## Tenability analysis for fire experiments conducted in a full-scale test house with basement fire scenarios

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



**Publisher's version / Version de l'éditeur:**

*INTERFLAM 2010: 05 July 2010, Nottingham, U.K. [Proceedings], pp. 1247-1258, 2010-07-05*

# Tenability analysis for fire experiments conducted in a full-scale test house with basement fire scenarios

## NRCC-53273

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

July 2010

A version of this document is published in / Une version de ce document se trouve dans:
INTERFLAM 2010, Nottingham, U.K. July 5-7, 2010, pp. 1247-1258

# TENABILITY ANALYSIS FOR FIRE EXPERIMENTS CONDUCTED IN A FULL-SCALE TEST HOUSE WITH BASEMENT FIRE SCENARIOS

Joseph Z. Su, Noureddine Bénichou, Alex C. Bwalya, Gary D. Lougheed, Bruce C. Taber, Patrice Leroux
Fire Research Program, National Research Council Canada, Ottawa, Canada K1A 0R6

## ABSTRACT

A full-scale experimental program was undertaken to study the fire performance of unprotected floor assemblies under two basement fire scenarios in a test facility that simulated a two-storey detached single-family house with a basement. Different floor assemblies constructed with solid-wood joists and engineered joists (wood I-joists, steel C-joists, metal plate wood trusses and metal web wood trusses), were used in the fire experiments. The experiments utilized relatively severe, fast-growing fires set in the basement to challenge the structural integrity of the unprotected floor assembly above the basement (i.e., without a finished ceiling), which would provide the normal egress route on the first storey for occupants. The test facility was well instrumented to measure smoke alarm activation times, temperatures, concentrations of key gaseous products of combustion and smoke obscuration at various locations within the test facility. The objectives of the program were to investigate the factors that affect the ability of occupants on the upper storeys to escape in the event of a basement fire, and to establish the sequence of fire events such as fire initiation, smoke alarm activation, onset of untenable conditions on the upper storeys, and structural failure of the floor assembly above the basement. This paper focuses on the analysis of tenability conditions in the test house in relation to the timing of loss of the structural integrity of the test floor assembly as the main egress route on the first storey.

## 1. INTRODUCTION

There is an ever increasing use of new materials and innovative construction products and systems in the construction of single-family houses in North America. A wide range of engineered floor joists and trusses, in addition to traditional solid wood joists, are available in the marketplace for use in the construction of floor assemblies in houses. This has created a need to better understand their performance and impact on the life safety of occupants under fire conditions.

An experimental program was undertaken to study the fire performance of various engineered floor systems used in single-family houses as construction moves away from the traditional solid sawn wood joists [1-6]. The experimental program was conducted using a test facility representing a two-storey detached single-family house with a basement (referred to as the test house hereafter). It involved full-scale fire experiments with unprotected floor assemblies located over the basement (unsheathed on the basement side) using two specific basement fire scenarios. The objective of the study was to better understand, from the perspective of tenability and structural integrity of the floor assemblies as egress routes, the impact of basement fires on the ability of occupants on the upper storeys to escape.

The experimental program used a timeline approach to establish the sequence that affects the life safety and egress of occupants under two specific basement fire scenarios. This sequence included fire initiation, smoke alarm activation, onset of untenable conditions on upper storeys, and structural failure of the test floor assembly as a viable egress route on the first storey. The experimental approach was designed to determine how long egress routes would remain viable from the perspective of both tenability and structural integrity of the test floor assembly. With the use of engineered joists and trusses in floor construction, it is desirable that the time to incapacitation of occupants should not be adversely affected. Structural failure of the floors constructed with alternative engineered products should not occur prior to the time taken to reach incapacitating levels of smoke, gases and heat. This involved calculations of the fractional effective dose (FED) and the available safe escape time (ASET) using experimental data and comparison between ASET and the floor failure time. This paper focuses on the analysis of onset of untenable conditions on the upper storeys in the test house relative to loss of the structural integrity of the test floor assembly as the egress route on the first storey.

