly relatively cool until the sprinkler CPVC piping failed (at 366 s). The fire then began to involve the entire test assembly, and the temperatures reached 600–800°C toward the end of the experiment.

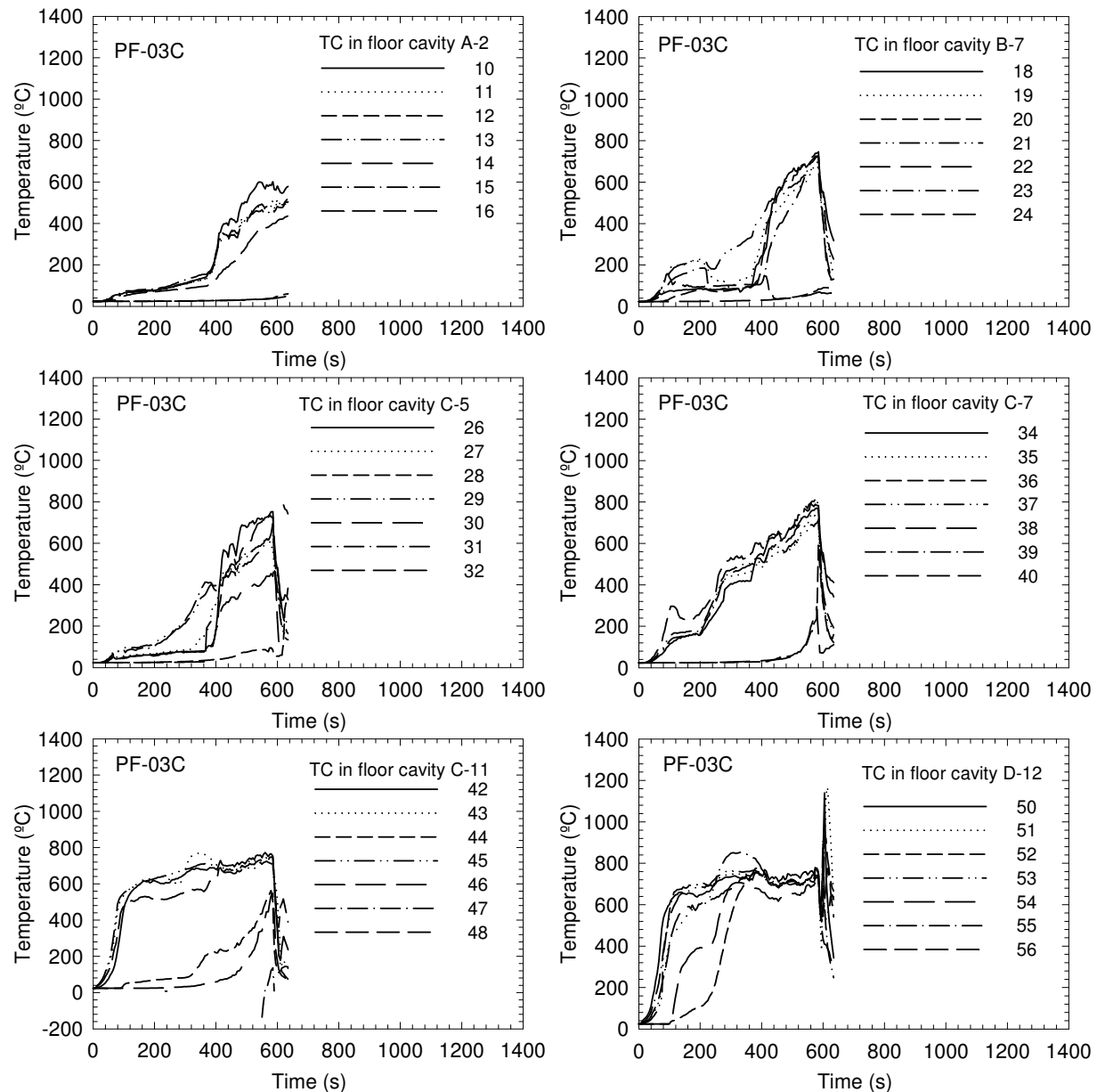


Figure 27. Temperatures in floor cavities in Test PF-03C.

Figure 28 shows results of the measurements using thermocouples, flame-sensing devices and deflection devices on the unexposed side of the test assembly on the first storey.

The temperatures measured by nine thermocouples under insulation pads on top of the subfloor (on the first storey) are consistent with the measurements in the standard fire-resistance test with respect to thermocouple type, installation and layout [15]. Floor failure under standard fire-resistance test conditions is defined as a temperature rise of 140°C on average of the nine padded thermocouples or a temperature rise of 180°C at any single point. Four bare thermocouples were also installed on the unexposed side of the test assembly for additional temperature measurements.

