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# Unprotected Floor Assemblies and Tenability Conditions in A Test House under Two Basement Fire Scenarios

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**Abstract.** A full-scale experimental program was undertaken to study the impact of two basement fire scenarios on the structural integrity of unprotected floor assemblies above a basement and the tenability conditions in a test facility representing a typical two-storey detached single-family house with a basement. The experiments utilized relatively severe, fast-growing fires set in the basement, which had an unprotected (unfinished) ceiling, to challenge the structural integrity of the floor system above the basement, which provides the normal egress route on the first storey for occupants. A range of floor assemblies constructed with various types of engineered floor joists and trusses (including wood I-joists, steel C-joists, metal plate wood trusses and metal web wood trusses) and with solid-wood joists, were used in the experiments with the basement side unprotected (unsheathed). Potential exposure to toxic gases, heat and smoke obscuration under the test conditions was analyzed to estimate the time available for escape. The results help establish the sequence of fire events such as fire initiation, smoke alarm activation, onset of untenable conditions, and structural failure of the floor assembly above the basement to understand how these factors affect the ability of occupants on the upper storeys to escape in the event of a basement fire.

**Key words:** *home fire safety, smoke alarms, tenability, engineered floor assemblies*

## 1. Introduction

The increasing use of innovative materials and construction products and systems in construction of houses has created a need to better understand their performance and their impact on life safety under fire conditions and to develop a technical basis for the evaluation of their fire performance. Some of this need regarding fire performance characteristics of engineered structural components was identified in a report by the National Fire Protection Research Foundation almost two decades ago [1]. Recently, Underwriters Laboratories completed an experimental study of engineered lumber in fire conditions with an emphasis on structural stability for firefighter safety [2].

This paper presents the results from a full-scale experimental program that was undertaken to study the fire performance of various engineered floor systems used in single-family houses. The study addressed the life safety of occupants from the perspective of tenability for occupants and structural integrity of structural elements as egress routes. The experimental program was conducted using a test facility representing a two-storey detached single-family house with a basement. It involved full-scale fire tests with unprotected floor assemblies located over the basement (unsheathed on the basement side) using two specific basement fire scenarios. Although a basement is not the most frequent origin of household fires, it is the fire location that is most likely to create the greatest challenge to the structural integrity of the first storey

structure, which typically provides the main egress routes. The objectives of the experimental program were to better understand the factors that impact on the ability of occupants on the upper storeys to escape in the event of a basement fire.

Although building codes in North America generally intend that major structural load-bearing elements (floors, walls and roofs) have sufficient fire resistance to limit the probability of premature failure or collapse during the time required for occupants to evacuate safely [3-6], these codes provide no specific guidance or criteria regarding the fire performance of structural systems for use in single-family houses. Because of this, the experimental program used a timeline approach to establish the key sequence of the fire events that affect the life safety and egress of occupants under two specific basement fire scenarios. This sequence included fire initiation, smoke alarm activation, onset of untenable conditions on upper storeys, and structural failure of the test floor assembly as a viable egress route on the first storey.

## **2. Experimental Setup and Procedure**

### **2.1. Facility**

A test facility was designed to represent a typical two-storey detached single-family house with a basement. The floor layout of the facility is shown in Figure 1. Each storey has a floor area of 95 m<sup>2</sup> and a ceiling height of 2.4 m. There were no openings that are normally associated with heating, ventilating and air-conditioning or plumbing systems in a house.

The basement was partitioned to create a fire room representing a 27.6 m<sup>2</sup> basement living area. This was the average size of basement compartments based on survey results [7]. The walls of the fire compartment were lined with 12.7 mm thick regular gypsum board. A rectangular exterior opening measuring 2.0 m wide by 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.

A 0.91 m wide by 2.05 m high doorway opening located on the north wall of the fire room led into a stairwell enclosure. At the top of this stairwell, a 0.81 m wide by 2.05 m high doorway led into the first storey. This doorway leading to the first storey either had a door in the closed position (closed basement doorway) or had no door (open basement doorway), depending on the scenario being studied.

The first storey had an open-plan layout with no partitions. A test floor assembly was constructed on the first storey directly above the fire room for each experiment. The remainder of the floor on the first storey was constructed out of non-combustible materials. A 0.89 m wide by 2.07 m high doorway led to the exterior. The staircase to the second storey was not enclosed. There were no window openings on the first storey.

The second storey was partitioned into a corridor and bedrooms (the two smaller bedrooms were of the same size and instrumented). The door on the southwest bedroom was kept open whereas other bedroom doors remained closed. Each bedroom doorway was 0.81 m wide by 2.05 m high.

There were no window openings on the second storey. The full-scale test facility is referred to as the test house hereafter.

## **2.2. Fire Scenarios**

Given the objectives of the research, a relatively severe, fast-growing basement fire, which gives a very reproducible fire exposure and lasts approximately 30 minutes, was determined to be the most suitable one to challenge the structural integrity of the unprotected floor structure. A series of bench-, medium- and full-scale fire tests [7, 8] were conducted in order to select a fuel package and fire scenarios for use in experiments with unprotected floor assemblies.

### *2.2.1. Fuel Package*

A simple and repeatable fuel package was developed for use in full-scale experiments to fuel a fire that simulated a basement living area fire. This fuel package consisted of a mock-up sofa constructed with 9 kg of exposed polyurethane foam (PUF), the dominant combustible constituent of upholstered furniture, and 190 kg of wood cribs beside and underneath the mock-up sofa. A photograph of the fuel package is shown in Figure 2.

The mock-up sofa was constructed with 6 blocks of flexible polyurethane foam (with a density of  $32.8 \text{ kg/m}^3$ ) placed on a metal frame. Each block was 610 mm long by 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 foam was used without any upholstery fabric that is typically used in upholstered furniture.

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

### *2.2.2. Fire Scenario Selection*

A series of full-scale fire scenario tests were conducted in the test facility using the fuel package to investigate the effect of fuel quantity, ventilation and other parameters on fire growth and development [8]. The placement of the fuel package in the basement fire compartment is illustrated in Figure 3. The mock-up sofa was located at the center of the fire compartment. The mock-up sofa was ignited in accordance with the ASTM 1537 test protocol [9] and the wood cribs provided the remaining fire load to sustain the fire for the desired period of time.

For the fire scenario tests, the ceiling of the basement fire room was lined with two layers of non-combustible cement board (no real structural floor was installed above the fire room). Based on the results from the fire scenario tests, two fire scenarios, FS-1 and FS-4, were selected for use in subsequent experiments with unprotected floor assemblies.

In FS-1, the doorway from the first storey to the basement had no door (referred to as the open basement doorway scenario). The exterior window opening in the basement fire room and the exterior door on the first storey were initially closed. The non-combustible panel that covered the fire room's exterior window opening during the initial stage was manually removed when the temperature, measured at the top-center of the opening, reached  $300^\circ\text{C}$ . This was done to

provide the ventilation necessary for combustion and to simulate the fire-induced breakage and complete fall-out of the window glass. To simulate occupants evacuating the test house, the exterior door on the first storey was opened at 180 s after ignition and left open.

In FS-4, a hollow-core interior door (an inexpensive moulded fibreboard door with minimal styles and rails) was used in the doorway at the top of the basement stairwell and the door was in the closed position (referred to as the closed basement doorway scenario). This was the only procedural difference between FS-1 and FS-4.

Figure 4 shows the average temperature profiles in the fire room at a height of 2.4 m for FS-1 and FS-4. The polyurethane foam used for the mock-up sofa dominated the initial fire growth (first 180 s). There was good repeatability of the ignition source and the initial fire development. Following this initial stage, the effects of ventilation became more pronounced and the fire became wood-crib-dominated.

FS-1 produced a fast-developing fire that resulted in the complete fire involvement of the fuel package. Temperatures at the ceiling level exceeded 700°C for about 600 s during the fully developed stage of the fire, indicating that this scenario would provide a relatively severe fire to challenge unprotected floor assemblies.

The temperatures in the fire room were lower in FS-4 than in FS-1 during the wood-crib-dominated period (Figure 4). Closing the basement door limited the oxygen supply to the fire in the basement and acted as a barrier to smoke movement into the upper storeys before the door burnt through. The effect of the limited ventilation became pronounced after the polyurethane foam was consumed and the fire became wood-crib-dominated due to limited oxygen to support active combustion of the wood cribs. Although FS-4 was less severe than FS-1, it would still provide a reasonably severe challenge to unprotected floor assemblies. This scenario was selected for use in subsequent experiments to understand the impact of a closed basement door on the tenability conditions in the test house and the structural integrity of unprotected floor assemblies.

The rate of fire growth for FS-1 and FS-4 in the early development stage agrees well with the test results from full-scale tests conducted by National Bureau of Standards [10] and the University of Canterbury [11] using residential living room settings.

### **2.3. Unprotected Floor Assemblies**

A range of engineered floor systems, including wood I-joist, steel C-joist, metal plate wood truss and metal web wood truss assemblies as well as solid wood joist assemblies as shown in Table 1, were used in the full-scale fire experiments. Various aspects were considered in designing the test assemblies, including what is typically used for framing and subfloor materials in houses today, consideration of serviceability limit states, typical spacing, typical spans, typical depths, etc. For each experiment, a floor assembly was constructed on the first storey directly above the basement fire compartment.

Oriented strandboard (OSB) is representative of subfloor materials typically used in single-family houses in recent years. Based on a series of cone calorimeter and intermediate-scale

furnace experiments on five different OSB materials [12], all OSB samples tested had comparable fire behavior and one OSB subfloor material was selected for use in the construction of all test floor assemblies.

A single layer of OSB panels was used for the subfloor of all assemblies without additional floor finishing materials on the test floor assemblies since there are no specific requirements for floor finishing materials atop the OSB subfloor in the building codes. This was considered the code minimum and reduced the number of experimental variables. The subfloor panels were 15.1 mm thick with a full panel size being 1.2 x 2.4 m. The longer panel edges had a tongue and groove profile while the short panel edges were square-butt ends.

Each floor assembly selected for testing was designed on the basis of an imposed load of 1.90 kPa, self-weight of 0.5 kPa and the span of the basement compartment. For the floor assemblies using solid wood joists and steel C-joists, the maximum allowable design spans for those members under residential occupancy loading resulted in the use of an intermediate support beam. For all other systems, the floor assemblies were designed and constructed to span the full width of the room, which resulted in them being at or near to their maximum allowable design span.

In the experiments, actual loading was applied on the floor assembly as follows: the self-weight (dead load) of the assembly, plus an imposed load (live load) of 0.95 kPa (i.e., half of the imposed load of 1.90 kPa prescribed by the code [3] for residential occupancies). This was based on the fact that in a fire situation, only part of the imposed load is available. This was also consistent with a number of international standards (Eurocode [13], New Zealand and Australian standards [14, 15], and ASCE standard [16]). The total imposed load applied to the floor assembly was 25 kN (i.e., 0.95 kPa multiplied by the floor area) using uniformly distributed concrete blocks.

Given that there are no specific fire resistance requirements for the floor structures in single-family houses in the building codes, the floor assemblies used in the experiments were unprotected or unsheathed on the basement side. Specific details of the design and construction of the floor assemblies tested are provided in a series of research reports [17-22].

