Fire Performance of Houses. Phase I. Study of Unprotected Floor Assemblies in Basement Fire Scenarios. Summary Report

RR-252

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EXECUTIVE SUMMARY

With the advent of new materials and innovative construction products and systems for use in construction of houses, there is a need to understand what impacts these materials and products will have on occupant life safety under fire conditions and a need to develop a technical basis for the evaluation of their fire performance. To address these needs, the Canadian Commission on Building and Fire Codes (CCBFC) and the Canadian Commission on Construction Materials Evaluation (CCCME) requested the National Research Council of Canada Institute for Research in Construction (NRC-IRC) to undertake research into fires in single-family houses to determine factors that affect the life safety of occupants.

The research sought to establish the typical sequence of events such as the smoke alarm activation, onset of untenable conditions, and structural failure of test assemblies, using specific fire test scenarios in a full-scale test facility. This test facility (referred to as the test house hereafter) simulated a typical two-storey detached single-family house with a basement, which complied with the minimum requirements in the National Building Code of Canada (NBCC). The full-scale experiments addressed the life safety and egress of occupants from the perspective of tenability for occupants and structural integrity of structural elements as egress routes.

The overall research is planned for a number of phases of experimental studies with each phase investigating specific structural systems of single-family houses based on specified fire scenarios. Phase 1 of the experimental studies focused on basement fires and the floor assembly located over a basement. The objectives were to understand the factors that impact on the ability of occupants on the upper storeys to escape in the event of a basement fire. The safety of emergency responders in a fire originating in single-family houses was not within the scope of this research project. This report provides a summary for Phase 1 of the research.

A range of engineered floor systems, including wood I-joist, steel C-joist, metal plate and metal web wood truss assemblies as well as solid wood joist assemblies, were used in the full-scale fire experiments. A single layer of oriented strandboard (OSB) was used for the subfloor of all assemblies without additional floor finishing materials on the test floor assemblies. This was considered the code minimum since there are no specific code requirements for floor finishing materials to be installed atop the OSB subfloor. For each experiment, a floor assembly was constructed on the first storey directly above the basement fire compartment under an imposed load of 0.95 kPa plus the dead load (mainly the weight of the assembly). Given that there are no specific fire resistance requirements in the NBCC for the floor assemblies in single-family houses, the floor assemblies used in the experiments were constructed with the structural elements unprotected (unsheathed) on the basement side (considered as the code minimum).

A simple fuel package was developed for use in Phase 1 full-scale experiments to create a repeatable fire that simulated a basement living area fire. This fuel package consisted of a mock-up sofa constructed with exposed polyurethane foam and wood cribs. As the first item ignited, the polyurethane foam produced a relatively severe, fast-growing fire, which was sustained by the wood cribs. With the flaming combustion of polyurethane foam and wood cribs, the primary gas products were toxic carbon monoxide (CO) and asphyxiant carbon dioxide (CO_2) in a vitiated oxygen (O_2) environment. Given the amount of polyurethane foam in the fuel package and the volume of the test house, hydrogen cyanide (HCN) produced from the combustion of polyurethane foam did not reach a concentration of concern to occupant life safety. The fuel package contained no chemical components that would produce acid halides or other irritant in the combustion gases.

Combined with different ventilation conditions, the fuel package provided two relatively severe basement fire scenarios with a reproducible fire exposure (above 800°C) to the unprotected floor-ceiling assemblies. There was good repeatability of the fire development and severity in all experiments. The only procedural difference between the two fire test scenarios was whether the doorway at the top of the basement stairwell had a hollow-core interior door in the closed position (closed basement doorway) or had no door at all (open basement doorway). There is no requirement for a basement door in the NBCC. 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 unprotected floor-ceiling assemblies. The structural integrity of the assemblies is essential for occupants on the first and second storeys to escape in the event of a serious fire. The results of this research must be interpreted within the context of the relatively severe fire scenarios used in the full-scale fire experiments.

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 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. For this project, *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. A fractional effective dose (FED) approach was used to estimate the time at which the accumulated exposure to each fire effluent exceeds a specified threshold criterion for incapacitation. The time available for escape thus calculated is the interval between the time of ignition and the time after which conditions become incapacitating for an individual occupant.

Since the general population has a wide range of susceptibility to fire effluents and heat, the exposure thresholds for incapacitation can change from subpopulation to subpopulation. Thus, each occupant is likely to have a different time available for escape. The tenability analysis for this project was conducted for 2 typical FED values (e.g. FED = 1 for a healthy adult of average susceptibility and FED = 0.3 for a more susceptible person). The methodology can be used to estimate the time available for escape associated with other FED values, if required.

Potential exposure to the toxic and asphyxiant gases, heat and smoke obscuration under the test conditions was analyzed independently to estimate the time available for escape, without consideration of the simultaneous exposure and their combined effect (the analysis for the gases involved CO and CO_2 and oxygen vitiation only). 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. In addition, CO_2 stimulates breathing that causes hyperventilation and smoke causes sensory irritation; both effects accelerate impairment from toxic gases. Although the test scenarios used in this project did not include typical furnishings, most house fires today create toxic combustion products as a result of the burning of synthetic materials.

Smoke obscuration was the first fire hazard to arise in the experiments. The smoke obscuration limit (optical density = 2 m^{-1} at which occupants cannot see more than a distance of an arm's length) 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 earlier at an optical density lower than 2 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.

Because of the variation in people's susceptibility to heat and/or gas exposure, the time to untenable conditions (incapacitation) is not a single value for a given fire condition. For the set of experiments using the fire scenario with the open basement doorway, the calculated time difference for incapacitation between an adult with average health (FED=1) and a more susceptible occupant (FED=0.3) was no more than 40 s. The tenability analysis indicates that, regardless what test floor assemblies were used, the untenable conditions (for incapacitation) were reached at a consistent time frame in the experiments with the open basement doorway. The incapacitation conditions due to heat or toxic fire gases were reached soon after smoke obscuration. The presence of a closed door in the doorway to the basement 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 untenable (incapacitation) conditions.

In all of the experiments, structural failure of the test floor assemblies occurred. The moment of floor failure was characterised by a sharp increase in floor deflection and usually accompanied by heavy flame penetration through the test assemblies as well as by a sharp increase in compartment temperature above the test floor assemblies. 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. In all experiments with the open basement doorway, the structural failure occurred after the inside of the test house had reached untenable (incapacitating) conditions. Results from replicate tests gave very repeatable durations to structural failure. Having a closed door to the basement limited the air available for combustion, given the relatively small size of the basement window opening, and prolonged the times for the test assemblies to reach structure failure (from 50-60% longer than with the open basement doorway).

There was structural deflection of all of the floor assemblies prior to their structural failure. The steel C-joist floor assembly produced the highest deflection rate, followed by metal-web and metal-plate wood trusses. The solid wood joist assemblies produced the lowest deflection rate. There were three distinct patterns for structural failure of the test assemblies. For the solid wood joist assemblies, the structure failure occurred after deflection of the floor, mainly in the form of OSB subfloor failure (burn through). For all other floor assemblies, after deflection of the floor, the structure failure occurred either in the form of complete collapse into the basement or in the form of a "V" shaped collapse due to joist or truss failure.

A literature review was conducted to estimate the time required to egress from single-family houses for ambulatory occupants assuming a tenable indoor environment and a structurally sound evacuation route. Each occupant is likely to have a different time required for escape because of different characteristics and behaviours of the occupants among other variables. In fire situations, occupants may not necessarily begin evacuation immediately upon recognizing the warning from smoke alarms. They may spend time in various pre-movement activities, such as confirming the existence of a fire, attempting to fight the fire, warning and gathering family members, gathering valuables and donning warm clothes in winter, etc. If occupants get involved in these various pre-movement activities rather than begin evacuation immediately, they may miss the window of opportunity to evacuate safely under certain circumstances. 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 to provide confident predictions.

The following conclusions can be drawn from this study on unprotected floor assemblies exposed to relatively severe basement fire scenarios selected for the study. The test facility represented a typical two-storey single-family house, which complied with the minimum code requirements in the NBCC. Overall, the fire scenario with the open basement doorway was more severe than the fire scenario with the closed basement doorway in terms of the structural integrity of the unprotected floor-ceiling assemblies and the life safety of occupants.

For Fire Scenario with Open Basement Doorway

- Under the relatively severe fire test scenario with the open basement doorway, fire events followed a chronological sequence: fire initiated and grew, smoke alarms activated, tenability limits were exceeded, and then structural failure of the test floor assembly occurred. There was a structural deflection of all of the floor assemblies prior to their structural failure.
- The estimated time to reach untenable conditions in the tests using engineered floor systems was similar to that in the test using a solid wood joist floor system. The change in floor construction basically did not change the estimated time to reach incapacitation for occupants. Data analysis indicates that tenability conditions and the time to reach untenable conditions appear to be the critical factors affecting the occupant life safety under the fire scenario tested.
- The failure of unprotected floor assemblies in the test fire scenario does not appear to be the critical issue affecting occupant life safety since the tenability limits were reached before the structural failure of the test floor assemblies.

For Fire Scenario with Closed Basement Doorway

- The presence of the closed door in the doorway to the basement reduced the rate of fire growth in the fire room and impeded the transport of combustion products from the basement to the upper storeys. The closed door prolonged the time available for escape and the time for the test assemblies 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 from 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 tenability limits were reached for healthy adults of average susceptibility. Because the floor failed structurally before the tenability limits were reached, this would represent a risk factor for the occupants.

For Both Fire Scenarios

- Fires started with polyurethane foam, a material widely used in upholstered furniture, developed rapidly to produce relatively severe fire conditions both to the occupant life safety and the structural integrity of the test assemblies.
- An early alert to a fire appears to be the key to occupant life safety. The smoke alarm located in the basement fire compartment consistently took 30-50 s to activate. (Note that the ionization smoke alarm was not installed in the basement fire room to avoid dealing with radioactive materials in the cleanup of debris after the fire tests and that using photoelectric smoke alarms in the basement resulted in more conservative activation times than using ionization smoke alarms for the flaming fire scenarios.) The experimental results highlight the importance of the requirements in the NBCC — that working smoke alarms be located on each level and that all smoke alarms be interconnected to ensure an early alert by one smoke alarm (the basement one in this study) will activate all the smoke alarms in the house. This would facilitate the occupants becoming aware of the fire sooner and would provide more time for occupant evacuation before the conditions in the house become untenable.
- 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 assemblies. The main mode of structural failure for the solid wood joist assemblies after they structurally deflected 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, after they structurally deflected, 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 closed.
- Data obtained from the test program demonstrated good repeatability of the fire severity (temperature profiles in the fire compartment), smoke alarm responses, times to untenable conditions and to structural failure.
- The results of this study reinforce the importance of continued public education on the awareness of fire hazards and the need for home fire emergency preparedness. In the event of fires similar to the relatively severe fire scenarios used in this study, the time window for safe evacuation can be very short and, therefore, it is vital for occupants to understand that when the smoke alarm sounds, everyone should leave the house immediately. It is important to have a home fire escape plan and practise the plan so that occupants know what to do in the event of a real fire in order to minimize the pre-movement activities and to quickly evacuate from their house before the conditions inside become untenable.
- More research is needed on the required egress times from single-family houses.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

FIRE PERFORMANCE OF HOUSES

PHASE I

STUDY OF UNPROTECTED FLOOR ASSEMBLIES IN BASEMENT FIRE SCENARIOS

SUMMARY REPORT

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1 INTRODUCTION

1.1 Background

Risk of fires in buildings and concerns about their potential consequences are always present. Canada's fire death rate has continuously declined for the last three decades; much of this decline is attributed to the introduction of residential smoke alarms (this is also the case in the United States). With the advent of new materials and innovative products for use in construction of single-family houses, there is a need to understand what impacts these materials and products will have on occupant life safety under fire conditions and a need to develop a technical basis for the evaluation of their fire performance.

The National Building Code of Canada (NBCC) [1] generally intends 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 [2]. Historically, the NBCC has not specified a minimum level of fire performance (fire resistance) of these structural elements in single-family houses.

In Canada, the Canadian Construction Materials Centre (CCMC) is called upon to evaluate the use of new materials and innovative construction products for compliance with the NBCC. Some of the more recent innovative structural products, seeking recognition for use in housing, are made of new composite and non-traditional materials that may have unknown fire behaviour. When evaluating new structural products, part of the CCMC challenge is related to the fact that no guidance or criteria are provided in the NBCC regarding the fire performance of structural systems used in single-family houses.

The Canadian Commission on Construction Materials Evaluation (CCCME) guides the operation of CCMC. Through the CCCME, CCMC sought the views of the Canadian Commission on Building and Fire Codes (CCBFC), which guides the development of the NBCC. After reviews and discussions, both the CCBFC and CCCME agreed that a study on the factors that affect the life safety of occupants of single-family houses should be conducted.