## 2. EXPERIMENTS

Brief descriptions of the experiments are provided in the following sections. Further details of the experimental setup can be found in a series of reports [1-6].

### 2.1. Facility

Each storey of the test house had a floor area of 95 $m^2$ and a ceiling height of 2.4 m. The basement was partitioned to create a fire compartment representing a 27.6 $m^2$ basement living area; the remaining area was not used during the experiments. The fire compartment had a rectangular exterior opening (2.0 m wide by 0.5 m high) covered with a removable noncombustible panel. The walls of the fire compartment were lined with 12.7 mm thick regular gypsum board. An enclosed stairwell connected the fire compartment to the first storey. At the top of this stairwell, a 0.81 m wide by 2.05 m high doorway led to the first storey. This doorway either had a door in the closed position (closed basement doorway) or had no door at all (open basement doorway), depending on the scenario being studied.

The first storey had an open-plan layout with no partitions. A test floor assembly was constructed on the first storey directly above the basement fire compartment for each experiment. A range of engineered floor systems, including wood I-joist, steel C-joist, metal plate wood truss and metal web wood truss assemblies as well as solid wood joist assemblies were used in the full-scale fire experiments. A 0.89 m wide by 2.07 m high doorway led to the exterior. The staircase to the second storey was not enclosed.

The second storey had a corridor (measuring 4.45 m long by 1.10 m wide) and bedrooms. Two bedrooms (each having a floor area of 16.8 $m^2$) were used as target bedrooms in the experiments. The door to one of the bedrooms was kept open whereas the door to the other bedroom remained closed. Each bedroom doorway was 0.81 m wide by 2.05 m high.

### 2.2. Fire scenarios

Two fire scenarios were used in the full-scale fire experiments: 1) the doorway from the first storey to the basement had no door (referred to as the open basement doorway scenario); 2) a hollow-core interior door was used in the doorway in the closed position (referred to as the closed basement doorway scenario).

A simple and repeatable fuel package was developed for use in full-scale experiments to fuel a fire that simulated a basement living area fire [7, 8]. This fuel package consisted of a mock-up sofa constructed with 9 kg of flexible polyurethane foam without any upholstery fabric, and 190 kg of wood cribs beside and underneath the mock-up sofa. The fuel package was located at the center of the fire compartment in order to provide a greater challenge to the unprotected floor assemblies above.

The mock-up sofa was ignited in accordance with the ASTM 1537 test protocol [9] and the wood cribs provided the remaining fire load to sustain the fire for a desired period of time.

To provide the ventilation necessary for combustion and to simulate the fire-induced breakage and complete fall-out of the window glass, the non-combustible panel that initially covered the exterior window opening of the fire compartment was manually removed when the temperature reached 300°C at the opening. This condition was normally reached within 90 to 120 s after ignition in the experiments. The exterior door on the first storey was opened at 180 s after ignition and left open to simulate some occupants evacuating the test house.

### 2.3. Measurements

Various measurement devices were used and data was collected at 5 s intervals in the experiments. Extensive thermocouple arrays were installed throughout the test house to measure temperatures. Flame-sensing devices and floor deflection devices were installed on the test floor assemblies. Residential ionization and photoelectric smoke alarms were installed on each level and in each bedroom.

Measurements of smoke density and gas concentrations were focused on upper storeys. On the first storey, smoke and gas sampling ports were located at a quarter point at 0.9 m and 1.5 m above the floor. On the second storey, smoke and gas sampling ports were located at the centre of the corridor at 0.9 m and 1.5 m above the floor. Smoke and gas samples from these sampling locations were connected to nondispersive infrared $CO/CO_2$ gas analyzers, $O_2$ gas analyzers and smoke density meters. Detailed gas analysis using Fourier Transform Infrared (FTIR) spectrometers was only conducted in a limited number of experiments.