## **2.4. Instrumentation**

Various measurement devices were used in the experiments. Extensive thermocouple arrays were installed in the test house to measure temperatures. Vertical arrays of thermocouples (at heights of 0.4, 0.9, 1.4, 1.9 and 2.4 m above the floor) were located at the four quarter points of the fire room, basement doorway, four quarter points on the first storey, centre of the corridor on the second storey, and centre of the bedrooms on the second storey. Extensive thermocouple arrays were also installed on the unexposed and exposed sides of the test floor assemblies. Thermocouples were installed at the basement exterior opening to monitor the temperature in the fire plume.

Smoke and gas measurements focused on upper storeys with four gas sampling locations. On the first storey, gas sampling ports were located at the southwest quarter point at 0.9 m and 1.5 m above the floor. On the second storey, gas sampling ports were located at the centre of the

corridor at 0.9 m and 1.5 m above the floor. Gas samples from these sampling locations were connected to nondispersive infrared CO/CO<sub>2</sub> gas analyzers, O<sub>2</sub> gas analyzers and smoke density meters. FTIR (Fourier Transform Infrared Spectroscopy) spectrometers were also used in selective experiments.

In addition to thermocouple arrays on the floor assemblies, flame-sensing devices and floor deflection devices were installed on the unexposed surface of the test floor assemblies. The flame-sensing devices were placed at some of the tongue and groove joints of the subfloor. The floor deflection was measured at nine locations on the floor assembly.

The instrumentation also included air velocity measurements at openings including the basement opening on the first storey, differential pressure measurements, and video cameras. Residential ionization and photoelectric smoke alarms were installed on each level and in each bedroom, which were powered by batteries and were not interconnected. Details of the instrumentation are provided in a series of reports [17-22].

## **2.5. Experimental Procedure**

The mock-up sofa was ignited in accordance with the ASTM 1537 test protocol [9] and data was collected at 5 s intervals throughout each test.

The non-combustible panel that covered the fire room's exterior opening during the initial stage of each test was manually removed when the temperature, measured at the top-center of the opening, reached 300°C. This condition was reached within 90 to 120 s after ignition in the experiments. The removal of the panel was to provide the ventilation necessary for combustion.

The exterior door on the first storey was opened in each test at 180 s after ignition and left open, simulating a situation where some occupants, who would have been in the test house, escaped leaving the exterior door open while other occupants may still have been inside the house.

The tests were terminated when excessive flame penetrated through the floor assembly and/or structural failure of any part of the floor assembly occurred.

## **3. Results and Analysis**

### **3.1. Fire Development**

Figure 5 and Figure 6 show the temperature profiles measured at the centre of the four quadrants of the basement fire room at a height of 2.4 m above the floor for all of the tests. Data on temperature stratification at different heights in the fire room can be found in a series of reports [17-22]. The polyurethane foam used for the mock-up sofa dominated the initial fire growth. The fast development of the fire from ignition to attainment of the first temperature peak was consistent for all of the tests. Following this initial stage, the effects of ventilation became more pronounced and the fire became wood-crib-dominated and also involved the unprotected floor assemblies.

There was good repeatability of the fire development and severity. The temperatures at the 2.4 m height exceeded 600°C at approximately 120 s in all of the tests, indicating that the basement fire compartment reached flashover conditions. Figure 5 indicates that under the full ventilation conditions (open basement doorway) the fire scenario provided a very reproducible fire exposure to the unprotected floor assemblies in all experiments. As shown in Figure 6, under the limited ventilation conditions (closed basement doorway), the fire scenario also provided a relatively severe and consistent fire exposure to the unprotected floor assemblies (the closed hollow-core interior door at the top of the basement stairwell was breached by the fire later in the experiments). There was a quick transition from a well-ventilated flaming fire to an under-ventilated fire in all experiments. The results from the fire scenario tests (FS-1 and FS-4), with a non-combustible ceiling in the fire room, are also included in Figure 5 and Figure 6 for reference.

### **3.2. Smoke Alarm Response**

Residential photoelectric and ionization smoke alarms were installed on the ceiling in each bedroom, second storey corridor, first storey and the basement fire compartment. These smoke alarms were powered by batteries and were not interconnected. The ionization smoke alarm was not installed in the basement fire room in order to avoid dealing with radioactive materials in the cleanup of debris after the fire tests. Since photoelectric smoke alarms are generally slower in detecting flaming fires than ionization smoke alarms, using photoelectric smoke alarms in the basement resulted in more conservative estimates for activation times for the fire scenarios used in the experiments. New smoke alarms were used in each experiment.

Table 2 shows the activation times of the smoke alarms in the test house. The photoelectric smoke alarms in the basement fire compartment took 30-50 s to activate. In the tests with an open basement doorway, it took up to 100 s longer for the smoke alarms in the second storey corridor to activate and up to 230 s longer for the smoke alarms in the closed bedroom to activate. In the tests with a closed basement doorway, the smoke alarms installed on the upper storeys took even longer to activate – up to 150 s longer for the smoke alarms in the second storey corridor and up to 500 s longer for the smoke alarms in the closed bedroom. This highlights the importance of having the smoke alarms interconnected to activate simultaneously when one of them detects a fire.

### **3.3. Upper Storey Conditions and Tenability Analysis**

Heat, combustion products and smoke produced from fires can, either individually or collectively, create conditions that are potentially untenable for occupants. Tenability analysis was conducted using temperatures, concentrations of combustion products and smoke optical densities measured during the full-scale fire experiments. The analysis focused on the conditions on the upper storeys of the test house (the conditions in the basement fire room would not be survivable once flashover occurred). The purpose of the tenability analysis was to provide an estimation of the time available for escape — the calculated time interval between the time of ignition and the time after which conditions become untenable for an individual occupant who would have been on the upper storeys of the test house. Incapacitation – a state when people lose the physical ability to take effective action to escape from a fire – was chosen as the endpoint when undertaking the tenability analysis.

ISO 13571 and the SFPE Handbook of Fire Protection Engineering provide guidance and methodologies for evaluating the time available for occupants to escape from a fire [23, 24]. Potential exposure to the toxic and asphyxiant gases, heat and smoke obscuration under the test conditions was analyzed independently without consideration of any interaction (combined effects). Each component was treated as acting independently on the occupant to create incapacitating conditions and the time available for escape was the shortest of the times estimated from consideration of exposure to combustion gas products, heat and smoke obscuration.

### *3.3.1. Exposure to Toxic Gases*

In regards to the fuel package used in this study, with the combined flaming combustion of polyurethane foam and wood cribs, the primary gas products were carbon monoxide (CO), carbon dioxide (CO<sub>2</sub>) and hydrogen cyanide (HCN) in a vitiated oxygen (O<sub>2</sub>) environment. Although HCN could be produced from the combustion of the polyurethane foam in the fuel package, FTIR measurements in selected tests indicated that the HCN concentrations on the upper storeys were well below 30 ppm. These concentrations would not cause concerns for occupant life safety on the upper storeys in the timeframe of incapacitation by CO exposure. The fuel package contained no chemical components that would produce acid halide irritants in the combustion gases. Other irritant gases were below the detection limits of the FTIR spectrometers used in this project. Therefore, the tenability analysis for the upper storeys involves CO and CO<sub>2</sub> and oxygen vitiation only.

Figure 7 shows the CO, CO<sub>2</sub> and O<sub>2</sub> concentration-time profiles measured during each experiment. For the experiments with the open basement doorway, within 220-300 s, oxygen was diminished to below 10% and CO<sub>2</sub> increased to above 10%, which could cause incapacitation and lead to loss of consciousness rapidly due to lack of oxygen alone or due to the CO<sub>2</sub> asphyxiant effect alone [24]. The concentrations reached a minimum of 3% O<sub>2</sub> and above 16% CO<sub>2</sub> near the end of the experiments. For the experiments with the closed basement doorway, the migration of smoke and hot fire gases into the upper storey(s) was significantly delayed and the O<sub>2</sub> concentrations on the upper storey(s) were 15% or above before structural failure occurred.

The toxic effect of CO is due to its affinity with the hemoglobin in human blood to form carboxyhemoglobin (COHb), which reduces the transport of oxygen in the blood to various parts of the body. The complexity of the CO uptake to the blood is described by the theoretical Coburn-Forster-Kane (CFK) equation [25]. In addition, CO<sub>2</sub> stimulates breathing in the concentration range of 2 to 6% — this hyperventilation could increase the uptake rate of CO and other toxic gases from the fire.

A fractional effective dose (FED) approach was used to estimate the time after which the accumulated exposure to each fire effluent exceeds a specified threshold for incapacitation. This time is then taken to represent the time available for escape relative to the specified threshold.

The fractional effective dose for incapacitation due to CO was calculated using the approach given in ISO TS 13571 for short exposure to CO at high concentrations [23]:

$$FED_{in,CO} = \sum_{t_0}^t \frac{[CO] \cdot \Delta t}{35000} \exp\left(\frac{\%CO_2}{5}\right)$$

where  $[CO]$  is the inhaled carbon monoxide concentration in *parts per million*;  $\Delta t$  (*minute*) is the discrete increment of time (i.e. the time interval for data sampling); 35000 (*ppm-min*) is the incapacitation dose for the CO exposure, and  $\exp(\%CO_2/5)$  is a CO<sub>2</sub>-induced hyperventilation factor for breathing [23, 24]. The uncertainty in the calculation of  $FED_{in,CO}$  is estimated to be  $\pm 40\%$  [23]. This approach is consistent with the methodology given in the SFPE Handbook of Fire Protection Engineering that was derived from human exposure experiments with healthy adults [24, 26].

Table 3 shows the calculated times for the fractional effective dose to reach 2 typical values ( $FED = 1$  and  $FED = 0.3$ ), including the uncertainty in the estimated times. The times associated with other FED values can be calculated, if required.

The general population has a wide range of susceptibility to fire effluents, the exposure thresholds for incapacitation can change from subpopulation to subpopulation. The CO uptake and the COHb increase are known to be faster in small children than in adults [27]. The incapacitation time for small children or a more susceptible subpopulation would be shorter than for average healthy adults. Thus, each occupant is likely to have a different incapacitation time.  $FED = 0.3$  represents an incapacitation dose for some susceptible people whereas  $FED = 1.0$  represents an incapacitation dose for healthy adults of average susceptibility.

For the tests with the open basement doorway, the calculated time difference between  $FED_{in,CO} = 0.3$  and  $FED_{in,CO} = 1.0$  was 40 s or less at any measurement location for any given test. The calculations were associated with the fixed positions where the concentrations were measured and an occupant would move through different locations in real fire situations. The time difference between the second storey and first storey reaching either of the two doses was less than 30 s for any given test. Moreover, the time difference between tests reaching either of the two doses was less than 40 s at any measurement location. These results indicate a consistent time frame for reaching the incapacitation doses for exposure to CO in this fire scenario.

For the experiments with the closed basement doorway, the calculated times were at least 60% longer to reach  $FED_{in,CO} = 0.3$  and at least doubled to reach  $FED_{in,CO} = 1$ , compared with the open basement doorway experiments. The closed door impeded the migration of smoke and hot fire gases into the upper storey(s) and delayed the onset of untenable conditions.