1.2 Objectives of the Research

The National Research Council of Canada Institute for Research in Construction (NRC-IRC) undertook research into fires in single-family houses to understand the impact of residential construction products and systems on occupant life safety.

This research sought to achieve the following goals:

1. To determine the significance of the fire performance of structural materials used in houses to the life safety of occupants.
2. To identify methods of measuring the fire performance of unprotected structural elements used in houses.
3. To measure and establish the fire performance of traditional house construction to facilitate the evaluation of the fire performance of innovative construction products and systems.

1.3 General Research Approach

The research included two components:

1. Full-scale experiments to address the key sequence of fire events that affect the life safety and egress of occupants from the perspective of tenability for occupants and structural integrity of egress routes;
2. Literature review of evacuation of occupants from single-family houses.

Figure 1 shows a possible chronological sequence of relevant critical events that might occur in a fire scenario. It is acknowledged that the chronology of the occurrence of events may differ, and in some cases can shift in ordering.

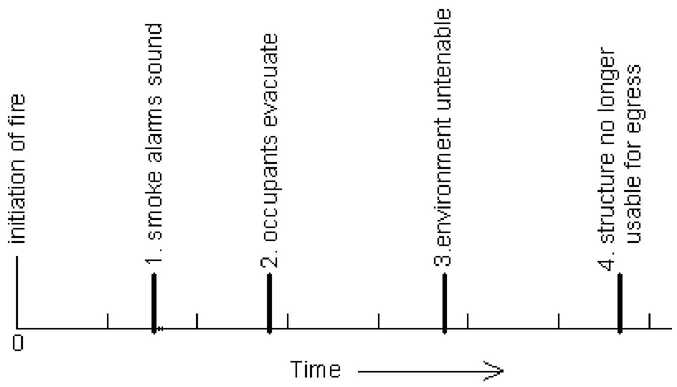

Figure 1. Possible chronological sequence of events affecting the life safety of occupants in a fire situation

The research sought to establish, through experimental studies and using specific fire test scenarios, the typical sequence of the following events (measured from initiation of a fire), using a test facility intended to represent a typical code-compliant single-family house:

1. Sounding of smoke alarms (Event 1 as shown in Figure 1)
2. Loss of tenability within the environment of the first, second or subsequent storey(s) (Event 3)

3. Loss of integrity of the floor assembly and/or loss of its function as a viable egress route on the first or second storey(s)[1] (Event 4)

The research also sought to establish a basis for prediction or estimation of the required safe egress times expected for ambulatory occupants assuming a tenable indoor environment and a structurally sound evacuation route. A review of the literature on the waking effectiveness of occupants to smoke alarms, the delay time to start evacuation and the timing of escape in single-family houses was conducted. The objective of the review was to identify a range of estimated times families would take to awake, prepare and move out of their home after perceiving the sound of a smoke alarm during the night in winter conditions (Event 2 shown in Figure 1).

1.4 Scope of the Research

The overall research was planned for a number of phases of experimental studies with each phase investigating a specific structural element based on specified fire scenarios.

Phase 1 (2004 to 2007) of the experimental study focused on basement fires and their impacts on the structural integrity of unprotected floor assemblies above a basement and the tenability conditions in a full-scale test facility. It is acknowledged that a basement is not the most frequent site of household fires but it is the fire location that is most likely to create the greatest challenge to the structural integrity of the 1st storey structure, which typically provides the main egress routes. The study of fires originating in basements also provides a good model for the migration of combustion products throughout the house and its egress paths. The data collected during this phase of the project provided important indicators for identifying and evaluating the sequence of critical events shown in Figure 1.

This research focused on the life safety of occupants in single-family houses. The safety of emergency responders in a fire originating in single-family houses was not within the scope of this research project. Technical data collected during this research could aid in clarifying the potential risks associated with firefighting activities. This report provides a summary of the findings of Phase 1.

2 LITERATURE REVIEW OF OCCUPANT EVACUATION

A review of current literature and scientific information on occupant evacuation was conducted to estimate the time required to egress from single-family houses [3]. Egress time is dependent on a wide range of factors including the location, cause, and time of the fire, the characteristics of the occupants, building design, the existence and location of working smoke alarms in the house, perceived threat or fire cues, and activities that may delay egress. There are no specific equations or methods to calculate egress times from single-family houses.

In this study, the egress time represents the time period required for an individual occupant to travel from his/her location at the time of ignition to a place of safety outside the house. The

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[1] The state of the egress route(s) on the first storey is relevant to the evaluation of the performance of the basement foundation walls and floor structure constructed over the basement; the state of the egress route on the second storey is relevant to the evaluation of the performance of the above-grade wall structures and floor structure over the first storey.

egress time can also be expressed as the activation time of a smoke alarm from ignition of a fire plus the evacuation time. The evacuation time is the time from the smoke alarm activation to the time at which the occupant reaches a place of safety outside the house.

The estimated evacuation time can be further divided into the pre-movement time and the travel time. The estimated pre-movement time is the interval between the time at which the smoke alarm is activated or fire cues are perceived and the time at which the occupant decides to evacuate. The travel time is the interval between the time at which the occupant starts to evacuate and the time at which the occupant reaches a place of safety outside the house. The travel time required to actually evacuate a normal-sized Canadian residence is likely to be small compared to the pre-movement time for most occupants.

Data related to egress time from single-family houses is very limited. Currently it is only possible to provide rough estimates of evacuation time, which should be used with great care. Based on the analysis of current literature and limited scientific information, the overall evacuation time (starting from smoke alarm activation) for a typical two-storey single-family house is estimated to be 60 s for the best-case scenario and 660 s for the worst-case scenario. The large difference in the estimated evacuation time between the best-case scenario and the worst-case scenario is mainly due to the variation in the pre-movement time. Occupants may not necessarily begin evacuation immediately upon recognizing the warning signal from smoke alarms. Rather than beginning the evacuation from the house, occupants may spend time in various pre-movement activities, such as confirming the existence of a fire, trying to fight the fire, warning and gathering family members, gathering valuables and donning warm clothes in winter, etc. The time spent in these pre-movement activities before deciding to leave the house can lengthen egress times and may result in their missing the window of opportunity to evacuate safely.

It is possible that the distribution of evacuation times is positively skewed – that the probability of short evacuation times resembling the best-case scenario might be more likely than times close to the worst-case scenario. There is not enough data in the literature at this time to develop a probabilistic analysis to provide a more precise estimate.

More research is needed on the required egress times from single-family houses to improve estimations for the times and distribution. Appropriate investigations would ideally include full evacuation drills of single-family houses in winter conditions, using a sample population of varied age whilst informing as few members of the houses as possible of the exercise. Conducting such evacuation drills using human subjects raises considerable ethical issues and has been difficult to obtain approval using realistic scenarios. Another strategy would be the investigation of actual fires in single-family houses. By interviewing survivors, the time spent doing different activities from the moment of smoke alarm notification to the time of reaching safety could be determined. The combination of these two research strategies, drills and case studies, would help provide more precise predictions.

The study also recognised that some occupants may be delayed in becoming aware of the alarm due to difficulties in arousal by smoke alarms or hearing problems etc. and that others may have limited mobility due to age and infirmity, etc., any one of which has the potential of significantly increasing evacuation time.

It is believed that the pre-movement time can be shortened by continued public education on fire hazards and emergency preparedness. It is important to have a home fire escape plan and practise the plan so that, when a real fire occurs, the pre-movement activities can be minimized and thus the evacuation time can be reduced.

3 EXPERIMENTAL STUDIES

The experimental studies involved full-scale fire tests with unprotected floor assemblies using specific basement fire scenarios to establish the sequence of events such as fire initiation, smoke alarm activation, onset of untenable conditions (an individual occupant is estimated to be incapacitated, i.e., unable to take effective action to escape to a place of safety outside), and structural failure.

3.1 Experimental Facility

The Fire Performance of Houses test facility was designed to represent a typical two-storey detached single-family house with a basement. A detailed description of the facility including the layout of the instrumentation can be found in separate reports [4-10]. Figure 2 is an elevation view showing the levels of the test facility: basement, first storey and second storey. Each of the three levels has a floor area of 95 m^2 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.

Figure 2. The test facility

The layout of the basement is shown in Figure 3. The basement was partitioned to create a fire room representing a 27.6 m^2 basement living area. This was the average size of basement compartments based on survey results [11]. 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.

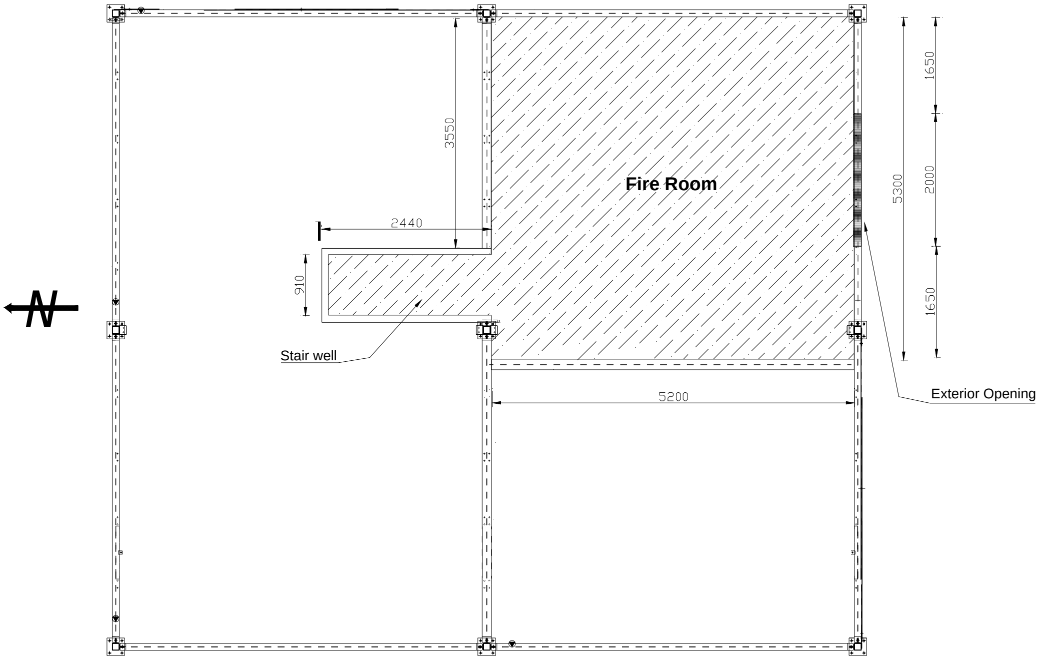


Figure 3. Basement plan view (all dimensions in mm)

A 0.91 m wide by 2.05 m high doorway opening located on 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 by 2.05 m high doorway led into the first storey, as shown in Figure 4. 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. There is no requirement for a basement door in the NBCC.

The first storey had an open-plan layout with no partitions, as shown in Figure 4. A test floor assembly was constructed on the first storey directly above the fire room for each experiment (more details are provided in Section 3.3). 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 layout of the 2nd storey is shown in Figure 5. It was partitioned to contain bedrooms, which were connected by a corridor. The experiments involved two target bedrooms of the same size. The door of the southeast bedroom remained closed whereas the door on the southwest bedroom was kept open. Each bedroom doorway was 0.81 m wide by 2.05 m high. There were no window openings on the second storey.