The deflection of the test assembly was measured at nine points located in the central area of the assembly. The deflections were recorded using an electro-mechanical method described in Reference [19]. The test assembly reached the maximum deflection capacity of the measurement devices at 570 s.

The flame-sensing device [16] at the central tongue-and-groove joint on the unexposed side of the OSB subfloor provided detection of flame penetration through the test assembly. A noticeable voltage signal was observed around 360 s and a large voltage spike was observed afterward, indicating that the device had been struck by flames that penetrated the test assembly along that joint. Flame penetration of the test assembly is also a failure criterion in standard fire-resistance testing [15].

All these measurements are consistent with the visual observations. The debris started falling at 540 s, some concrete blocks that were used to apply loading on top of the ceiling/floor assembly fell through the OSB subfloor at 565 s, and finally a total collapse of the test assembly occurred at 585 s.

Post-fire examination confirmed that the structural collapse of the test assembly was due mainly to structural member failure. The web materials of the wood I-joists were burned through; the test assembly broke at the mid-points of the I-joists and collapsed into the basement in the form of a “V” shape. The OSB subfloor in the southern part of the test assembly (the area above the fuel package and the fire channels) was also consumed by the fire.

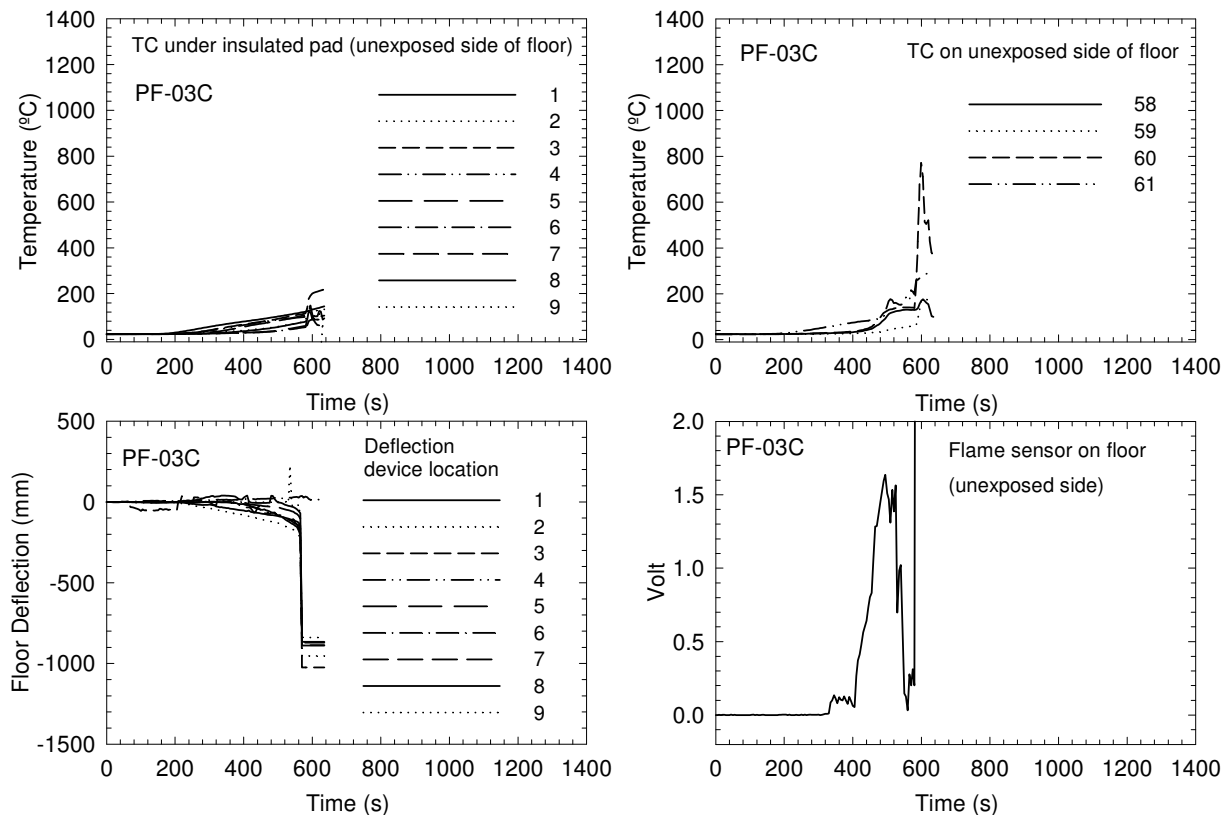


Figure 28. Temperatures, deflections and flame sensor voltage signal on the unexposed side of the test assembly on the first storey in Test PF-03C.