The fractional effective doses for incapacitation due to O<sub>2</sub> vitiation alone, and due to asphyxiant effect of CO<sub>2</sub> alone, were also calculated using the methodology given in the SFPE Handbook of Fire Protection Engineering [24]. Under the experimental conditions of this study, these calculations indicated that the effect of O<sub>2</sub> vitiation and the asphyxiant effect of CO<sub>2</sub> would cause incapacitation at a later time than the toxic effect of CO.

### 3.3.2. Exposure to Heat

Figure 8 and Figure 9 show exemplar temperature profiles measured on the first and second storeys during the experiments. These temperature profiles are representative for the tests using the open basement doorway scenario (Figure 8) and for the tests using the closed basement doorway scenario (Figure 9), respectively. The temperatures depended on the locations inside the test house. In the bedroom with the door closed, the temperatures never exceeded 50°C in any experiment.

The presence of the closed door in the basement doorway made significant difference in the thermal conditions on the first and second storeys. The closed door impeded the migration of smoke and hot fire gases into the upper storeys until it was breached by the fire, and delayed onset of untenable thermal conditions on the upper storeys.

The rate of convected heat transfer from hot gases to the skin depends on temperature, ventilation, humidity of the enclosure and clothing over the skin [24]. For hot air at temperatures above 120°C and with water vapour of less than 10%, pain and skin burns would be likely to occur in a few minutes. Assuming unclothed or lightly clothed subjects, the fractional effective dose for incapacitation due to the convected heat exposure was calculated using the following equation [23, 24]:

$$FED_{in,heat} = \sum_{t_0}^t \frac{T^{3.4}}{5 \times 10^7} \Delta t$$

where  $T$  (°C) is the temperature and  $\Delta t$  (minute) is the discrete increment of time (i.e. the time interval for data sampling). The uncertainty in the calculation of  $FED_{in,heat}$  is estimated to be  $\pm 25\%$ . Since there was temperature stratification, the temperatures at the 1.4 m height above the floor were used for the analysis of convected heat exposure on each storey, as this is the height of the nose/mouth of an average height individual.

Radiant heat is important when the hot smoke layer is over 200°C, which corresponds to the threshold radiant heat flux of 2.5 kW·m<sup>-2</sup> to produce second degree burning of skin [28]. The calculation indicated that the convected heat exposure would result in incapacitation before the radiant heat began to play a major role on the first and second storeys. Convected heat was the most important source of heat exposure for occupants on the first and second storeys for the fire scenarios used.

The convective heat exposure depended on the location in the test house. In the closed bedroom, heat exposure would not cause incapacitation ( $FED_{in,heat} = 0.01\text{--}0.07$  in all experiments). On the first storey, in the corridor or in the open bedroom on the second storey, the calculated times to incapacitation due to exposure to the convected heat are given in Table 4 for  $FED_{in,heat} = 0.3$  and  $FED_{in,heat} = 1$ , including the uncertainty in the estimated times. Depending on the test conditions (floor assembly type, condition of doorway to the basement) and locations in the test house, the heat exposure could cause incapacitation before CO exposure or vice versa.

For the tests with the open basement doorway, except for Test UF-01, the calculated times to reach the heat incapacitation doses on the first storey were shorter than, or similar to, those for CO exposure; the time difference for  $FED_{in,heat}$  to change from 0.3 to 1.0 was also much shorter than that for  $FED_{in,CO}$ . In the corridor on the second storey, except for Test UF-07, the calculated times to reach the incapacitation doses for heat exposure were longer than those for CO exposure. The CO incapacitation doses were reached earlier in Test UF-01 on both storeys while the heat incapacitation doses were reached earlier in Test UF-07 on both storeys.

For the tests with the closed basement doorway, the incapacitation doses for heat exposure on the first storey were only reached near the end of the experiments. The calculated times for heat incapacitation were at least double that for the tests with the open basement doorway. The closed door to the basement impeded the heat transfer to the upper storey(s) and delayed the onset of untenable heat conditions. For the tests with the closed basement doorway, the CO exposure dominated incapacitation on both storeys.

### 3.3.3. Visual Obscuration by Smoke

Visual obscuration by the optically dense smoke tended to be the first hazard to arise that could impede evacuation by the occupants. Although visual obscuration would not directly cause incapacitation, it would cause delays in movement by the occupants and thus prolong exposure of occupants to other hazards. Visibility through smoke and the optical density of smoke are related (the visibility is proportional to the reciprocal of the  $OD$  for non-irritating smoke, for example) [29]. The smoke obscuration can be expressed as the optical density per meter ( $OD$  in  $m^{-1}$ ):

$$OD = \frac{1}{L} \log_{10} \left( \frac{I_0}{I} \right)$$

where  $I_0$  is the intensity of the incident light;  $I$  is the intensity of the light transmitted through the path length,  $L$  (m), of the smoke. The optical density is related to the extinction coefficient  $k$  ( $m^{-1}$ ) by  $OD = k/2.303$ .

Various threshold  $OD$  values have been suggested as the tenability limit for smoke obscuration for small buildings with occupants familiar with the egress route [24, 29-32]. In ISO 13571, the minimum visible brightness difference between an object and its background is used to estimate the smoke obscuration limit at which occupants cannot see their hands in front of their faces (a distance of 0.5 m or less) [23]. These calculations indicate that occupants cannot see their hands in front of their faces and become disoriented at an optical density of  $3.4 m^{-1}$ . For an occupant whose vision is impaired, this can happen at an optical density of  $2 m^{-1}$  or lower. Psychological effects of smoke on occupants may accelerate the loss of visibility [29]. Possible reduction of time to untenable smoke level due to psychological effect is not addressed in this paper. A tenability limit of  $OD_{Limit} = 2 m^{-1}$  is used in this study.

During the experiments, the optical density was measured at 0.9 and 1.5 m heights above the floor on the first and second storeys (simulating the height of the nose/mouth of an average height individual crawling and standing, respectively). Figure 10 shows exemplar optical density-time profiles. These profiles are also representative for other tests using corresponding scenarios. It was observed that in the experiments with the open basement doorway, the optical

density temporarily decreased shortly after the exterior door on the first storey was opened at 180 s, then increased again.

Table 5 shows the times to reach various optical density levels at the 1.5 m height, which were very similar from one experiment to another. The increase in the optical density was faster with the open basement doorway than with the closed basement doorway. It must be pointed out that the smoke density meters used for the first storey had a narrow working range and could not measure the smoke obscuration of  $OD = 2 \text{ m}^{-1}$  and beyond. It is reasonable to assume that the first storey lost the visibility shortly before the second storey, given the comparable times for reaching the OD's of 1.0 and 1.7 on both storeys. It can be seen from Table 3 and Table 5 that the times when the optical density reached  $3.4 \text{ m}^{-1}$  were generally very close to the times when  $FED_{in,CO} = 0.3$ , which is a CO incapacitation dose for some susceptible persons.

### 3.3.4. Summary of Tenability Analysis

Potential exposure to the toxic and asphyxiant gases, heat and smoke obscuration under the test conditions was analyzed to estimate the time available for escape, using incapacitation as the endpoint. In fire situations, occupants would be exposed simultaneously to the gases, heat and smoke. The combined effect as a result of the simultaneous exposure is not well understood. In this paper, the gas exposure, heat exposure and smoke obscuration are analyzed independently without consideration of the combined effect. Table 6 summarizes the estimated times to the onset of various conditions.

The uncertainty in the calculation of the fractional effective dose is estimated to be  $\pm 25\%$  for the heat exposure and  $\pm 40\%$  for the CO exposure (with  $\text{CO}_2$  induced hyperventilation) [23]. With the fast-growing fire used in the experiments, the resulting uncertainty in the estimated time is much smaller than the uncertainty in the calculated fractional effective dose ( $FED_{in,CO}$  or  $FED_{in,heat}$ ) due to the non-linear relationship. The uncertainty in the timing of the optical density measurement is  $\pm 5$  s. Table 6 lists the uncertainty in the estimated times.

Smoke obscuration was the first hazard to arise. Although smoke obscuration would not directly cause incapacitation, it could impede evacuation and prolong exposure of occupants to other hazards. With the open basement doorway, the combustion of polyurethane foam was mainly responsible for reaching the smoke obscuration limit and the smoke obscuration  $OD_{Limit} = 2 \text{ m}^{-1}$  was reached consistently around 180 s. With the closed basement doorway, the time to the tenability limit  $OD_{Limit} = 2 \text{ m}^{-1}$  was significantly increased. It must be pointed out that people with impaired vision could become disoriented at a lower optical density.

The calculated time for reaching the specific FED, either due to the heat exposure or due to the CO exposure (exacerbated by  $\text{CO}_2$ -induced hyperventilation), whichever occurred first, is listed in Table 6. Heat exposure tended to be more severe on the first storey than on the second storey. In most cases, the time difference for heat exposure and CO exposure to reach the specific FED was not significant with the open basement doorway.

Because of the variation in people's susceptibility to heat and/or gas exposure, the time to untenable conditions (incapacitation) was not a single value. The calculated time based on

FED = 1 represents the time available for escape before incapacitation for a healthy adult of average susceptibility. The time based on FED = 0.3 represents the time available for escape before incapacitation for a more susceptible person. For the experiments with the open basement doorway, the time for FED to change from 0.3 to 1 was no more than 40 s. The times to reach each FED level were also very consistent for the different experiments. The tenability data indicates that, regardless what test floor assemblies were used, the untenable conditions (for incapacitation) were reached in a consistent timeframe soon after smoke obscuration.

The presence of the closed door in the doorway to the basement fire room reduced the rate at which combustion products were conveyed to the upper storeys and thereby prolonged the time available for escape before the onset of incapacitation conditions. The time available for escape was at least doubled for an occupant of average susceptibility (FED=1) and was increased by at least 60% for a more susceptible occupant (FED=0.3) with the closed basement doorway, compared to the scenario with the open basement doorway. It should be noted that, in Test UF-08, the incapacitation doses for an occupant of average susceptibility (FED=1) were reached after structural failure.

For the closed bedroom on the second storey, based on the temperature measurements in all experiments and the heat exposure calculation, the conditions in the closed bedroom would not reach untenable conditions associated with FED = 0.3 or 1.

The location of the occupant in the test house has an effect on the time available for escape. The analysis focused on the fire conditions affecting tenability, as measured on the first and second storeys of the test facility, and the impact on any occupant assumed to be present at the time of ignition. Each calculation was associated with a particular position where the concentration or temperature was measured. In real fire situations, the occupant would move through different locations during egress. Therefore, the time to incapacitation would be in-between the times calculated for different locations.

### **3.4. Structural Response**

A floor system provides an egress route for occupants and its structural integrity directly impacts the safe evacuation of the occupants from the house in a fire emergency. During the fire experiments, the conditions of the test floor assemblies were monitored using thermocouples, flame-sensing devices and deflection devices on the floor of the first storey. Figure 11 shows exemplar data plots of these measurements, which are representative for other tests with the engineered floor assemblies.

Flame penetration through the floor assembly is considered to be an initial indicator of the impending failure of the assembly, and is a failure criterion in standard fire resistance testing [33, 34]. Flame penetration could also impact the ability of occupants to evacuate. Any openings created by flame penetration would weaken the floor assembly and provide additional means for hot fire gases to migrate into the upper storey(s). Both the temperatures and the signals from the flame-sensing devices on the unexposed side of the floors were used to determine whether there was flame penetration through the floors.