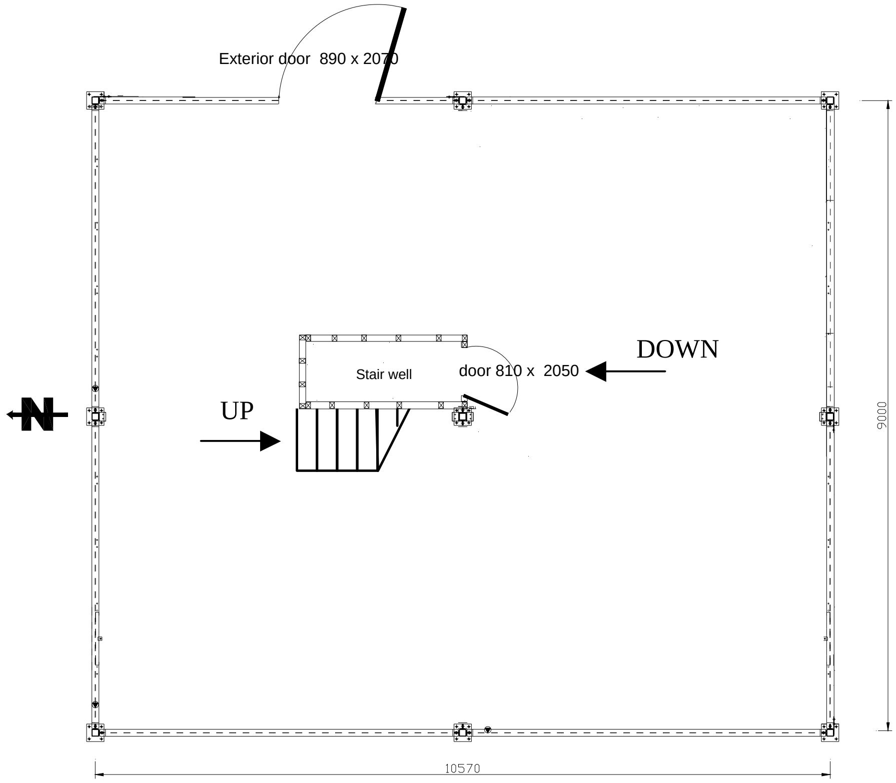


Figure 4. First storey plan view (all dimensions in mm)

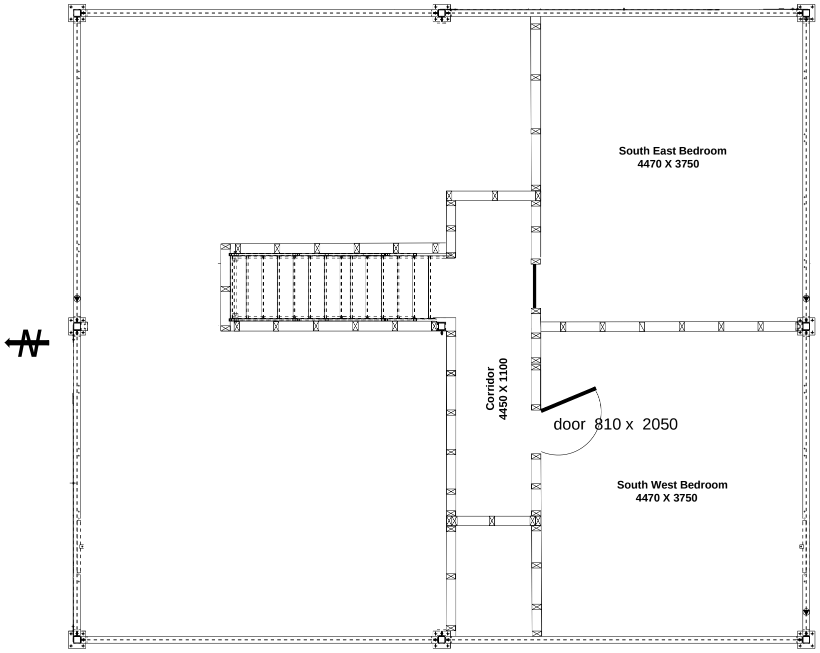


Figure 5. Second storey plan view (all dimensions in mm)

3.2 Fire Scenarios

Given the objectives of the research, the standard fire resistance test [12] was not suitable for this project. 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 [4, 13, 14, 15] were conducted in order to select fire scenarios for use in subsequent experiments with unprotected floor assemblies.

3.2.1 Fuel Package

Through a series of bench- and medium-scale calorimetric tests [13, 14], a simple and repeatable fuel package was developed for use in Phase 1 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 6. The mock-up sofa was constructed with 6 blocks of flexible polyurethane foam (with a density of 32.8 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 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. 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.

The placement of the fuel package in the basement fire compartment is illustrated in Figure 7. The mock-up sofa was located at the center of the floor area. The mock-up sofa was ignited in accordance with the ASTM 1537 test protocol [16] and the wood cribs provided the remaining fire load to sustain the fire for the desired period of time.

Figure 6. Fuel package

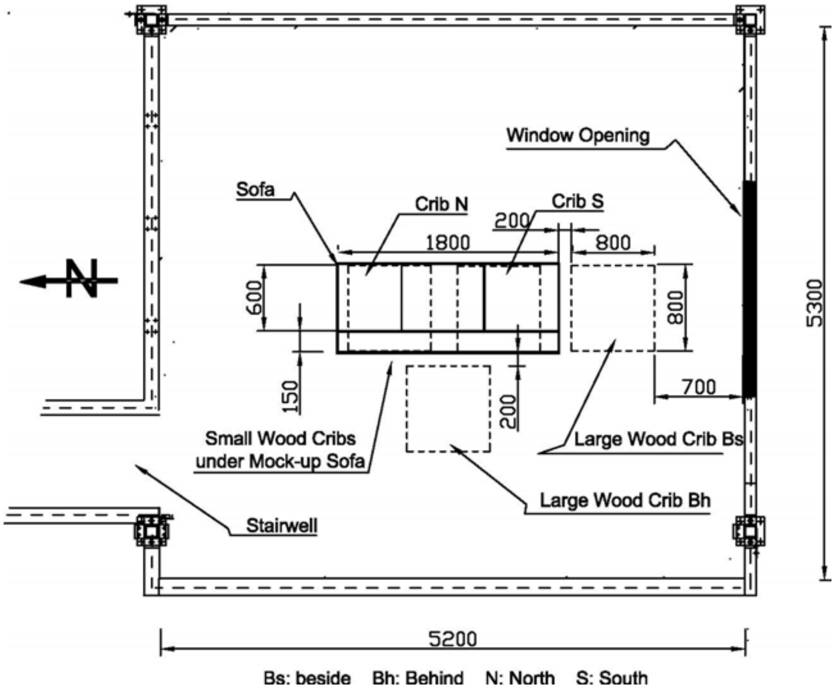


Figure 7. Layout of the fuel package (all dimensions in mm)

3.2.2 Fire Scenario Selection

A series of full-scale fire scenario tests were conducted in the Fire Performance of Houses test facility to investigate the effect of fuel quantity, ventilation and other parameters on fire growth and development [4, 15] (the full-scale test facility is referred to as the test house hereafter). For these 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 [4, 15], two fire scenarios, FS-1 and FS-4, were selected for use in subsequent experiments with unprotected floor assemblies. Ventilation parameters for the selected fire scenarios are listed in Table 1.

Table 1. Ventilation and Doorway Opening Conditions

Scenario	Basement exterior opening uncovered at*	Doorway at top of basement stairs	First storey exterior door opened at	SW Bedroom door	SE Bedroom door
FS-1	110 s	**Open**	180 s	Open	Closed
FS-4	105 s	**Closed**	180 s	Open	Closed

Note:

1. * When the temperature at the top-center of the opening reached 300°C.

3.2.2.1 FS-1 (Open Basement Doorway)

In FS-1, the doorway from the first storey to the basement fire room had no door. Since there is no requirement for a basement door in the NBCC, this scenario was considered the code minimum. The door to the southwest bedroom on the second storey was also open. The door to the southeast bedroom on the second storey was closed. The exterior window opening in the basement fire room and the exterior door on the first storey were initially closed. The mock-up sofa was ignited in accordance with the ASTM 1537 test protocol [16]. 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°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.

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 (Figure 8), indicating that this scenario would provide a relatively severe fire to challenge unprotected floor assemblies.

3.2.2.2 FS-4 (Closed Basement Doorway)

The only procedural difference between FS-1 and FS-4 was that 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 in FS-4 and the door was in the closed position. Closing the door limited the oxygen supply to the basement in the initial phase of the fire and acted as a barrier to smoke movement into the upper storeys during the early stages of the fire. The effect of the limited ventilation became pronounced after the polyurethane foam was consumed when the fire became wood-crib-dominated due to limited oxygen to support active combustion of the wood cribs.

The temperatures in the fire room were lower in FS-4 than in FS-1 during the wood-crib-dominated period (Figure 8). 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 study the effectiveness of a closed door in the basement doorway as a barrier to smoke movement into the upper storeys and as a barrier to additional oxygen supply to the fire. The experiments with this fire scenario were used 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.

3.2.2.3 Temperatures in the Fire Room

Figure 8 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.

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 NIST [17] and the University of Canterbury [18] using residential living room settings. (The results from NIST tests are shown in Figure 8 for comparison). The NIST tests were conducted with higher fuel load densities and ventilation rates and hence the higher peak temperatures.)

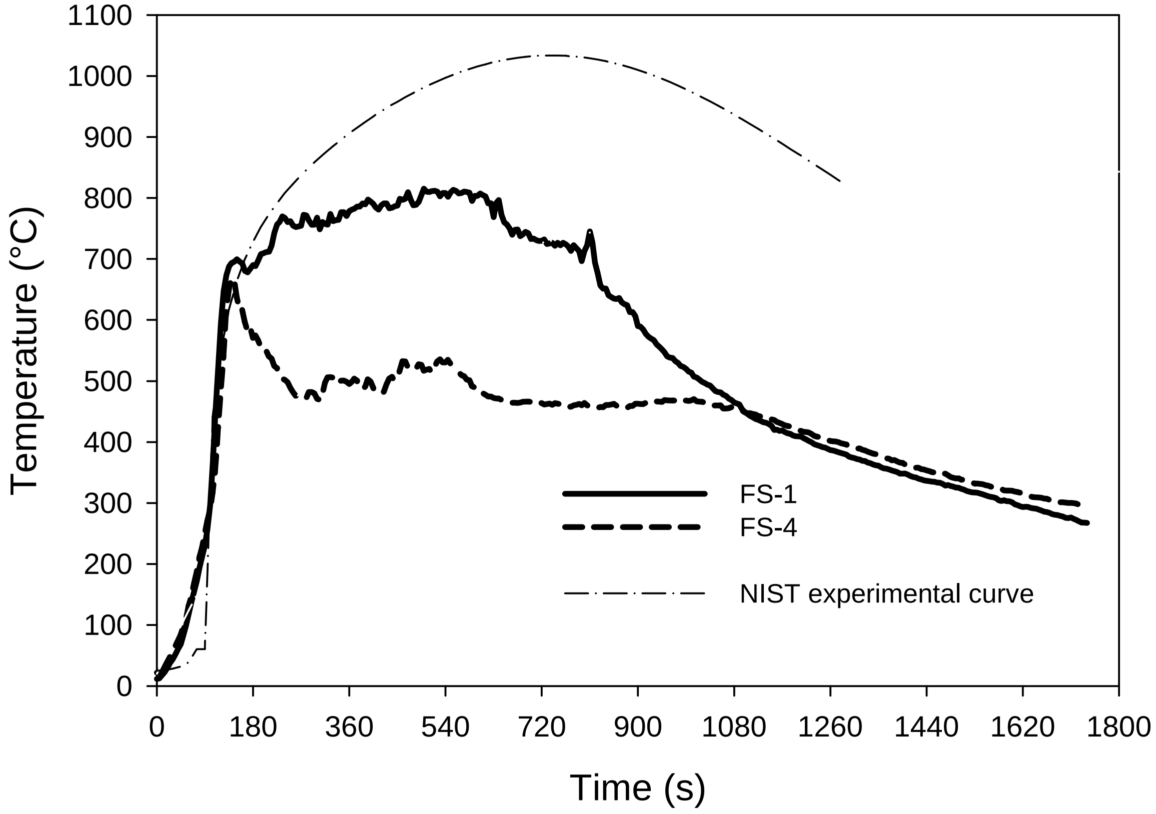


Figure 8. Average temperature profiles at 2.4 m height for FS-1 and FS-4

It is acknowledged that neither fire scenario, FS-1 or FS-4, represents a frequent household fire scenario. These scenarios were used in the project to provide a reasonable challenge to the structural integrity of the floor structure on the first storey in subsequent tests with unprotected floor assemblies.

3.3 Fire Tests with Unprotected Floor Assemblies

3.3.1 Floor Assemblies Used

A series of fire experiments were conducted in the full-scale test house with a solid wood joist system and a range of engineered floor systems available in the marketplace [5-10]. Table 2 shows the floor systems used in the full-scale fire experiments with the two fire scenarios. For each experiment, a floor assembly was constructed on the first storey directly above the 5.3 m long by 5.2 m wide basement fire compartment. Various aspects were considered in designing the test assemblies, including what is typically used for framing and subfloor materials in housing today, consideration of serviceability limit states, typical spacing, typical spans, typical depths, etc.

Oriented strandboard (OSB) is representative of subfloor materials typically used in single-family residential applications in recent years. Based on a series of cone calorimeter and intermediate-scale furnace experiments on five different OSB materials [19], an OSB subfloor material was selected for use in construction of all test floor assemblies. (Note: all OSB samples tested had comparable fire behaviour; reference [19] also contains fire test data for other subfloor and floor finishing materials used in Canadian homes.)

A single layer of OSB 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 NBCC. This was considered the code minimum and reduced the number of experimental variables.

Given that there are no specific fire resistance requirements for the floor structures in single-family houses in the NBCC, the floor assemblies used in the experiments were unprotected or unsheathed on the basement side.

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 NBCC [1] 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 [20], New Zealand and Australian standards [21, 22], and ASCE [23]). 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.

Specific details of the design and construction of the floor assemblies tested are provided in a series of research reports [5-10].