3.2.9 Sequence of Events

Table 8 summarizes the chronological sequence of the fire events in Test PF-03C — fire initiation, smoke alarm activation, sprinkler activation, onset of untenable conditions and structural failure of the test assembly. Smoke obscuration was the first hazard to arise. The incapacitation conditions were reached after smoke obscuration became a hazard. The structural failure of the test assembly occurred after the untenable conditions were reached. The fuel package arrangement in this experiment generated a severe fire with an ultra-fast growth rate, which is not a commonly-occurring fire scenario in residential settings.

For comparison purposes, Table 8 shows data from previous experiments using the same floor structure. Tests PF-03B and PF-03C used the same test assembly and residential sprinkler system. But in Test PF-03B [8], the fuel package was placed close to the centre of the fire room, the large wood cribs were not stacked and the mock-up sofa was ignited using a gas burner in accordance with the ASTM 1537 test protocol [14]. The residential sprinkler system was able to suppress the fire, untenable conditions were not created on the upper storeys, and there was no structural damage to the test assembly in Test PF-03B.

Table 8. Summary of Sequence of Events in Test PF-03C (in seconds).

Ceiling/Floor Assembly Type	Test	First Alarm	OD = 2 m ⁻¹	FED=0.3-1 1 st storey	FED=0.3-1 2 nd storey	Structural Failure
Sprinkler-protected wood I-joists	PF-03C*	55	225-255	<i>290-355</i>	<i>330-390</i>	585*
Sprinkler-protected wood I-joists	PF-03B	34	not reached	not reached	not reached	not reached

Notes:

1. Sprinkler activated at 70 s;
2. Values determined using the measurements at 1.5 m height (for gas concentrations and OD) or 1.4 m height (for temperatures);
3. The number with the *Italic* font represents the calculated time for reaching the CO incapacitation dose, while the number in **bold** represents the calculated time for reaching the heat incapacitation dose, whichever occurred first;
4. *Values of the structural failure time of the test assemblies determined by visual observation;
 - a. The maximum deflection capacity of the measurement devices reached at 570 s.

4 CONCLUSIONS

In Phase 1B of the FPH research project, the residential sprinkler system had been proved to be very effective in suppressing the fire, protecting the ceiling/floor assemblies as egress routes and maintaining tenable conditions in the test house. Among the protection measures studied in Phase 1B, the sprinkler protection was the only measure that provided both the structural protection and the tenable conditions for the safety of occupants. Because of this, the sprinkler protection measure was investigated further in the full-scale experiments using more stringent fire scenarios in order to test the limitations of the residential sprinkler system. The further investigation involved two challenging fire scenarios.

The first fire scenario involved a more challenging fire location, compared to the experiments conducted in Phase 1 and Phase 1B. The fuel package was essentially the same as that used in Phase 1 and Phase 1B but was moved from the centre to the southeast corner of the fire room, which was at the edges of the sprinkler coverage. The residential sprinkler system successfully controlled the fire, effectively protected the structural integrity of the metal-web wood truss assembly and maintained tenable conditions in the test house. The experiment demonstrated that a single-sprinkler arrangement was an effective protection measure to protect the structural integrity of the test assembly and maintain tenable conditions in the test house.

The second fire scenario involved both the more challenging fire location (in the southeast corner of the fire room; at the edges of the sprinkler coverage) and a much more aggressive fire. To test the limit of the residential sprinkler system, a deep-seated test fire was used and two litres of methyl hydrate was used to ignite the stacked large wood cribs of 1.5-m high. This arrangement of the fuel package and ignition source produced a severe fire with an ultra fast growth rate. It is recognized that the ultra-fast fire is an extreme case, which is not a commonly-occurring fire in residential settings and may represent a limited number of fire scenarios including a possible arson scenario. Since the water spray from the pendent sprinkler could not reach the ceiling space where the fire was developing, the exposed CPVC sprinkler piping installed in that space failed due to heat. This led to the interruption of the water spray, the full involvement of the room in fire, and eventually the collapse of the test assembly.

But even under such a scenario, fire events followed the chronological sequence seen in previous experiments: fire initiated and grew, smoke alarms activated, tenability limits were exceeded, and then structural failure of the test assembly occurred. The structural failure of the test assembly occurred after the untenable conditions were reached in the open spaces on the upper storeys. Untenable conditions were not reached, for the duration of the tests, in the second storey bedroom where the door to the bedroom was closed. Tenable conditions on the upper storeys lasted longer, the heat flux measured in the fire room was much lower, and the test assembly remained intact for a longer period of time than in previous non-sprinklered experiments where less severe fires had been used.

5 REFERENCES

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