The temperatures shown in Figure 11(a) are from measurements by nine thermocouples under insulated pads on top of the OSB subfloor of the first storey. A rapid increase in temperature indicates that the floor was being significantly breached. The subsequent rapid decrease in temperature was due to the termination of the experiment by extinguishing the fire with water. Under standard fire resistance test conditions [33, 34], the temperature criterion for floor failure 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.

The flame-sensing devices were placed at three of the tongue and groove joints on the unexposed side of the OSB subfloor in all experiments (except for Test UF-01) to detect flame penetration through the floor. As shown in Figure 11(b), the flame-sensing devices produced noticeable voltage spikes, which is an indication of the devices being struck by flames that penetrated through the floor assembly.

The floor deflection was measured at nine points in the central area of the test assembly just above the fuel package where the impact of the fire on the assembly was anticipated to be the greatest. Some measurement points were aligned with one of the joists or trusses, while the others were positioned between joists or trusses. Figure 11(c) shows examples of the deflection measurements. The sharp increase in deflection is an indication that the structural collapse occurred.

Table 7 shows the times to failure ( $t_f$ ) for the test floor assemblies, which are based on the measurements of the temperatures, flame penetration and floor deflection on the floor of the first storey and confirmed by visual observations through the window opening in the fire room.

With the relatively severe fire scenarios used in the experiments, the times to reach structural failure for the wood I-joist, steel C-joist, metal plate and metal web wood truss assemblies were 35-60% shorter than that for the solid wood joist assembly ( $[t_{f,i} - t_{f, \text{solid wood}}] / t_{f, \text{solid wood}} \times 100\%$ , where  $t_{f,i}$  is for test assembly  $i$  and  $t_{f, \text{solid wood}}$  for the solid wood joist assembly). As shown by the results from the three replicate tests with one of the wood I-joist assembly types (Tests UF-06, UF-06R and UF-06RR), the times to structural failure were very repeatable. Having a closed door to the basement limited the air available for combustion and delayed the time for the test assemblies to reach structure failure (50-60% longer than with the open basement doorway; calculated by  $[t_{f,i, \text{closed}} - t_{f,i, \text{open}}] / t_{f,i, \text{open}} \times 100\%$ , where  $t_{f,i, \text{open}}$  is with the open basement doorway and  $t_{f,i, \text{closed}}$  with the closed basement doorway for test assembly  $i$ ).

There was structural deflection of all of the floor assemblies prior to their structural failure. Figure 12 shows a comparison of the floor deflection near the centre of all of the test assemblies prior to the structural failure. The steel C-joist floor assembly produced the highest deflection rate, followed by the metal-web and metal-plate wood truss assemblies. The solid wood joist assemblies produced the lowest deflection rate.

There were three distinct patterns of failure of the test floor assemblies. In Tests UF-01 and UF-02, the subfloor failed, with most of the solid wood joists significantly charred but still in place at the end of the tests. The fire consumed the OSB subfloor in many areas, particularly in areas

directly above the fuel package. Some of the concrete blocks, which were used to apply loading to the floor, fell through the subfloor.

In Tests UF-03, UF-05, UF-06R, UF-06RR, UF-07 and UF-08, the floor assemblies with wood I-joists or wood trusses structurally deflected and then broke at the mid-point and the floor assemblies collapsed into the basement in the form of a “V” shape. In Tests UF-04, UF-06 and UF-09, floor assemblies with steel- C-joists and wood I-joists structurally deflected and then the entire floor assemblies collapsed into the basement.

The structural failure of these engineered floor assemblies were mainly due to joist or truss failure. The steel C-joists lost their strength and deformed at high temperatures. The metal-wood connections broke for the metal-web and metal-plate wood trusses. The web materials of wood I-joists were burned through. For the wood I-joist B, whose lumber flanges were made of finger-joint lumber bonded with a non-phenol based adhesive, structural failure was the combination of web materials being burned through and breakdown at finger joints of the lumber flanges.

### **3.5. The Sequence of Events**

Two relatively severe fire scenarios were used in the full-scale fire experiments to challenge the structural integrity of the unprotected floor assemblies above the basement fire compartment. The scenarios were designed to better understand how the structural integrity and tenability conditions would affect the ability of occupants on the first and upper storeys to escape a single-family house in the event of a serious basement fire. Table 8 summarizes the chronological sequence of the fire events in the full-scale experiments — fire initiation, smoke alarm activation, onset of untenable conditions, and structural failure of the test floor assembly.

The smoke alarm in the basement fire compartment consistently took 30-50 s to activate. The experimental results highlight the importance of having the smoke alarms on each level of a house interconnected to activate simultaneously when one of them detects the fire to allow more time for evacuation.

Smoke, heat and combustion products created untenable conditions for occupants. Because of the variation in people’s susceptibility to smoke, heat and/or gas exposure, the time to untenable conditions (incapacitation) was not a single value for a given fire condition.

Smoke obscuration was the first hazard to arise in all the experiments. The smoke obscuration limit (optical density =  $2 \text{ m}^{-1}$ ) was reached consistently around 180 s in the experiments with the open basement doorway. Although smoke obscuration would not directly cause incapacitation, it could impede evacuation and prolong exposure of occupants to other hazards. It must be pointed out that people with impaired vision could become disoriented at an optical density lower than  $2 \text{ m}^{-1}$ .

For the experiments with the open basement doorway, heat exposure reached the incapacitation doses on the first storey at times shorter or similar to CO exposure (except for Test UF-01); on the second storey, CO exposure reached the incapacitation doses earlier than heat exposure (except for Test UF-07). In most cases, the time difference for heat exposure and CO exposure

to reach the incapacitation doses was not significant with the open basement doorway. The time range from  $FED = 0.3$  on the first storey to  $FED = 1$  on the second storey covers the occupants of different susceptibility (more susceptible or average) who would have been at different locations in the test house. The calculations based on the experimental results show that regardless what test assembly was used, the untenable conditions (for incapacitation) were reached at a consistent time frame in the experiments with the open basement doorway. Depending on the susceptibility and location of occupants who would have been in the test house, the untenable conditions generally occurred within 180 to 240 s from ignition under this fire scenario (shortly after smoke obscuration). The structural failure of the test floor assemblies occurred after the untenable conditions were reached.

The presence of the closed door to the basement limited the air available for combustion and also reduced the rate at which combustion products were conveyed to the upper storeys. For each of the three assemblies tested with the closed basement doorway, the time available for escape before the onset of untenable (incapacitation) conditions was roughly doubled and the time to reach structural failure was 50-60% longer than with the open basement doorway scenario. The floor assembly constructed using the metal web wood truss (Test UF-08) failed before the incapacitation condition was reached for occupants of average susceptibility ( $FED = 1$ ). The structural failure of the solid wood joist assembly (Test UF-02) and wood I-joist Type A assembly (Test UF-09) occurred well after untenable conditions were reached.

It must be pointed out that the times to reach structural failure for the wood I-joist, steel C-joist, metal plate and metal web wood truss assemblies were 35-60% shorter than that for the solid wood joist assembly in all tests, resulting in smaller time difference between the onset of untenable conditions and structural failure of these engineered floor assemblies. In one case, the sequence was even reversed with structural failure prior to the onset of untenable conditions.

A recent literature review on the time required to egress from single-family houses indicates that the occupants may not necessarily begin evacuation immediately upon recognizing the warning signal from smoke alarms [35]. They may spend time in various pre-movement activities, such as to confirm the existence of a fire, to fight the fire, to warn and gather family members, to gather valuables, and to don warm clothes in winter, etc. These activities can result in missing the window of opportunity to reach safety. Data related to egress time from single-family houses is very limited. It is not possible with the limited data available to provide precise estimates at this time. More research is needed on the required egress times from single-family houses.

## 4. Conclusions

Two relatively severe basement fire scenarios with good repeatability of the fire development and severity were used in the full-scale fire experiments to meet the objectives of the research. It is acknowledged that neither fire scenario represents a frequent household fire scenario since a basement is not the most frequent site of fires for single-family houses. On the other hand, the basement is the location where a fire is most likely to create the greatest challenge to the structural integrity of the floor structure on the first storey with the floor assemblies unprotected on the basement side. These floor assemblies would provide the normal egress route for occupants on the first and upper storeys to escape in the event of a basement fire.

Data obtained from the test program demonstrated good repeatability of the fire severity, smoke alarm responses, times to untenable conditions and to structural failure. Overall, the fire scenario with the open basement doorway was more severe than the fire scenario with the closed basement doorway to the structural integrity of the unprotected floor assemblies and the life safety of occupants on upper storeys. The following conclusions can be drawn from this study.

#### *For Fire Tests with Open Basement Doorway*

- In all tests with the open basement doorway, fire events followed a chronological sequence: initiation and growth of the fire, activation of smoke alarms, loss of tenable conditions in open areas on upper storeys, and finally structural failure of the test floor assembly over the basement (loss of the main egress route on first storey).
- The estimated times to reach untenable conditions for occupants in open areas on upper storeys were similar in all the tests regardless of the type of floor joists and trusses used to construct the test floor assembly.
- Tenability conditions appear to be the critical factors affecting occupant life safety under the fire scenario used since the untenable conditions were reached before structural failure of the unprotected floor assemblies occurred.

#### *For Fire Tests with Closed Basement Doorway*

- The presence of the closed door to the basement reduced the rate of fire growth in the basement, slowed the transport of combustion products from the basement to the upper storeys, and also delayed the time for the test floor assemblies above the basement to reach structural failure. The times available for escape before the onset of untenable (incapacitation) conditions were roughly doubled and the times to reach structural failure were 50-60% longer than with the open basement doorway scenario.
- Limited experiments using the closed basement doorway scenario were conducted with the solid wood joist assembly and two selected engineered floor assemblies. One engineered floor assembly, which gave the shortest time to reach structural failure in the open basement doorway scenario, failed structurally in the closed basement doorway scenario before the untenable conditions (for healthy adults of average susceptibility) were reached in open areas on the upper storeys.

#### *For All Fire Tests*

- With the relatively severe fire scenarios used in the experiments, the times to reach structural failure for the unprotected engineered floor assemblies above the basement (constructed with the wood I-joists, steel C-joists, metal plate wood trusses and metal web wood trusses) were 35-60% shorter than that for the solid wood joist assemblies. There was a structural deflection of all of the floor assemblies prior to their structural failure. The main mode of structural failure for the solid wood joist assemblies was by flame penetration through the OSB subfloor, with most of the wood joists significantly charred but still in place at the end of the tests. Whereas for all other floor assemblies, they failed by complete structural collapse due to joist or truss failure. The time gap between the onset of untenable conditions and the structural failure of the floor assembly was smaller for the engineered floor assemblies than for the solid wood joist assembly used in the experiments.

- Untenable conditions were not reached, for the duration of the tests, in the second storey bedroom where the door to the bedroom was kept closed.

The results of this study reinforce the importance of continued public education on fire safety in the home and the need for occupants to be prepared for a fire emergency. They also support the code requirements for working interconnected smoke alarms on each level of a house to alert occupants as early as possible in the event of a fire. The findings confirm the importance of immediate evacuation by occupants upon a fire alert.