Table 2. Fire Tests with Unprotected Floor Assemblies

Unprotected assemblies	**Open basement doorway**	**Closed basement doorway**
Solid wood joist (235 mm depth)	UF-01 (June 7, 2005)	UF-02 (September 21, 2005)
Wood I-joist A (302 mm depth)	UF-03 (November 29, 2005)	UF-09 (August 30, 2007)
Steel C-joist (203 mm depth)	UF-04 (March 23, 2006)	N/A
Metal-plate wood truss (305 mm depth)	UF-05 (June 29, 2006)	N/A
Wood I-joist B (302 mm depth)	UF-06 (September 21, 2006)	N/A
	UF-06R (March 15, 2007)	N/A
	UF-06RR (October 11, 2007)	N/A
Metal web wood truss (302 mm depth)	UF-07 (February 8, 2007)	UF-08 (April 24, 2007)

Notes:

1. The test date is indicated in brackets.
2. 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.
3. N/A – no test was conducted.

3.3.2 Instrumentation

Various measurement devices were used in the experiments. Instrumentation in the floor assemblies included extensive thermocouple arrays on the unexposed and exposed sides of the assemblies, flame-sensing devices [24] and floor deflection devices [25] on the unexposed surface of the floor assemblies. Extensive thermocouple arrays were also installed in the test house to measure temperatures. Measurements of smoke optical density and primary gases from combustion were taken at the southwest quarter point on the first storey and in the corridor on the second storey. The instrumentation also included air velocity measurements at openings and stairwells, differential pressure measurements, and video cameras. Details of the instrumentation are provided in a series of NRC research reports [5-10].

3.3.3 Experimental Procedure

The mock-up sofa was ignited in accordance with the ASTM 1537 test protocol [16] and data was collected at 5 s intervals throughout each test.

The non-combustible panel that covered the fire room's exterior window 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 one of the following occurred (singly or in combination):

- Excessive flame penetration through the floor assembly;
- Structural failure of any part of the floor assembly;
- Safety of the test facility compromised.

3.4 Fire Development

Figure 9 and Figure 10 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 [5-10]. 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 9 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 10, 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 9 and Figure 10 for reference.

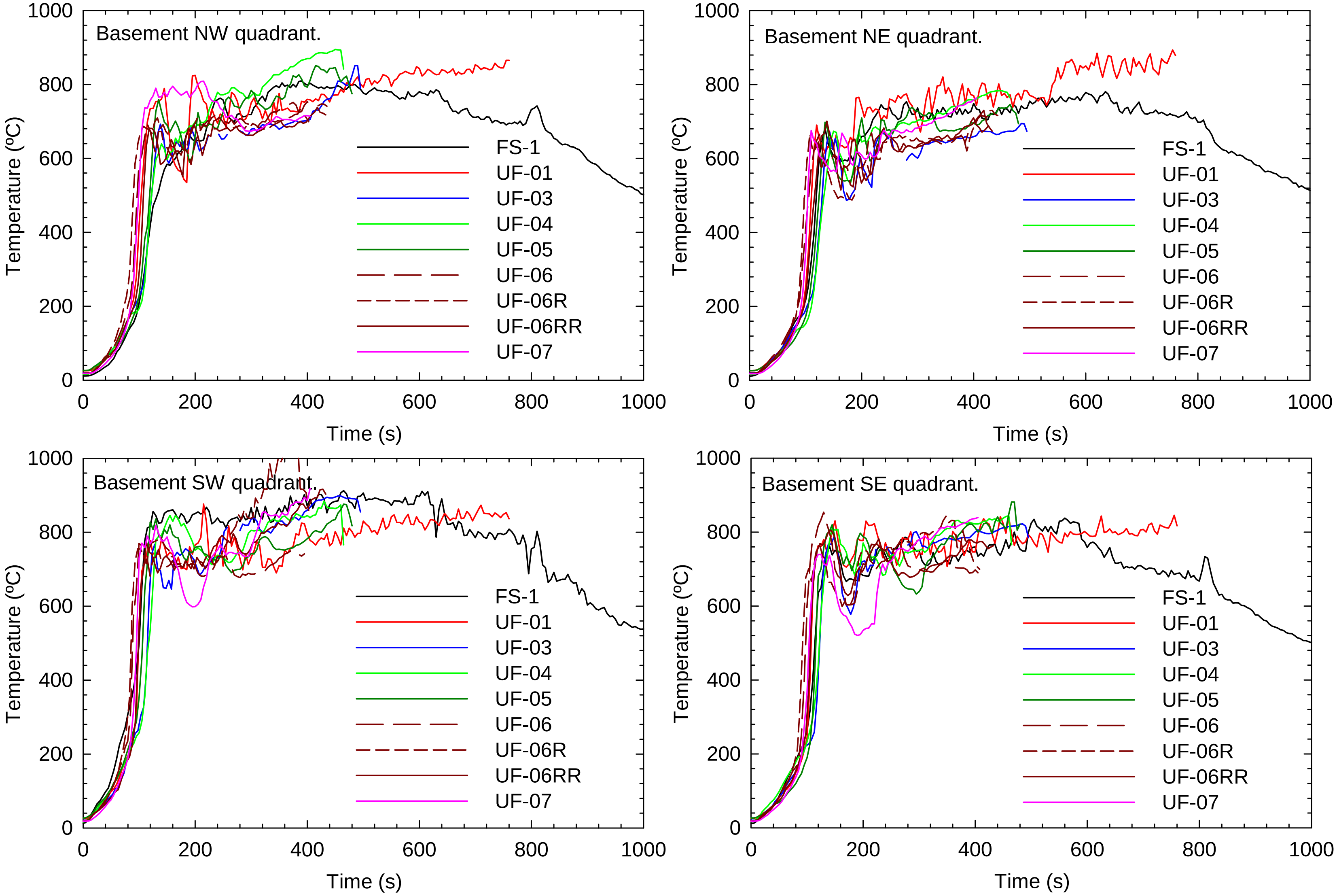


Figure 9. Temperature profiles in the basement fire compartment at 2.4 m height for experiments with open basement doorway

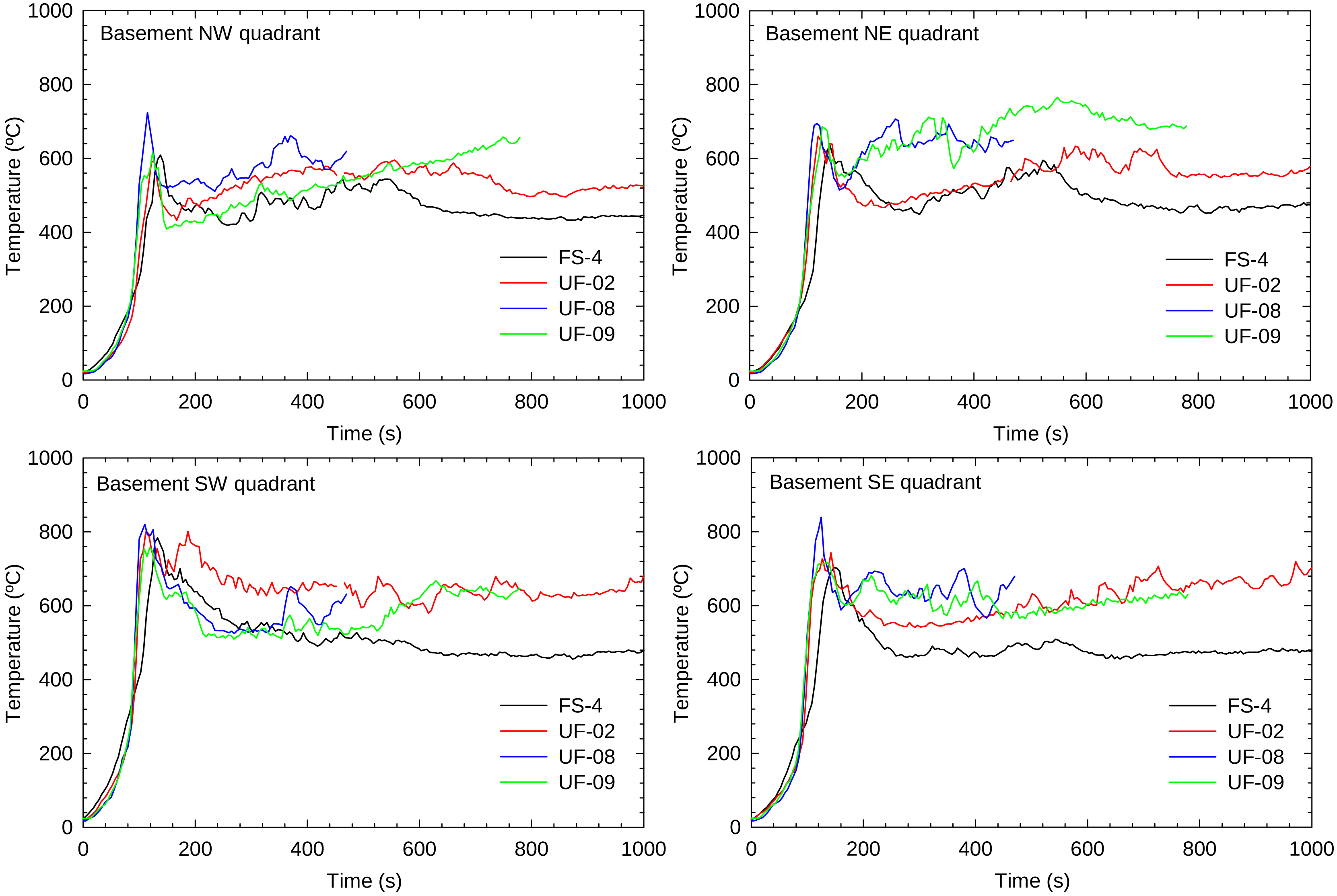


Figure 10. Temperature profiles in the basement fire compartment at 2.4 m height for experiments with closed basement doorway

3.5 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. Preliminary tests (conducted before Phase 1 of the experimental studies) using the FS-1 fire scenario indicated that the ionization alarm would activate approximately 14 seconds prior to the photoelectric alarm in the fire room. New smoke alarms were used in each experiment.

Table 3. Smoke Alarm Activation Times (in seconds) after Ignition

Location	Basement fire room		1st storey		2nd storey corridor		2nd storey SW bedroom (door open)		2nd storey SE bedroom (door closed)	
Smoke alarm type	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

Note:

1. I: Ionization P: Photoelectric malf: malfunction

Table 3 shows the activation times of the smoke alarms installed in the test facility. The photoelectric smoke alarms in the basement fire compartment took 30-50 s to activate consistently. 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. Interconnecting the smoke alarms would shorten the detection and alarm time and allow more time for evacuation. If the smoke alarms are not interconnected, the occupants in the upper storey bedrooms may not hear a smoke alarm in the basement until nearby smoke alarms activate, which could be too late for safe evacuation for the fire scenarios used in this project.

3.6 Tenability Analysis

Fires produce heat, narcotic and irritant gases, and smoke that obscures vision. The temperature and the production of combustion products depend upon the fire characteristics, enclosure geometry and ventilation. The increased temperature and combustion products can, either individually or collectively, create conditions that are potentially untenable for occupants.

Tenability analysis involves examination of the production of heat and toxic products of combustion during the fire tests. It also involves estimation of the potential exposure of occupants, who would have been in the test house, to heat and toxic smoke and of the potential effects as a result of the exposure. The purpose of tenability analysis is 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.

There are various endpoints for tenability analysis, such as incapacitation, lethality/fatality, etc. For this project, *incapacitation* – a state when people lose the physical ability to take effective action to escape from a fire – was chosen as the endpoint for the tenability analysis related to heat and toxic products of combustion. The time available for escape thus calculated is the interval between the time of ignition and the time after which conditions become incapacitating for an individual occupant.

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 [26, 27]. These methodologies were used in this project to calculate the time available for escape as an input to the hazard analysis for each fire scenario used in the project. The methodologies include a fractional effective dose (FED) approach to quantify the time at which the accumulated exposure to each fire effluent exceeds a specified threshold criterion for incapacitation. This time then is taken to represent the time available for escape relative to the specified threshold.

The calculated time available for escape depends not only on the time-dependent temperatures, concentrations of combustion gas products and density of smoke in the test house, but also on the characteristics of occupants. The age and health of the occupants (such as body weight and height, lung and respiratory system function, blood volume and hemoglobin concentration, skin, vision, etc.) as well as the degree of activity at the time of exposure have an effect on the consequences of exposure to fire effluents and heat. Since the general population has a wide range of susceptibility to fire effluents and heat, the exposure thresholds for incapacitation can change from subpopulation to subpopulation. Thus, each occupant is likely to have a different time available for escape.

This report does not try to debate what FED criterion should be used as the incapacitation threshold but rather to present the results of the analysis for 2 typical FED values (e.g. FED = 1 and FED = 0.3). The methodology can be used to estimate the time available for escape associated with other FED values, if required.

The time available for escape calculated based on FED = 1 represents the time available for a healthy adult of average susceptibility. The distribution of human responses to the fire effluents is unknown but is assumed to be a logarithmic normal distribution [26]. Under this distribution, the time available for escape calculated at FED = 1 also represents statistically the time by which 50% of the general population would have been incapacitated but the conditions would still be tenable for the other 50% of the population.