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## Figure Legend

**Figure 1** Facility plan view (all dimensions in mm)

**Figure 2** Fuel package

**Figure 3** Layout of the fuel package (all dimensions in mm)

**Figure 4** Average temperature profiles in basement fire compartment at 2.4 m height for FS-1 and FS-4

**Figure 5** Temperatures in basement fire compartment at 2.4 m height (open basement doorway)

**Figure 6** Temperatures in basement fire compartment at 2.4 m height (closed basement doorway)

**Figure 7** Exemplar CO, CO<sub>2</sub> and O<sub>2</sub> concentrations measured at the southwest quarter point on the first storey at 1.5 m height

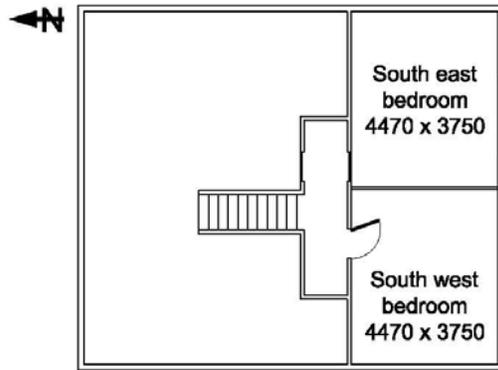
**Figure 8** Exemplar temperature profiles on upper storeys (open basement doorway)

**Figure 9** Exemplar temperature profiles on upper storeys (closed basement doorway)

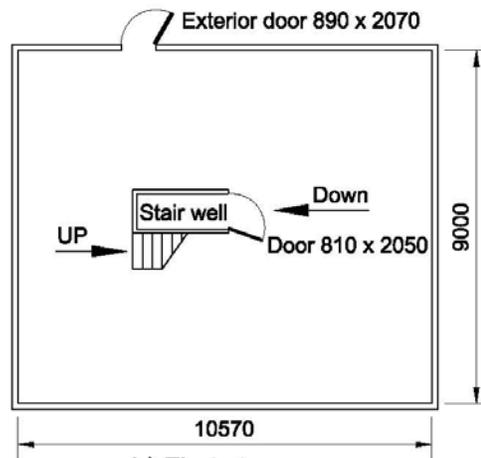
**Figure 10** Exemplar data of smoke optical density (measured in the corridor on the second storey for Test UF-06RR and Test UF-09)

**Figure 11** Exemplar plots of measurements for determination of floor structural failure (Test UF-06R)

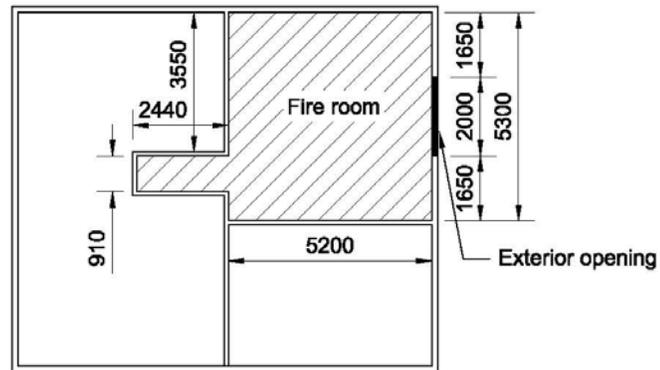
**Figure 12** Floor deflection near the centre of the test assemblies prior to structural failure



a) Second storey



b) First storey

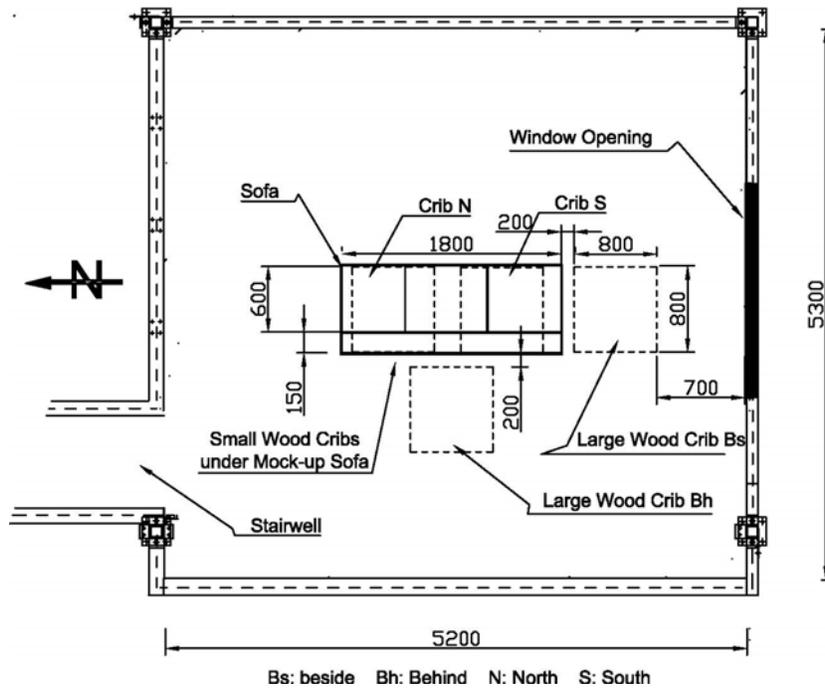


c) Basement

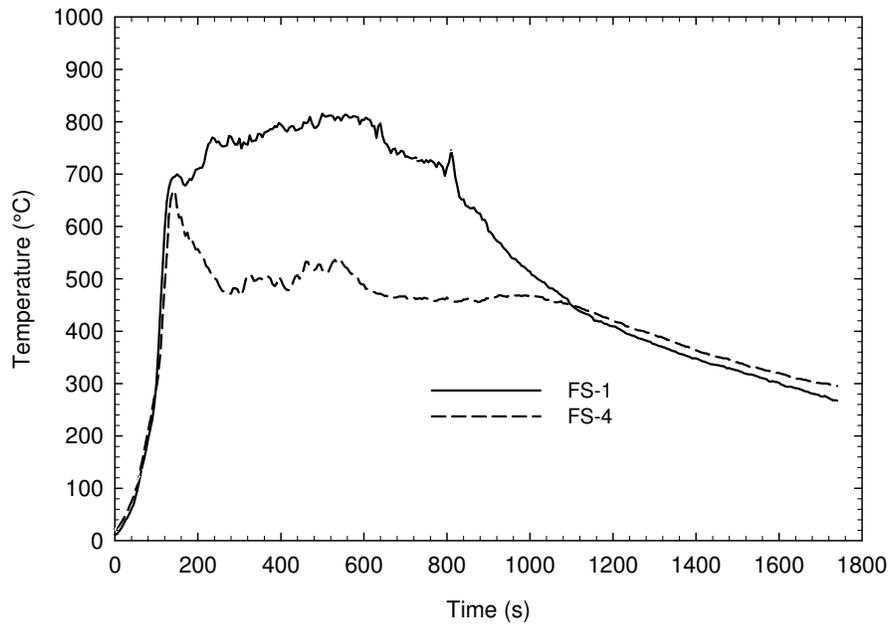
Figure 1. Facility plan view (all dimensions in mm)



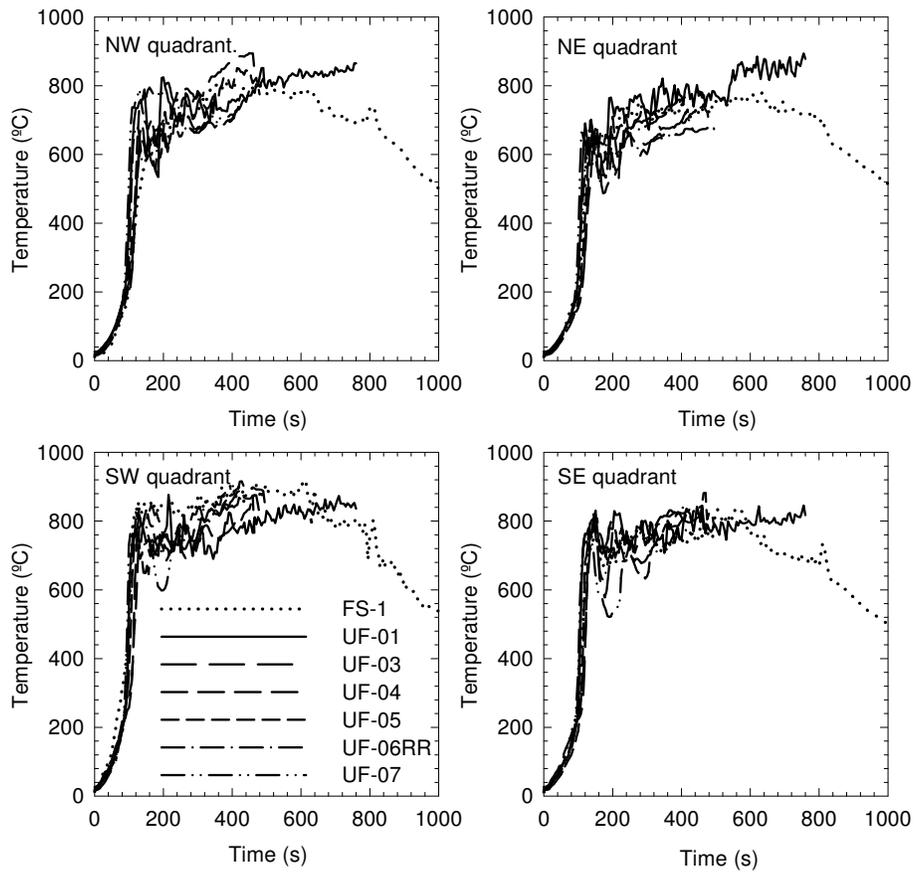
**Figure 2.** Fuel package



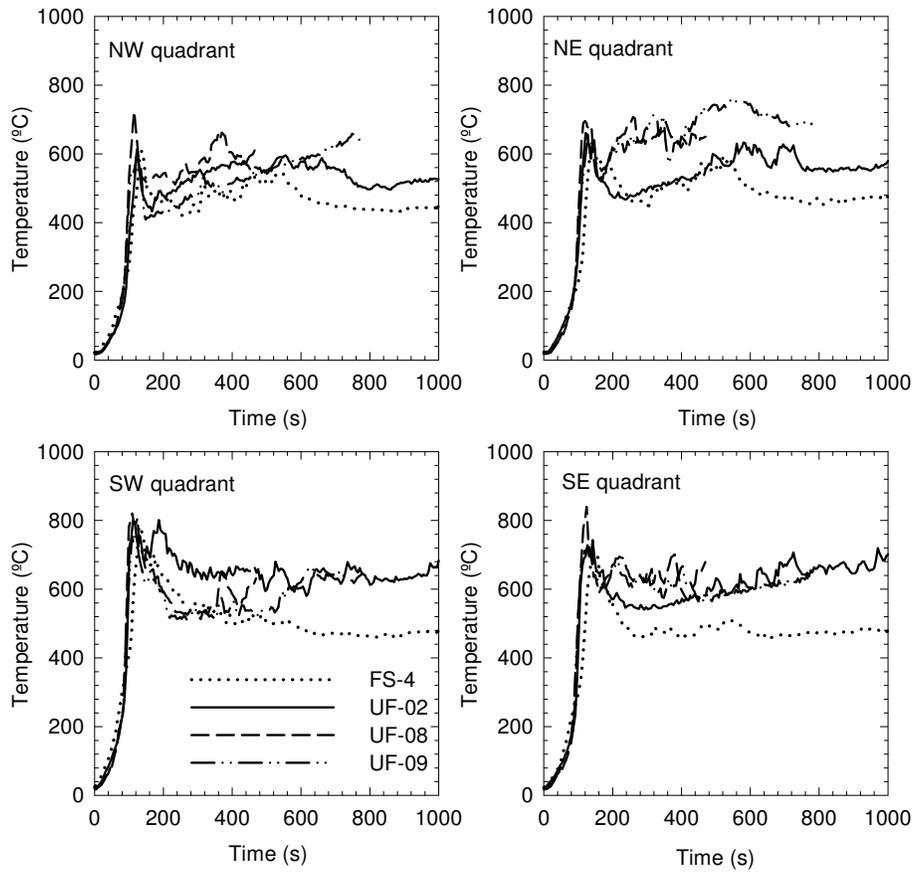
**Figure 3.** Layout of the fuel package (all dimensions in mm)



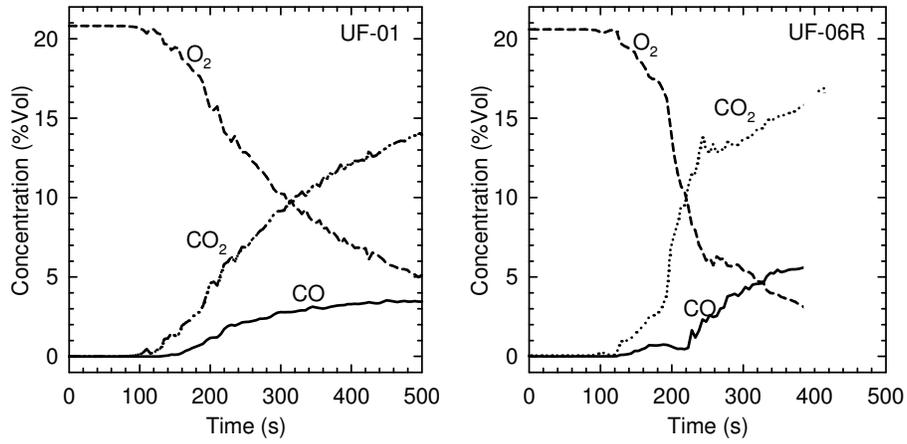
**Figure 4.** Average temperature profiles in basement fire compartment at 2.4 m height for FS-1 and FS-4



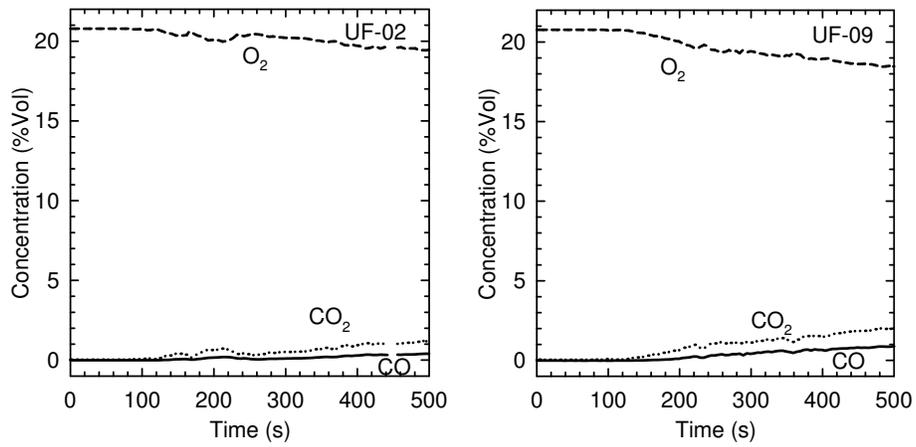
**Figure 5.** Temperatures in basement fire compartment at 2.4 m height (open basement doorway)



**Figure 6.** Temperatures in basement fire compartment at 2.4 m height (closed basement doorway)

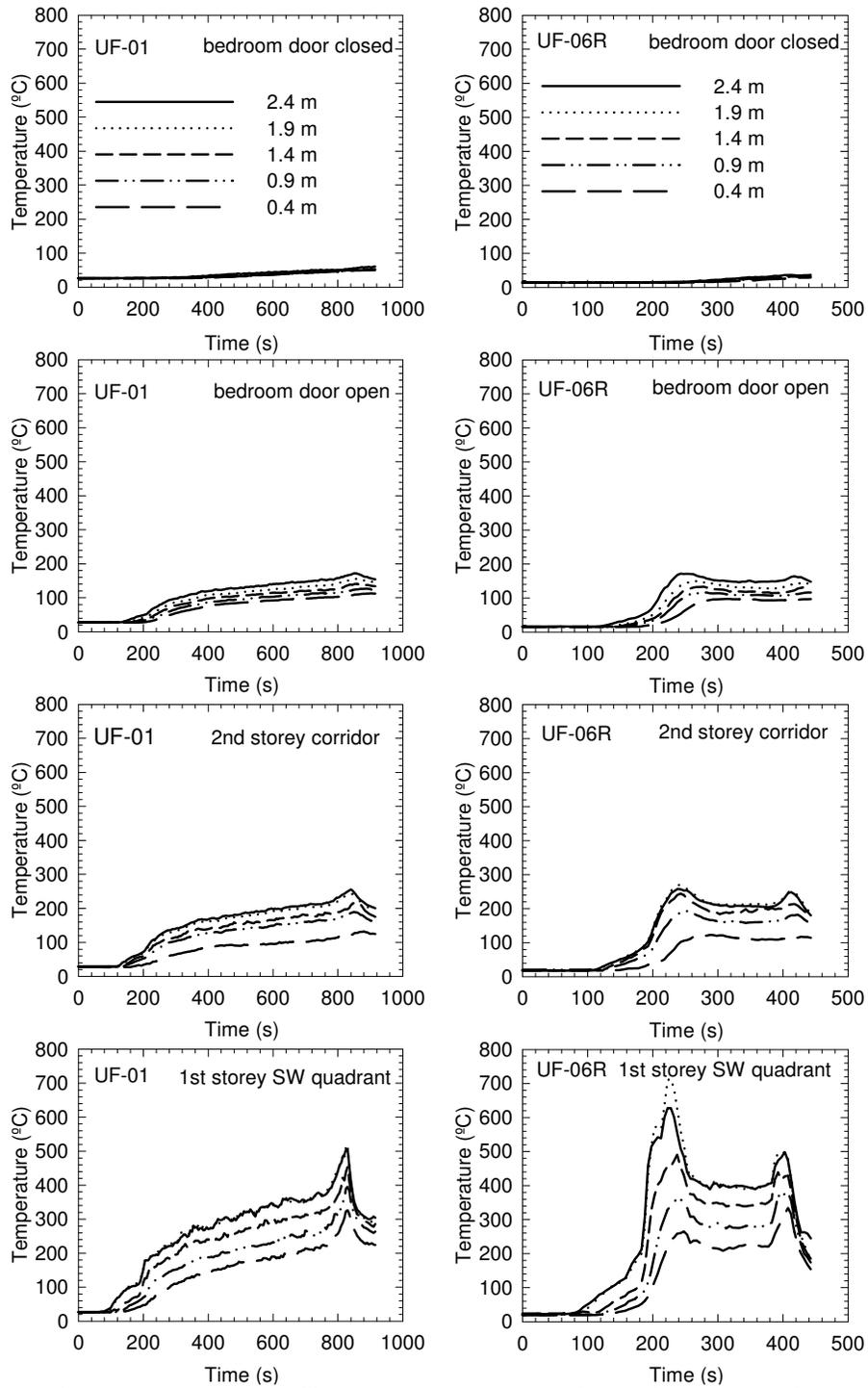


a) Open basement doorway

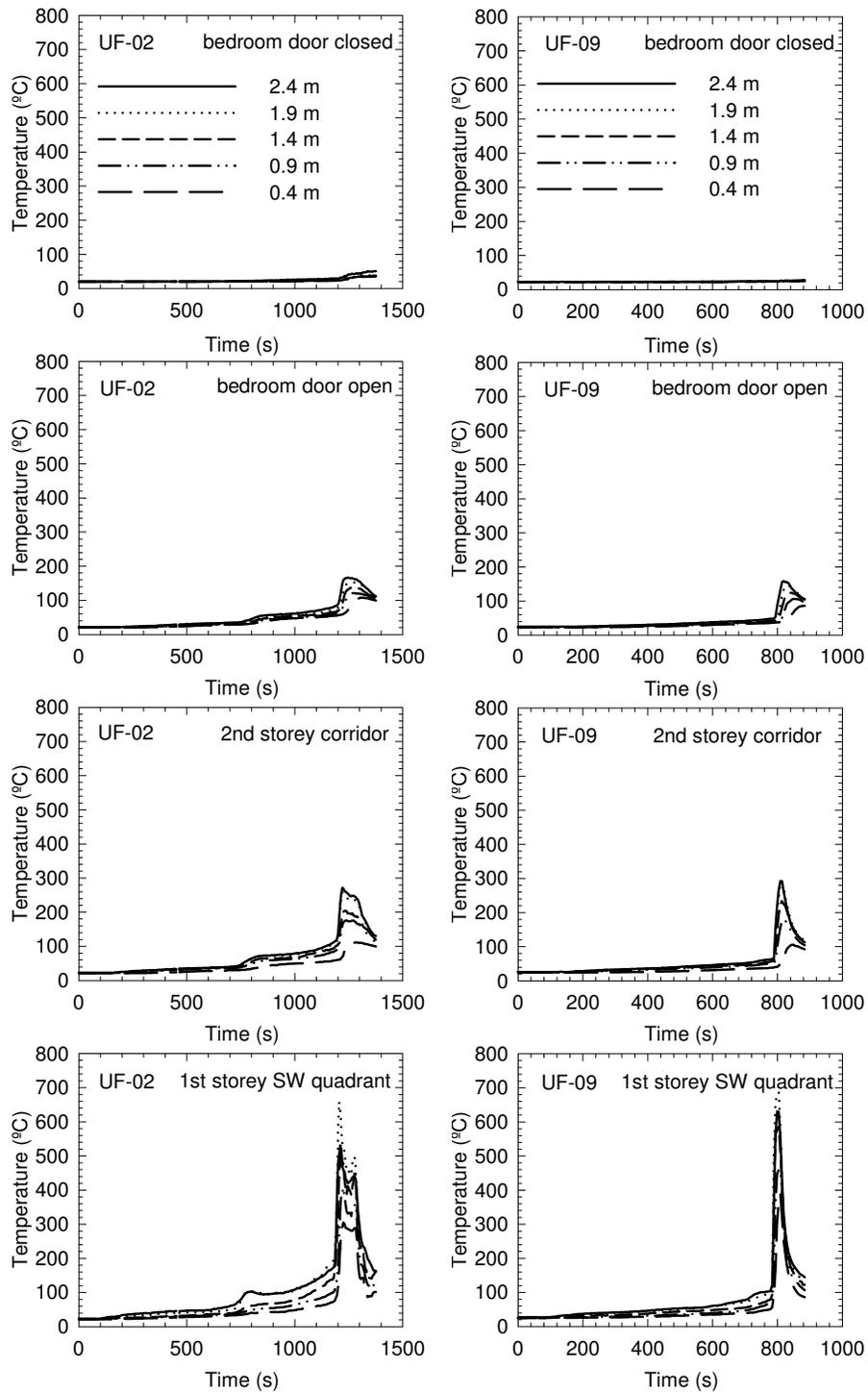


b) Closed basement doorway

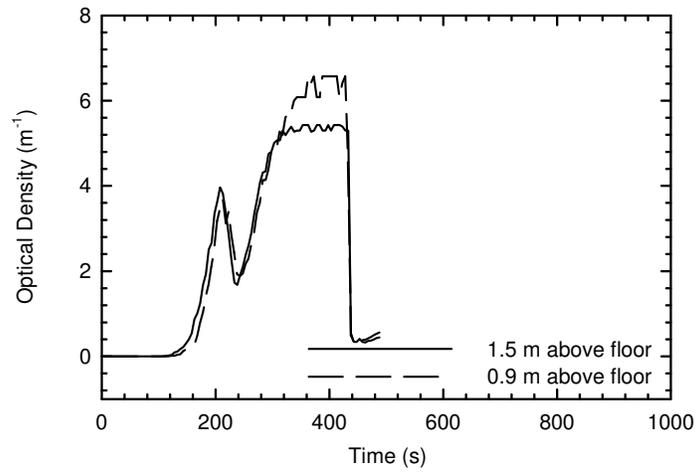
**Figure 7.** Exemplar CO, CO<sub>2</sub> and O<sub>2</sub> concentrations measured at the southwest quarter point on the first storey at 1.5 m height