For a more susceptible person, the threshold can be lower and the time available for escape would be shorter than for an average healthy adult. If FED = 0.3 is used as a criterion to determine the time available for escape, it would statistically represent the time by which 11% of the population would have been incapacitated but the conditions would still be tenable for the other 89% of the population.

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 in the following sections was associated with a particular position where the concentration or temperature was measured, and should apply to an occupant who would stay at that location. 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. For this project, tenability analysis focused on potential impact on occupants who would have been on the upper storeys of the test house. The conditions in the basement fire room would not be survivable once flashover occurred.

The methodology used does not address quantitatively any interaction (combined effects) between heat, combustion gas products and smoke obscuration. Each component is treated as acting independently on the occupant to create incapacitating conditions and the time available for escape is the shortest of the times estimated from consideration of exposure to combustion gas products, heat and visual obscuration.

It is necessary to recognize that 2 types of uncertainty exist in the tenability analysis: the uncertainties associated with the experimental data and the uncertainties associated with the equations for FED calculations. Fortunately, with the fast-growing fire used in the project, the resulting uncertainty in the estimated time available for escape is much smaller than the uncertainty in the calculated FED due to their non-linear relationship.

3.6.1 Exposure to Toxic Gases

Exposure to toxic products of combustion from fires has been a major cause of death and injury in many fire incidents. Understanding the toxic effect of the smoke products and predicting the exposure time necessary to cause incapacitation are complex problems.

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 toxic carbon monoxide (CO) and asphyxiant carbon dioxide (CO_2) in a vitiated oxygen (O_2) environment. Given the amount of polyurethane foam in the fuel package and the volume of the test house, hydrogen cyanide (HCN) produced from the combustion of polyurethane foam would not reach a concentration of concern for occupant life safety. A recent review concluded that exposure to products of flaming combustion of flexible polyurethane foam would result in CO levels in the blood of test animals generally consistent with simple CO exposure, despite the toxicological role of HCN [28]. The fuel package contained no chemical components that would produce acid halides in the combustion gases. In this project, the analysis involved CO and CO_2 and oxygen vitiation only.

Figure 11 shows the CO, CO_2 and O_2 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_2 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_2 asphyxiant effect alone [27]. The concentrations reached a minimum of 3% O_2 and above 16% CO_2 near the end of the experiments. As shown in a series of detailed reports [5-10], the toxic effect of CO would be capable of causing incapacitation at an earlier time than the effect of O_2 vitiation and the asphyxiant effect of CO_2. 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_2 concentrations on the upper storey(s) were 15% or above before structural failure occurred.

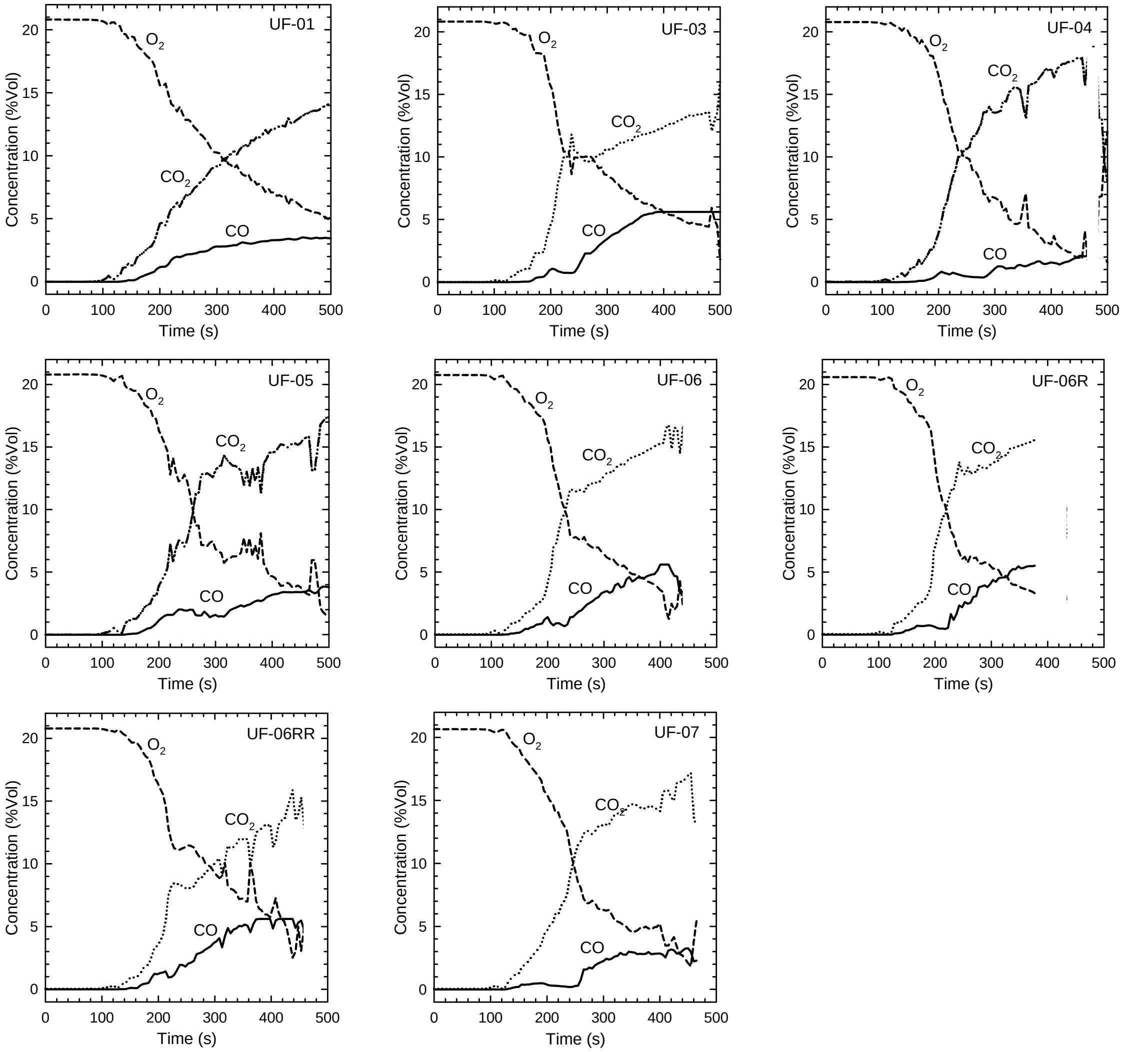
The toxic effect of CO is due to its affinity with the hemoglobin in human blood to form carboxyhemoglobin (COHb), which reduces the transport of oxygen in the blood to various parts of the body. When COHb in the blood increases to a threshold concentration, loss of consciousness or death may occur. The time for the toxic effect to occur depends on the uptake rate of CO into the blood of a victim and the threshold COHb concentration for that victim.

The CO uptake rate is determined by the difference between the CO concentration inhaled and that already in the body, and varies with the breathing rate, the degree of activity, the lung function, the body size, the blood volume and hemoglobin concentration of the victim and the exposure duration. The complexity of the CO uptake is described by the theoretical Coburn-Forster-Kane (CFK) equation, which takes account of a wide range of variables to predict the COHb concentration [29]. In addition, CO_2 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.

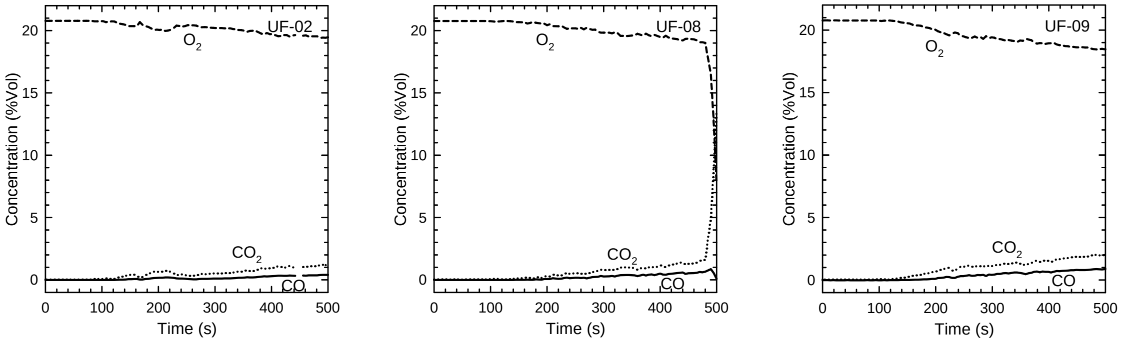
The COHb incapacitating concentration at which loss of consciousness may occur is in the range of 25-40% depending on the degree of activity of the occupant among other variables [27, 30]. The threshold of 40% is more appropriate for those at rest and 30% for those engaged in light activity [27]. Certain susceptible populations may be incapacitated at lower COHb concentrations.

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 [26]:

$$FED_{in,CO} = \sum_{t1}^{t2} \frac{[CO]\cdot\Delta t}{35000} \exp(\frac{\%CO_2}{5})$$



a) Open basement doorway



b) Closed basement doorway

Figure 11. CO, CO_2 and O_2 concentrations measured at the southwest quarter point on the first storey at 1.5 m height

where *[CO]* is the inhaled carbon monoxide concentration in *parts per million*, *Δt (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_2-induced hyperventilation factor for breathing [26, 27]. 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 [27, 31]. The uncertainty in the calculation of $FED_{in,CO}$ is estimated to be ±40% [26].

Table 4 shows the calculated times for the fractional effective dose reaching 0.3 (an incapacitation dose for some susceptible people) and 1.0 (an incapacitation dose for healthy adults of average susceptibility), including the uncertainty in the estimated times. The CO uptake and the COHb increase are known to be faster in small children than in adults [32]. The incapacitation time for small children or a more susceptible subpopulation would be shorter than for average healthy adults. These can be addressed, to a certain degree, by using $FED_{in,CO}$ = 0.3 as a criterion to determine the incapacitation time.

Table 4. Time (in seconds) to the Specified Fractional Effective Dose for Exposure to CO with CO_2 hyperventilation

	1st storey SW quadrant		2nd storey corridor	
$FED_{in, CO}$ =	**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)

Notes:

1. Calculated based on concentrations at 1.5 m height above the floor;
2. All values shown in the table are before fire suppression;
3. *Upper range of uncertainty in timing is unavailable due to commencement of fire suppression.

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. Assuming the rate of CO uptake remains unchanged, the time required from the incapacitation dose $FED_{in,CO}$ = 1.0 to the lethal dose for an average adult was estimated to be within 60 s under the test conditions.

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.

3.6.2 Exposure to Heat

Figure 12 and Figure 13 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 12) and for the tests using the closed basement doorway scenario (Figure 13), 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 [27]. 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 [26, 27]:

$$FED_{in,\,heat} = \sum_{t1}^{t2} \frac{T^{3.4}}{5 \times 10^{7}} \Delta t$$

where T *(°C)* is the temperature and Δt *(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 ±25%. Since there was temperature stratification, the temperatures at the 1.4 m height from 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 $kW \cdot m^{-2}$ to produce second degree burning of skin [33]. 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.