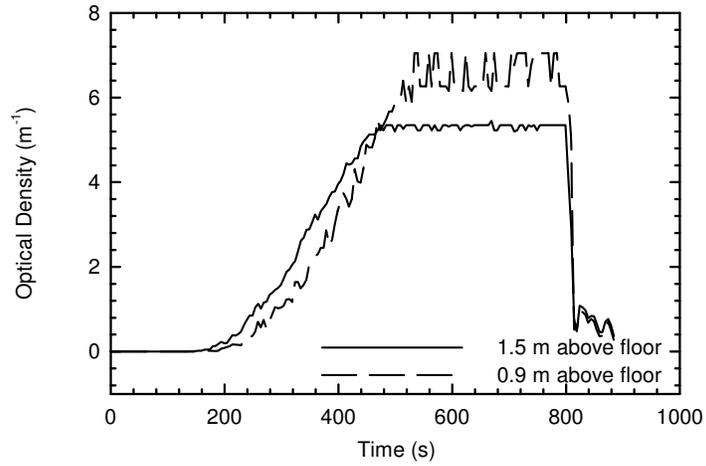
**Figure 8.** Exemplar temperature profiles on upper storeys (open basement doorway)



**Figure 9. Exemplar temperature profiles on upper storeys (closed basement doorway)**

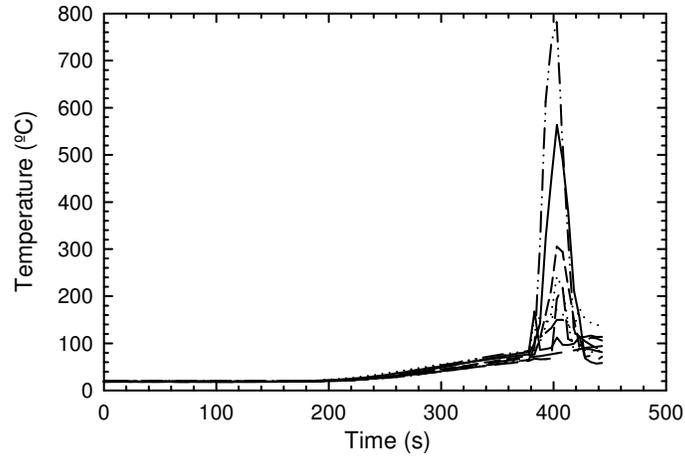


a) Test UF-06RR with open basement doorway

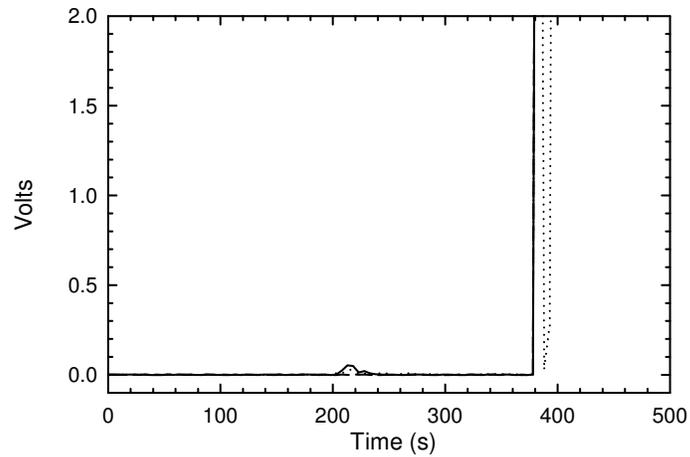


b) Test UF-09 with closed basement doorway

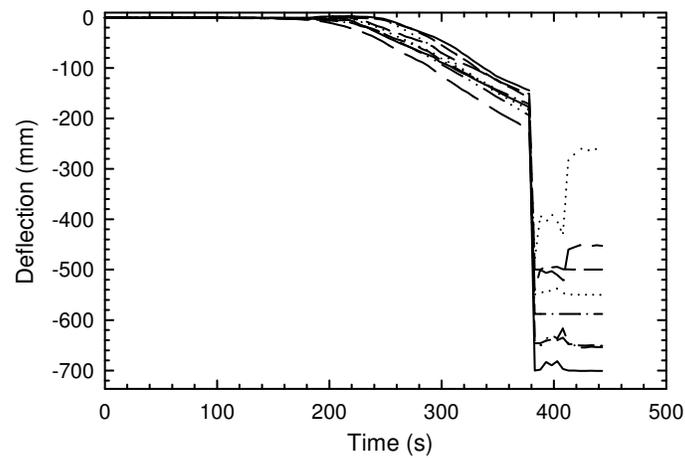
**Figure 10.** Exemplar data of smoke optical density (measured in the corridor on the second storey for Test UF-06RR and Test UF-09)



a) Thermocouples under insulated pad on top of the subfloor

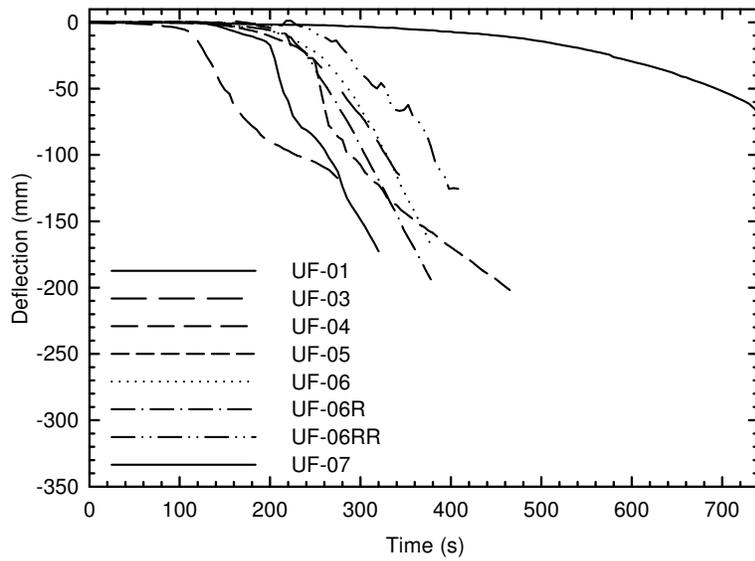


b) Flame sensors at 3 tongue and groove joints of the subfloor

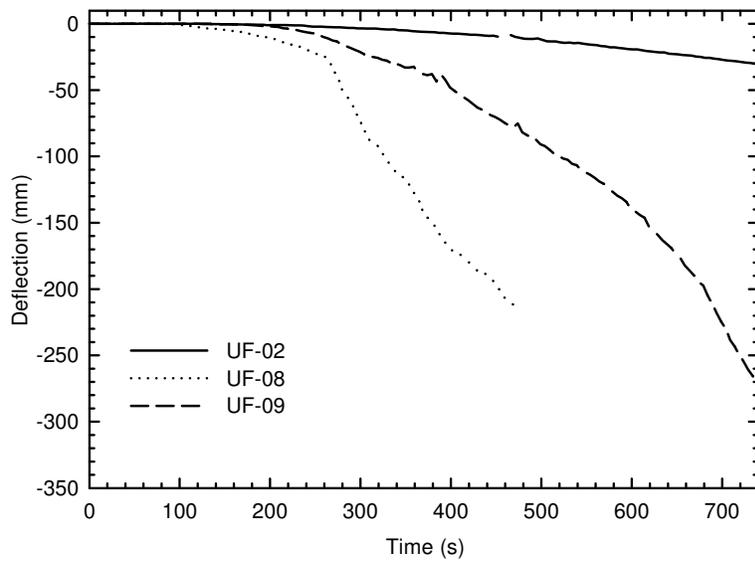


c) Floor deflections at 9 points on top of the floor assembly

**Figure 11.** Exemplar plots of measurements for determination of floor structural failure (Test UF-06R)



a) Tests with open basement doorway



b) Tests with closed basement doorway

**Figure 12.** Floor deflection near the centre of the test assemblies prior to structural failure

Table 1  
Fire Tests with Unprotected Floor Assemblies

<b>Unprotected assemblies</b>	<b>Assembly dimension (m x m)</b>	<b>Maximum span (m)</b>	<b>Intermediate support beam</b>	<b>Open basement doorway</b>	<b>Closed basement doorway</b>
<b>Solid wood joist</b> (235 mm depth by 38 mm spruce-pine-fir No. 2 and better)	5.054 x 5.175	4.17	Yes	UF-01	UF-02
<b>Wood I-joist A</b> (302 mm depth, OSB web 9.5 mm thick, laminated veneer lumber flanges 35 mm by 59 mm)	5.275 x 5.175	4.813	None	UF-03	UF-09
<b>Steel C-joist</b> (203 mm depth, 41 mm flanges, 1.438 mm thick)	5.250 x 5.150	4.477	Yes	UF-04	N/A
<b>Metal-plate wood truss</b> (305 mm depth, 38 mm x 89 mm wood members, 20 gauge metal plates)	5.079 x 5.150	4.813	None	UF-05	N/A
<b>Wood I-joist B</b> (302 mm depth, OSB web 9.5 mm thick, finger-joint lumber flanges 38 mm by 64 mm)	5.250 x 5.150	4.813	None	UF-06	N/A
				UF-06R	N/A
				UF-06RR	N/A
<b>Metal web wood truss</b> (302 mm depth, 38 mm x 64 mm wood cords, 20 gauge metal web)	5.079 x 5.150	4.813	None	UF-07	UF-08

<sup>a</sup> Floor joists or trusses were spaced at 400 mm on centre.