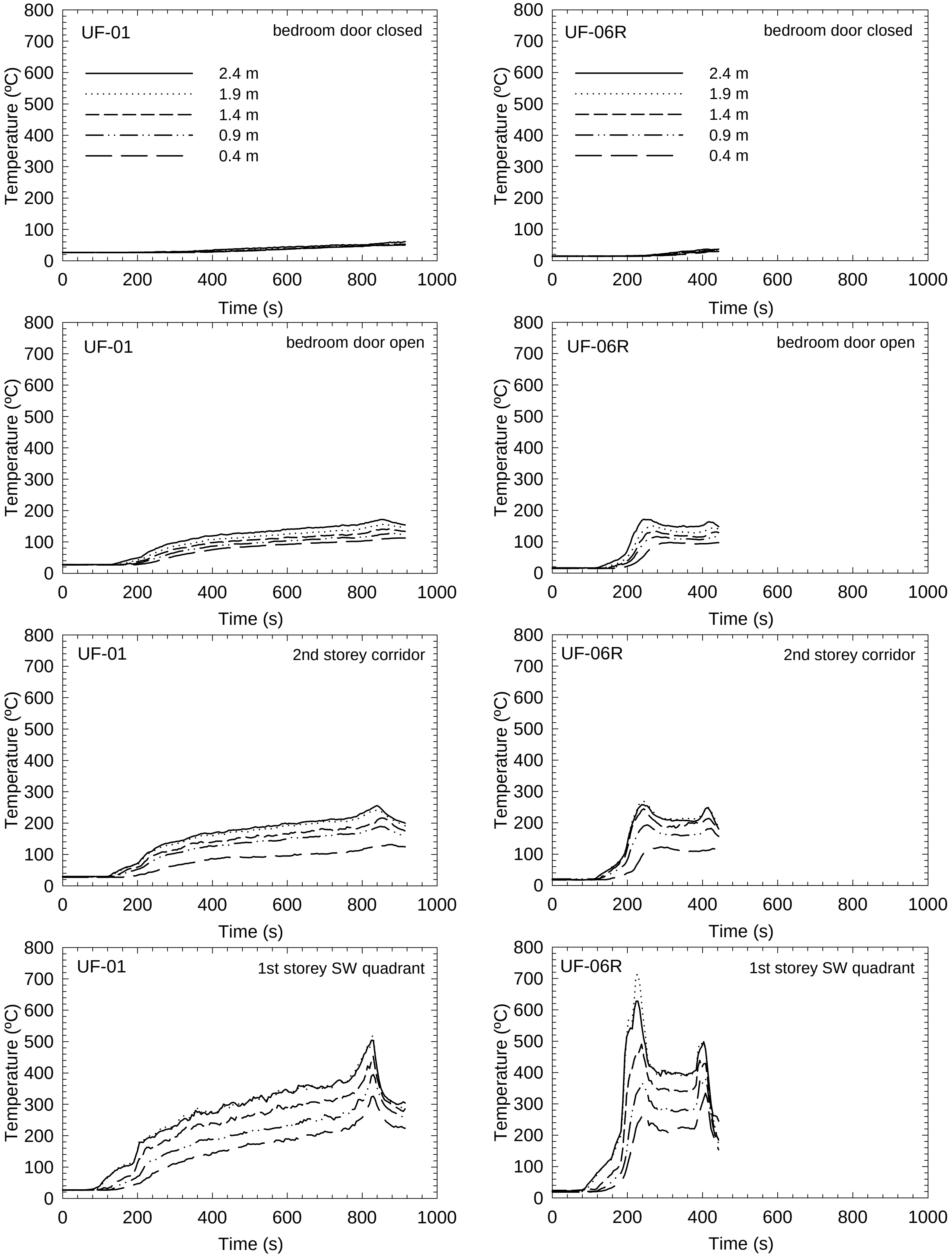


Figure 12. Exemplar temperature profiles measured on the first and second storeys (open basement doorway)

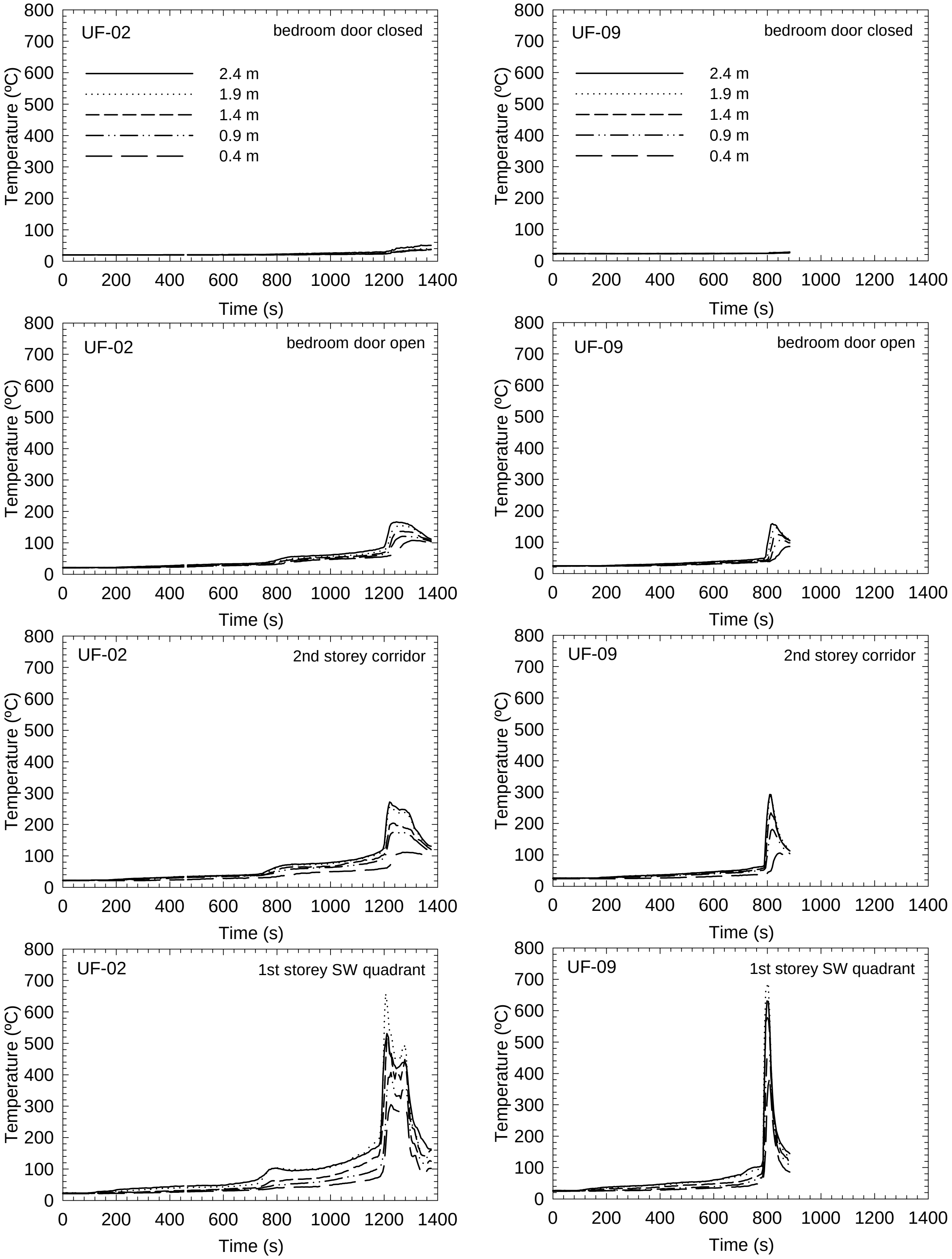


Figure 13. Exemplar temperature profiles measured on the first and second storeys (closed basement doorway)

Table 5. Time (in seconds) to the Specified Fractional Effective Dose for Exposure to Convective Heat

	1st storey SW quadrant		2nd storey corridor		2nd storey open bedroom	
$FED_{in,\ heat}$=	**0.3**	**1.0**	**0.3**	**1.0**	**0.3**	**1.0**
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)

Notes:

1. Calculated based on temperatures at 1.4 m height above the floor;
2. All values shown in the table are before the fire suppression;
3. *Upper range of uncertainty in timing is unavailable due to commencement of fire suppression.

The convective heat exposure depended on the location in the test house. In the closed bedroom, heat exposure would not cause incapacitation ($FED_{in,heat}$ = 0.01~0.07 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 5 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.

3.6.3 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) [34]. In this report, the smoke obscuration is expressed as the optical density per meter (*OD* in m^{-1}):

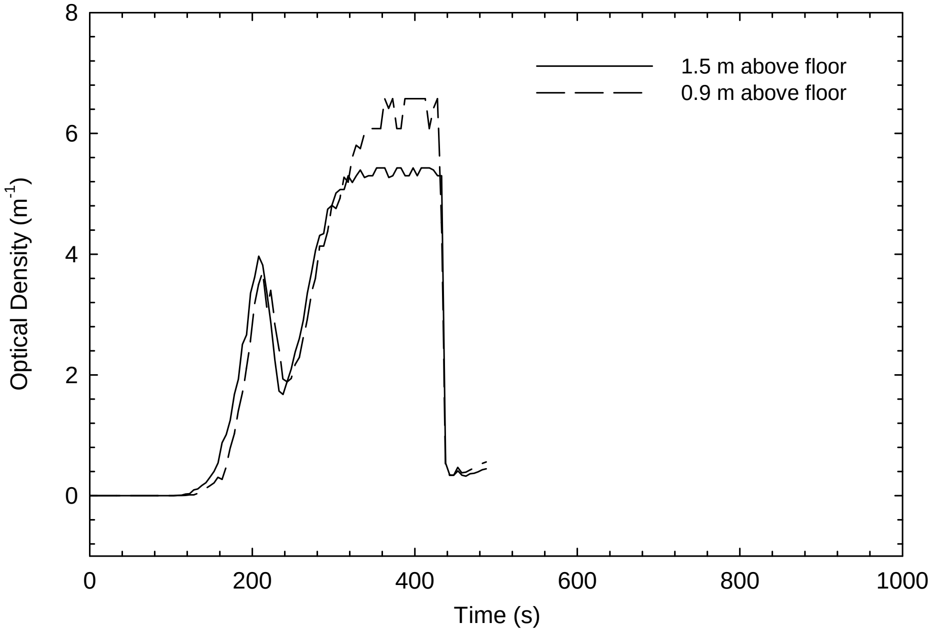
$$OD = \frac{1}{L}\log_{10}\left(\frac{I_0}{I}\right)$$

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 $OD = k/2.303$.

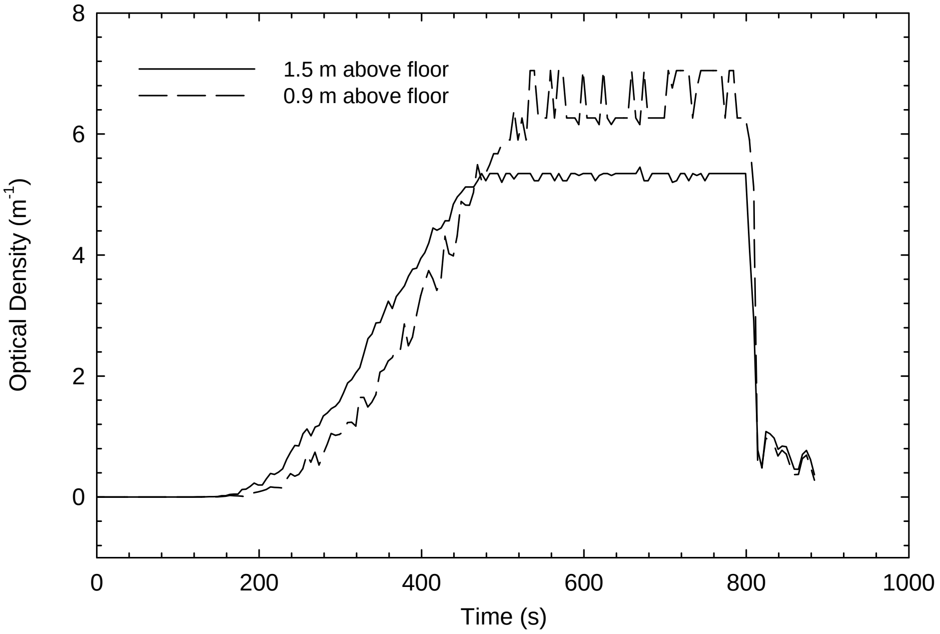
Various threshold *OD* values have been suggested as the tenability limit for smoke obscuration for small buildings with occupants familiar with the egress route [27, 30, 34, 35, 36]. In ISO 13571[26], the minimum visible brightness difference between an object and its background is used to estimate the smoke obscuration limit at which occupants cannot see their hands in front of their faces (a distance of 0.5 m or less). 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 [34]. Possible reduction of time to untenable smoke level due to psychological effect is not addressed in this report. 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 14 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 6 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, which was further reduced by smoke residue from the preceding tests inside the meters. These meters could not measure the smoke obscuration of OD = 2 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 4 and Table 6 that the times when the optical density reached 3.4 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.



a) Test UF-06RR with open basement doorway



b) Test UF-09 with closed basement doorway

Figure 14. Exemplar data of smoke optical density measurements (in the corridor on the second storey for Test UF-06RR and Test UF-09)

Table 6. Time (in seconds) to the Specified Smoke Optical Density

	1st storey SW quadrant				2nd storey corridor			
OD =	**1 m^{-1}**	**1.7 m^{-1}**	**2 m^{-1}**	**3.4 m^{-1}**	**1 m^{-1}**	**1.7 m^{-1}**	**2 m^{-1}**	**3.4 m^{-1}**
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

Notes:

1. Determined based on optical density measurements at 1.5 m height above the floor;
2. *OD = 1.0 m^{-1} 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^{-1} reached again at 342 s;
3. n.a. – not available due to limited measurement range of the smoke meters used for the first storey.

3.6.4 Summary of Estimation of Time to Incapacitation

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 obscuration. The combined effect as a result of the simultaneous exposure is not well understood. In this report, the gas exposure, heat exposure and smoke obscuration are analyzed independently without consideration of the combined effect. Table 7 summarizes the estimated times to the onset of various conditions.

The uncertainty in the calculation of the fractional effective dose is estimated to be ±25% for the heat exposure and ±40% for the CO exposure (with CO_2 induced hyperventilation) [26]. 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 ±5 s. Table 7 lists the uncertainty in the estimated times.

Table 7. Summary of Time to Specified FED_{in} and OD (in seconds)

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

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. n.a. – not available due to limited measurement range of the smoke meters used for the first storey;
4. All values shown in the table are before fire suppression;
5. *Upper range of uncertainty in timing is unavailable due to commencement of fire suppression.

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 m^{-1} was reached consistently around 180 s. With the closed basement doorway, the time to the tenability limit OD_{Limit} = 2 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 CO_2-induced hyperventilation), whichever occurred first, is listed in Table 7. Heat exposure tended to be more severe on the first storey than on the second storey. For the experiments with the open basement doorway, except for Test UF-01, heat exposure reached the specific FED on the first storey at times shorter or similar to CO exposure. On the second storey (in the corridor), except for Test UF-07, CO exposure reached the specific FED earlier than heat exposure. 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. More detailed information for each test is available in individual test reports [5-10].

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 at a consistent time frame soon after smoke obscuration.

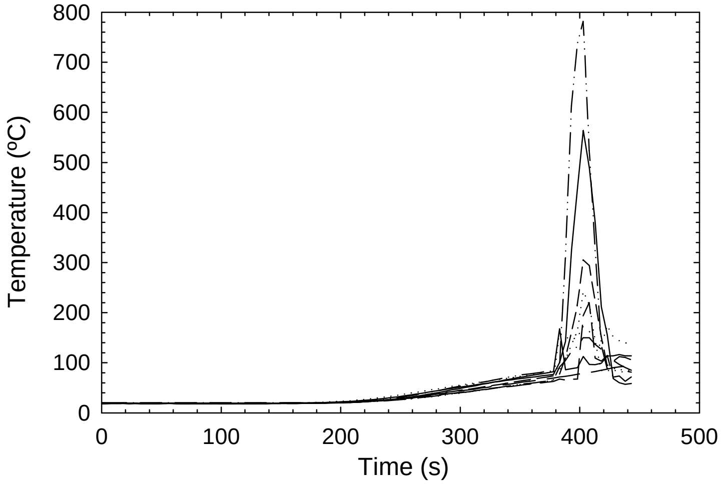
The presence of the closed door in the doorway to the basement fire room reduced the rate at which combustion products were conveyed to the upper storeys and thereby prolonged the time available for escape before the onset of incapacitation conditions. The time available for escape was at least doubled 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 the 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. Further analysis was conducted for occupants who would have been in the closed bedroom and attempting to escape by opening the bedroom door and following the normal routes. This analysis indicated that they would have likely obtained the incapacitation doses at about the same time as occupants who would have remained in the open areas of the test house.

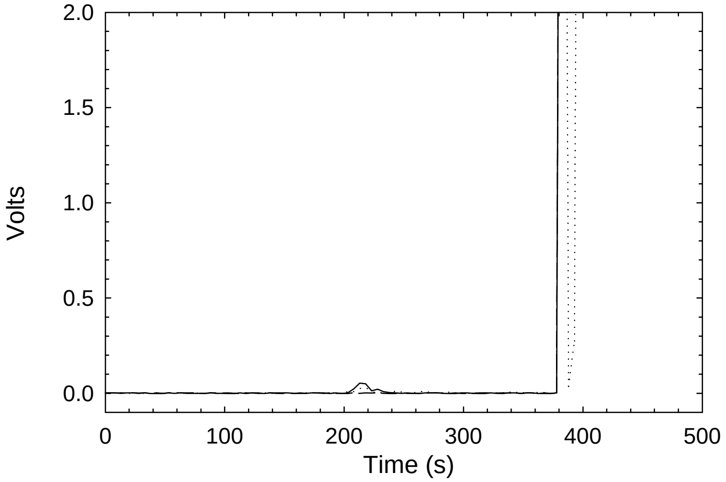
3.7 Structural Response

A floor system provides an egress route for occupants and its structural integrity directly impacts the safe evacuation of the occupants from the house during 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 15 shows exemplar data plots of these measurements, which are also representative for other tests with the engineered floor assemblies.

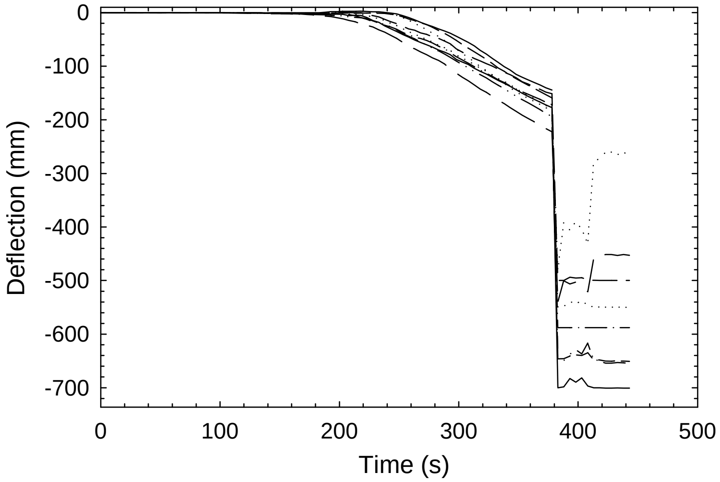
Flame penetration through the floor assembly is considered to be an initial indicator of the impending failure of the assembly, and is a failure criterion in standard fire resistance testing [12]. Flame penetration could also impact the time available for escape and the ability of occupants to evacuate. Any openings created by the 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.



a) Thermocouples under insulated pads 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 15. Exemplar plots of measurements for determination of floor structural failure (Test UF-06R)

The temperatures shown in Figure 15(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. It is worth mentioning that failure under standard fire resistance test conditions [12], on the basis of temperature, 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 [24] 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 [5-10]. As shown in Figure 15(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 deflection of the floor assemblies was measured at nine points using an electro-mechanical method described in Reference [25]. The measurement points were located in the central area of the test floor 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 (see references [5-10] for details). Figure 15(c) shows examples of the deflection measurements. The sharp increase in deflection is an indication that the structural collapse occurred.

Table 8 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.

Table 8. Time to Failure (t_f) of Unprotected Floor Assemblies

	Open basement doorway		**Closed basement doorway**	
Assemblies tested	**Test**	**t_f (s)**	**Test**	**t_f (s)**
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

Note:

1. 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.

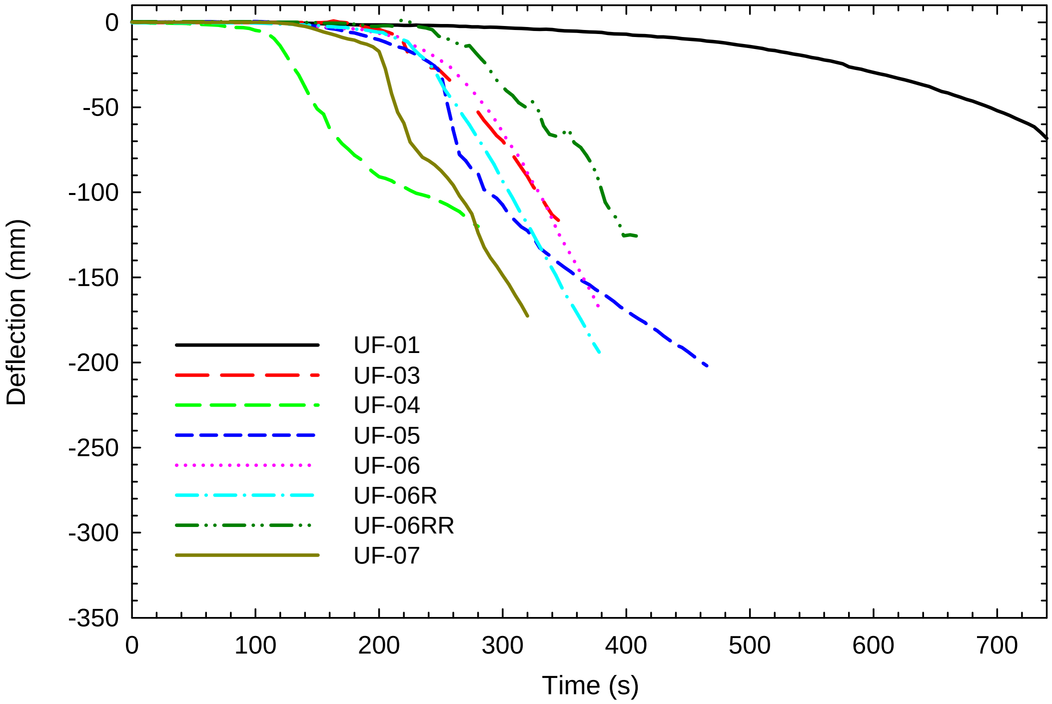
With the relatively severe fire scenarios used in the experiments, the times to reach structural failure for the wood I-joist, steel C-joist, metal plate and metal web wood truss assemblies were 35-60% shorter than that for the solid wood joist assembly ($[t_{f,\,i} - t_{f,\,solid\ wood}] / t_{f,\,solid\ wood} \times 100\%$, where $t_{f,\,i}$ is for test assembly i and $t_{f,\,solid\ wood}$ 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 prolonged the time for the test assemblies to reach structure failure (from 50-60% longer than with the open basement doorway; calculated by $[t_{f,\,i,\,closed} - t_{f,\,i,\,open}] / t_{f,\,i,\,open} \times 100\%$, where $t_{f,\,i,\,open}$ is with the open basement doorway and $t_{f,\,i,\,closed}$ 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 16 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 metal-web and metal-plate wood trusses. The solid wood joist assemblies produced the lowest deflection rate.

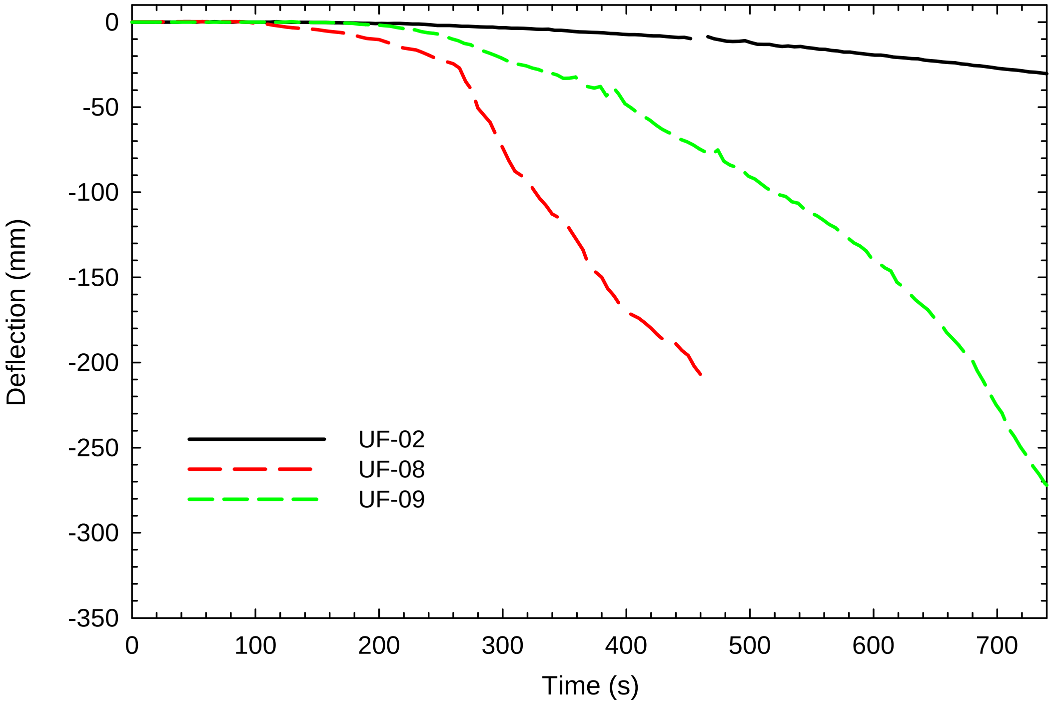
There were three distinct patterns of failure of the test floor assemblies. In Tests UF-01 and UF-02, the subfloor failed, with most of the solid wood joists significantly charred but still in place at the end of the tests. The fire consumed the OSB subfloor in many areas, particularly in areas directly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



a) Tests with open basement doorway



b) Tests with closed basement doorway

Figure 16. Floor deflection near the centre of the test assemblies prior to structural failure

4 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. The results of this research must be interpreted within the context of the fire scenarios used in the experiments. Table 9, Figure 17 and Figure 18 summarize 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 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 earlier at an optical density lower than 2 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 shown in Table 9 for reaching the incapacitation dose FED = 0.3 due to either CO exposure or heat exposure at either the first storey or the corridor on the second storey, whichever occurred first, is illustrated in Figure 17. The time shown in Table 9 for reaching the incapacitation dose FED = 1 due to either CO exposure or heat exposure at either the first storey or the corridor on the second storey, whichever occurred last, is illustrated in Figure 17. Therefore, the time range from FED = 0.3 to FED = 1 cover the occupants of different susceptibility (more susceptible or average) who would have been at different locations in the test house. Figure 17 shows that, regardless what test assemblies were used, the untenable conditions (for incapacitation) were reached at a consistent time frame in the experiments with the open basement doorway; the incapacitation conditions were reached shortly after smoke obscuration (optical density = 2 m^{-1}).