<sup>b</sup> In addition to the solid wood joist assembly, two engineered floor assemblies – one with the longest time and the other with the shortest time to reach structural failure in the open basement doorway scenario – were selected for testing with the closed basement doorway

<sup>b</sup> N/A – no test was conducted

Table 2

## Smoke Alarm Activation Times (in seconds) after Ignition

Location	Basement fire room		1 <sup>st</sup> storey		2 <sup>nd</sup> storey corridor		2 <sup>nd</sup> storey SW bedroom (door open)		2 <sup>nd</sup> storey SE bedroom (door closed)	
	I	P 2	I 3	P 4	I 5	P 6	I 9	P 10	I 7	P 8
Tests with open basement doorway										
Test UF-01	-	40	75	85	125	135	140	150	200	205
Test UF-03	-	48	58	73	123	133	143	143	218	228
Test UF-04	-	30	65	85	115	130	160	225	230	250
Test UF-05	-	45	40	55	130	145	155	165	245	275
Test UF-06	-	45	75	85	115	125	130	200	230	255
Test UF-06R	-	38	58	78	113	123	138	163	198	223
Test UF-06RR	-	43	73	78	128	138	143	153	223	248
Test UF-07	-	50	40	55	110	130	130	145	190	210
Tests with closed basement doorway										
Test UF-02	-	42	72	97	172	182	212	malf	427	541
Test UF-08	-	50	85	95	205	205	220	210	515	515
Test UF-09	-	44	79	89	179	179	209	204	479	459

<sup>a</sup> I: Ionization P: Photoelectric malf: malfunction

Table 3

Time (in seconds) to the Specified Fractional Effective Dose for Exposure to CO with CO<sub>2</sub> hyperventilation

FED <sub>in, CO</sub> =	1 <sup>st</sup> storey SW quadrant		2 <sup>nd</sup> storey corridor	
	0.3	1.0	0.3	1.0
Tests with open basement doorway				
UF-01	205 ± 10	235 ± 15	225 ± 10	255 ± 15
UF-03	209 ± 5	240 (-15, +5)	225 ± 10	247 ± 15
UF-04	220 (-10, +5)	260 ± 20	245 ± 10	280 ± 20
UF-05	206 ± 7	232 ± 13	235 ± 7	260 ± 10
UF-06	198 ± 10	233 (-15, +5)	208 ± 12	241 ± 10
UF-06R	198 ± 10	228 ± 5	207 ± 15	241 ± 10
UF-06RR	203 ± 10	233 ± 10	218 ± 10	248 ± 15
UF-07	225 ± 25	265 ± 7	230 ± 25	275 ± 10
Tests with closed basement doorway				
UF-02	466 ± 60	676 ± 90	362 ± 30	501 ± 70
UF-08	400 (-55, +40)	510 (-25, +*)	375 ± 35	510 (-50, +*)
UF-09	329 ± 40	484 ± 70	364 ± 35	504-70, +60)

<sup>a</sup> Calculated based on concentrations at 1.5 m height above the floor

<sup>b</sup> All values shown in the table are before fire suppression

\*Upper range of uncertainty in timing is unavailable due to commencement of fire suppression

Table 4

Time (in seconds) to the Specified Fractional Effective Dose for Exposure to Convective Heat

	1 <sup>st</sup> storey SW quadrant		2 <sup>nd</sup> storey corridor		2 <sup>nd</sup> storey open bedroom	
<b>FED<sub>in, heat</sub></b> =	<b>0.3</b>	<b>1.0</b>	<b>0.3</b>	<b>1.0</b>	<b>0.3</b>	<b>1.0</b>
Tests with open basement doorway						
UF-01	230±7	280±15	320±15	435±30	455±30	690±60
UF-03	205±3	213±3	252±5	330±25	370±30	(FED<0.8)
UF-04	207±2	215±3	250±5	290±10	325±15	460 (-35, +*)
UF-05	220±3	240±5	270±10	320±15	345±15	500(-60, +*)
UF-06	202±2	211±3	229±3	254±10	315±20	(FED<0.8)
UF-06R	193±2	199±2	217±3	238±6	293±15	(FED<0.8)
UF-06RR	209±2	216±2	234±3	298±25	393±30	(FED<0.4)
UF-07	192±2	207±5	225±5	255±10	305±15	(FED<0.9)
Tests with closed basement doorway						
UF-02	1086±30	1196 (-10, +5)	1171 (-55, +35)	1241 (-10, +5)	1263±10	(FED<0.5)
UF-08	482±1	486±1	507±2	(FED<0.5)	(FED<0.1)	(FED<0.1)
UF-09	786±1	796±1	(FED<0.2)	(FED<0.2)	(FED<0.1)	(FED<0.1)

<sup>a</sup> Calculated based on temperatures at 1.4 m height above the floor<sup>b</sup> All values shown in the table are before the fire suppression

\*Upper range of uncertainty in timing is unavailable due to commencement of fire suppression

Table 5

Time (in seconds) to the Specified Smoke Optical Density

OD =	1 <sup>st</sup> storey SW quadrant				2 <sup>nd</sup> storey corridor			
	1 m <sup>-1</sup>	1.7 m <sup>-1</sup>	2 m <sup>-1</sup>	3.4 m <sup>-1</sup>	1 m <sup>-1</sup>	1.7 m <sup>-1</sup>	2 m <sup>-1</sup>	3.4 m <sup>-1</sup>
Tests with open basement doorway								
UF-01	155	170	n.a.	n.a.	170	185	185	200
UF-03	158	168	n.a.	n.a.	173	178	183	198
UF-04	160	n.a.	n.a.	n.a.	180	190	195	210
UF-05	160	n.a.	n.a.	n.a.	175	186	190	200
UF-06	147	155	n.a.	n.a.	160	167	170	185
UF-06R	133	153	n.a.	n.a.	150	158	161	178
UF-06RR	168	n.a.	n.a.	n.a.	168	178	184	198
UF-07	134	140	n.a.	n.a.	155	165	170	330
Tests with closed basement doorway								
UF-02	187/342*	n.a.	n.a.	n.a.	247	277	297	377
UF-08	220	325	n.a.	n.a.	265	330	360	450
UF-09	186	n.a.	n.a.	n.a.	254	304	319	374

<sup>a</sup> Determined based on optical density measurements at 1.5 m height above the floor

<sup>b</sup> n.a. – not available due to limited measurement range of the smoke meters used for the first storey

\*OD = 1.0 m<sup>-1</sup> first reached at 187 s on the first storey but OD then decreased due to the exterior door was opened at 180 s, OD = 1.0 m<sup>-1</sup> reached again at 342 s

Table 6

Summary of Time to Specified  $FED_{in}$  and OD (in seconds)

Test	OD = 2 m <sup>-1</sup>		$FED_{in, CO}$ or $FED_{in, heat} = 0.3$		$FED_{in, CO}$ or $FED_{in, heat} = 1$	
	1 <sup>st</sup> storey	2 <sup>nd</sup> storey	1 <sup>st</sup> storey	2 <sup>nd</sup> storey	1 <sup>st</sup> storey	2 <sup>nd</sup> storey
Tests with open basement doorway						
UF-01	n.a.	185±5	<i>205±10</i>	<i>225±10</i>	<i>235±15</i>	<i>255±15</i>
UF-03	n.a.	183±5	<b>205±3</b>	<i>225±10</i>	<b>213±3</b>	<i>247±15</i>
UF-04	n.a.	195±5	<b>207±2</b>	<i>245±10</i>	<b>215±3</b>	<i>280±20</i>
UF-05	n.a.	190±5	<i>206±7</i>	<i>235±7</i>	<i>232±13</i>	<i>260±10</i>
UF-06	n.a.	170±5	<i>198±10</i>	<i>208±12</i>	<b>211±3</b>	<i>241±10</i>
UF-06R	n.a.	161±5	<i>198±10</i>	<i>207±15</i>	<b>199±2</b>	<i>241±10</i>
UF-06RR	n.a.	184±5	<i>203±10</i>	<i>218±10</i>	<b>216±2</b>	<i>248±15</i>
UF-07	n.a.	170±5	<b>192±2</b>	<i>230±25</i>	<b>207±5</b>	<b>255±10</b>
Tests with closed basement doorway						
UF-02	n.a.	297±5	<i>466±60</i>	<i>362±30</i>	<i>676±90</i>	<i>501±70</i>
UF-08	n.a.	360±5	<i>400</i> (-55, +40)	<i>375±35</i>	<b>486±1</b>	<i>510</i> (-50, +*)
UF-09	n.a.	319±5	<i>329±40</i>	<i>364±35</i>	<i>484±70</i>	<i>504</i> (-70, +60)

<sup>a</sup> Values determined using the measurements at 1.5 m height (for gas concentrations and OD) or 1.4 m height (for temperatures)

<sup>b</sup> 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

<sup>c</sup> n.a. – not available due to limited measurement range of the smoke meters used for the first storey

<sup>d</sup> All values shown in the table are before fire suppression

\*Upper range of uncertainty in timing is unavailable due to commencement of fire suppression

Table 7

Time to Failure ( $t_f$ ) of Unprotected Floor Assemblies

<b>Assemblies tested</b>	<b>Open basement doorway</b>		<b>Closed basement doorway</b>	
	<b>Test</b>	<b><math>t_f</math> (s)</b>	<b>Test</b>	<b><math>t_f</math> (s)</b>
Solid wood joist (235 mm depth)	UF-01	740	UF-02	1200
Wood I-joist A (302 mm depth)	UF-03	490	UF-09	778
Steel C-joist (203 mm depth)	UF-04	462	-	-
Metal-plate wood truss (305 mm depth)	UF-05	469	-	-
Wood I-joist B (302 mm depth)	UF-06	382	-	-
	UF-06R	380	-	-
	UF-06RR	414	-	-
Metal web wood truss (302 mm depth)	UF-07	325	UF-08	474

<sup>a</sup> In addition to the solid wood joist assembly, two engineered floor assemblies – one with the longest time and the other with the shortest time to reach failure in the open basement doorway scenario – were selected for testing with the closed basement doorway

Table 8

## Summary of Sequence of Events (in seconds)

Floor Assembly Type	Test	First Alarm	OD = 2 (m <sup>-1</sup> )	FED=0.3-1 1 <sup>st</sup> storey	FED=0.3-1 2 <sup>nd</sup> storey	Structural Failure
Tests with open basement doorway						
Solid wood joist	UF-01	40	185	<i>205-235</i>	<i>225-255</i>	740
Wood I-joist A	UF-03	48	183	<b>205-213</b>	<i>225-247</i>	490
Steel C-joist	UF-04	30	195	<b>207-215</b>	<i>245-280</i>	462
Metal-plate wood truss	UF-05	40	190	<i>206-232</i>	<i>235-260</i>	469
Wood I-joist B	UF-06	45	170	<i>198-211</i>	<i>208-241</i>	382
	UF-06R	38	161	<i>198-199</i>	<i>207-241</i>	380
	UF-06RR	43	184	<i>203-216</i>	<i>218-248</i>	414
Metal web wood truss	UF-07	40	170	<b>192-207</b>	<i>230-255</i>	325
Tests with closed basement doorway						
Solid wood joist	UF-02	42	297	<i>466-676</i>	<i>362-501</i>	1200
Metal web wood truss	UF-08	50	360	<i>400-486</i>	<i>375-510</i>	474
Wood I-joist A	UF-09	44	319	<i>329-484</i>	<i>364-504</i>	778

<sup>a</sup> Values determined using the measurements at 1.5 m height (for gas concentrations and OD) or 1.4 m height (for temperatures)

<sup>b</sup> 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

<sup>c</sup> All values shown in the table are before fire suppression