Under the fire scenario with the open basement doorway, the structural failure of the test floor assemblies occurred after the untenable conditions were reached, suggesting that tenability conditions are more critical than structural issues for occupant life safety. 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, resulting in smaller time difference between the onset of untenable conditions and structural failure of these engineered floor assemblies. The times to structural failure were very repeatable as demonstrated by the three replicate tests with the wood I-joist assemblies (Tests UF-06, UF-06R and UF-06RR).

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 the three assemblies tested with the closed basement doorway, as shown in Figure 18, the times available for escape before the onset of untenable (incapacitation) conditions were roughly doubled and the times to reach structural failure were from 50-60% longer than with the open basement doorway scenario. However, 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.

Table 9. Summary of Sequence of Events (in seconds)

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

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. All values shown in the table are before fire suppression.

Overall, the fire scenario with the open basement doorway was more severe than the fire scenario with the closed basement doorway for the structural integrity of unprotected floor assemblies and the life safety of occupants. In the open basement doorway scenario, untenable conditions were reached before structural failure and, therefore, tenability conditions determined the life safety of occupants. The calculations based on the experimental results show that, 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.

In the experimental procedure, the exterior door on the first storey was opened at 180 s after ignition. Opening the exterior door on the first storey should have no impact on the relative sequence of events shown in Figure 17 and Figure 18. Both the exterior window opening in the basement, which was opened much earlier, and the presence or absence of the closed door to the basement made significant impact on the ventilation of the basement fire compartment and the fire growth.

The literature review on egress [3] indicates that the occupants may not necessarily begin evacuation immediately upon recognizing the warning signal from smoke alarms. 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. Continued public education on fire hazards and emergency preparedness is important so that occupants have and practise home fire escape plans and when a real fire occurs, they can quickly escape to the outside before the conditions inside become untenable.

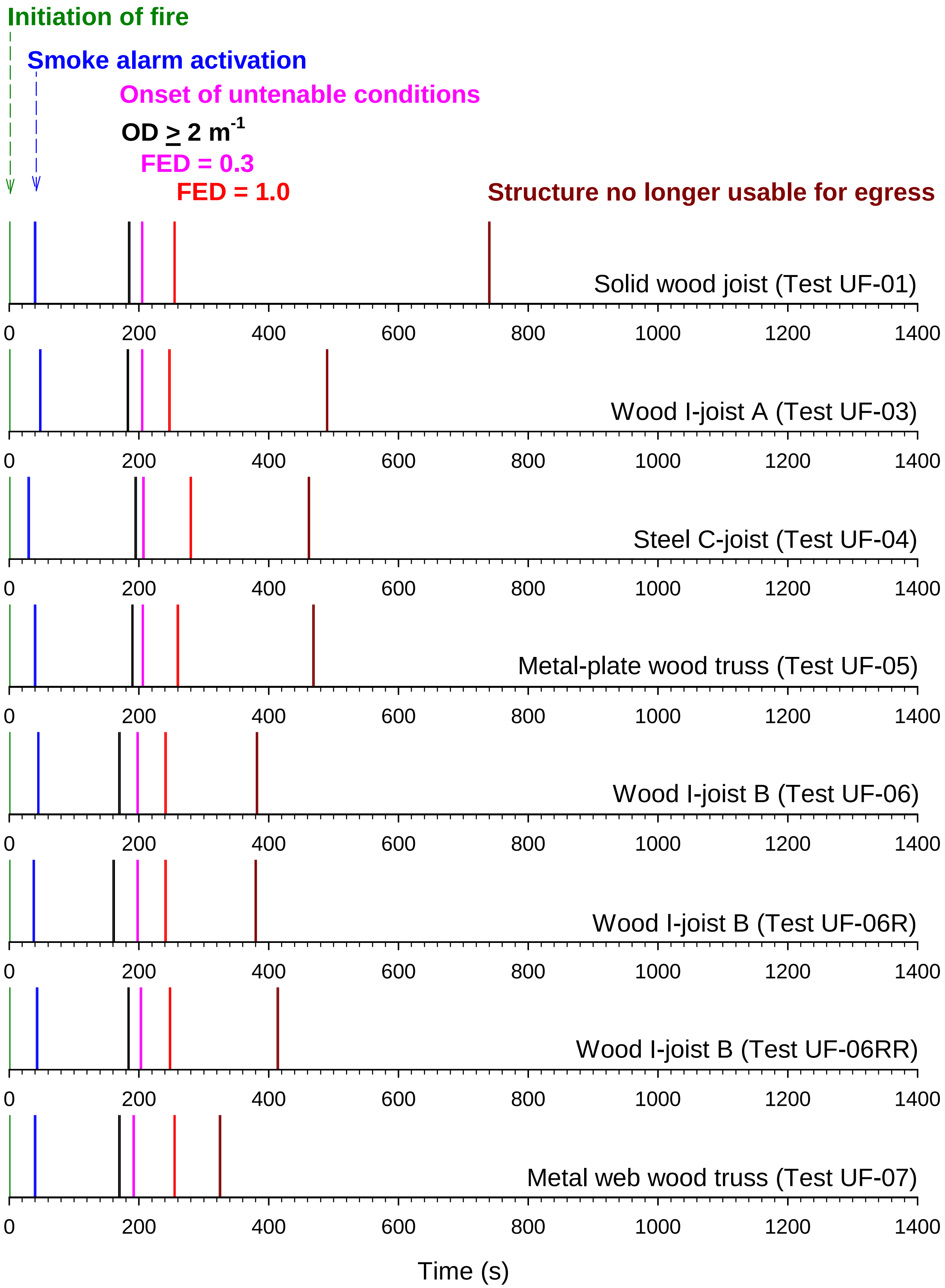


Figure 17. Sequence of fire events in the full-scale experiments (open basement doorway)

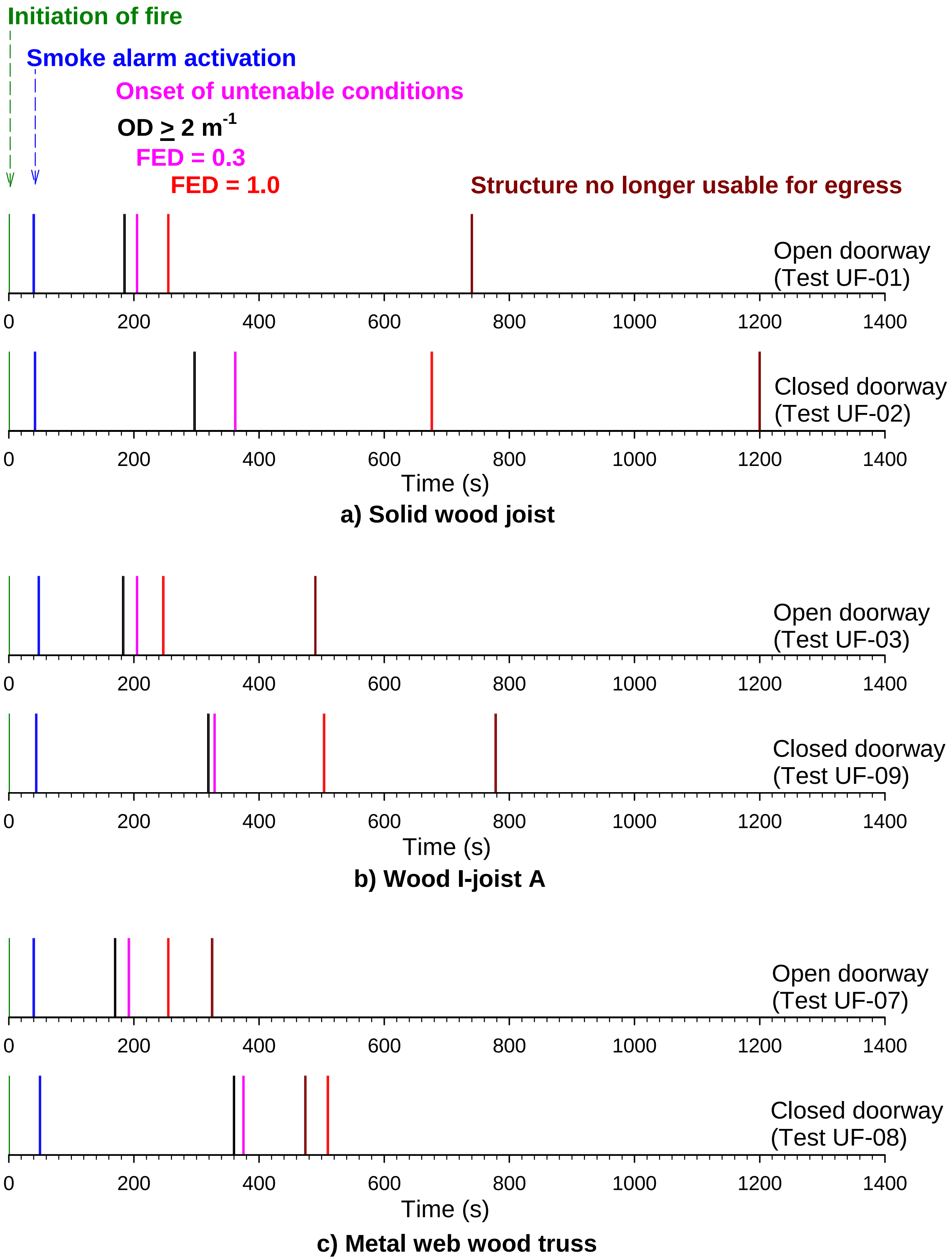


Figure 18. Comparison of sequence of events between open and closed basement doorway

5 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 project. 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 serious basement fire. The results of this research must be interpreted within the context of the fire scenarios used in the experiments.

The following conclusions can be drawn from this study on unprotected floor assemblies on the basis of the relatively severe basement fire scenarios selected for the study. 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 unprotected floor assemblies and the life safety of occupants.

For Fire Scenario with Open Basement Doorway

- Under the fire test scenario with the open basement doorway, fire events followed a chronological sequence: fire initiated and grew, smoke alarms activated, tenability limits were exceeded, and then structural failure of the test floor assembly occurred. There was a structural deflection of all of the floor assemblies prior to their structural failure.
- The estimated time to reach untenable conditions in the tests using the engineered floor systems was similar to that in the test using the solid wood joist floor system. The change in floor construction basically did not change the estimated time to reach incapacitation for occupants. Data analysis indicates that tenability conditions and the time to reach untenable conditions appear to be the critical factors affecting occupant life safety under the fire scenario tested.
- The failure of unprotected floor assemblies in the test fire scenario does not appear to be the critical issue affecting occupant life safety since the tenability limits were reached before the structural failure of the test floor assemblies.

For Fire Scenario with Closed Basement Doorway

- The presence of the closed door to the basement reduced the fire growth rate and impeded the transport of combustion products from the basement to the upper storeys. The closed door prolonged the time available for escape and the time for the test assemblies 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 from 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 tenability limits were reached for healthy adults of average susceptibility. Because the floor failed structurally before the tenability limits were reached, this would represent a risk factor for the occupants.

For Both Fire Scenarios

- Fires started with polyurethane foam, a material widely used in upholstered furniture, developed rapidly to produce relatively severe fire conditions for the life safety of occupants and the structural integrity of the test assemblies.
- An early alert to a fire appears to be the key to occupant life safety. The smoke alarm located in the basement fire compartment consistently took 30-50 s to activate. (Note that the ionization smoke alarm was not installed in the basement fire room to avoid dealing with radioactive materials in the cleanup of debris after the fire tests and that using photoelectric smoke alarms in the basement resulted in more conservative activation times than using ionization smoke alarms for the flaming fire scenarios.) The experimental results highlight the importance of the NBCC requirements for houses — that working smoke alarms be located on each level and that all smoke alarms be interconnected to ensure an early alert by one smoke alarm (the basement one in this study) will activate all the smoke alarms in the house. This would facilitate the occupants becoming aware of the fire sooner and would provide more time for occupant evacuation before the conditions in the house become untenable.
- 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 assemblies. The main mode of structural failure for the solid wood joist assemblies after they structurally deflected 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, after they structurally deflected, 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 closed.
- Data obtained from the test program demonstrated good repeatability of the fire severity (temperature profiles in the fire compartment), smoke alarm responses, times to untenable conditions and to structural failure.
- The results of this study reinforce the importance of continued public education on the awareness of fire hazards and the need for home fire emergency preparedness. In the event of fires similar to the relatively severe fire scenarios used in this study, the time window for safe evacuation can be very short and, therefore, it is vital for occupants to understand that when the smoke alarm sounds, everyone should leave the house immediately. It is important to have a home fire escape plan and practise the plan so that occupants know what to do in the event of a real fire in order to minimize the pre-movement activities and to evacuate from their house immediately.
- More research is needed on the required egress times from single-family houses.

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