### 2.4. Fire development in the basement fire compartment

Figure 1 shows typical temperature profiles measured in the basement fire compartment at the ceiling height for all of the experiments. 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 experiments. The temperatures at the ceiling height exceeded 600°C at approximately 120 s in all of the experiments, indicating that the basement fire compartment reached flashover conditions. 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. Both fire scenarios provided relatively severe and consistent fire exposure to the unprotected floor assemblies in all experiments.

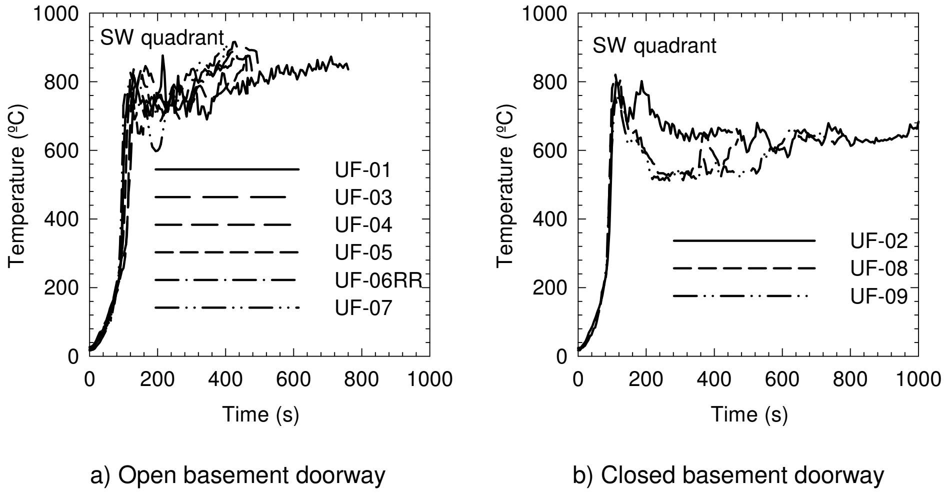



**Figure 1.** Temperatures in basement fire compartment at 2.4 m height.

## 3. UPPER STOREY CONDITIONS AND TENABILITY ANALYSIS

Heat, combustion products and smoke produced from fires can, either individually or collectively, create conditions that are potentially untenable for occupants. Tenability analysis was conducted using temperatures, concentrations of combustion products and smoke optical densities measured during the experiments to provide an estimation of the ASET with incapacitation as the endpoint. The analysis focused on the conditions on the upper storeys of the test house. The conditions in the basement fire compartment would not be survivable once flashover occurred.

Potential exposure to the toxic and asphyxiant gases, heat and smoke obscuration under the experimental conditions was analyzed independently. Each component was treated as acting independently on the occupant to create incapacitating conditions and the ASET was the shortest of the times estimated from consideration of exposure to combustion gas products, heat and smoke obscuration.

### 3.1. Exposure to toxic gases

In regards to the fuel package used in this study, with the combined flaming combustion of polyurethane foam and wood cribs, the primary gaseous products were expected to be carbon monoxide (CO), carbon dioxide ($CO_2$) and hydrogen cyanide (HCN) in a vitiated oxygen ($O_2$) environment. Although HCN could be produced from the combustion of the polyurethane foam in the fuel package, FTIR spectroscopy measurements in selected experiments indicated that the HCN concentrations on the upper storeys were well below 30 ppm. These concentrations would not be a concern for occupant life safety on the upper storeys in the timeframe for incapacitation by CO exposure. The fuel package contained no chemical components that would produce acid halide irritants in the combustion gases. Other irritant gases transported to the upper storeys were below the detection limits of the FTIR spectrometers used in the experiments. Therefore, the analysis for the upper storeys involved CO and $CO_2$ and oxygen vitiation only. Figure 2 shows exemplar concentration-time profiles for CO, $CO_2$ and $O_2$ measured during experiments.

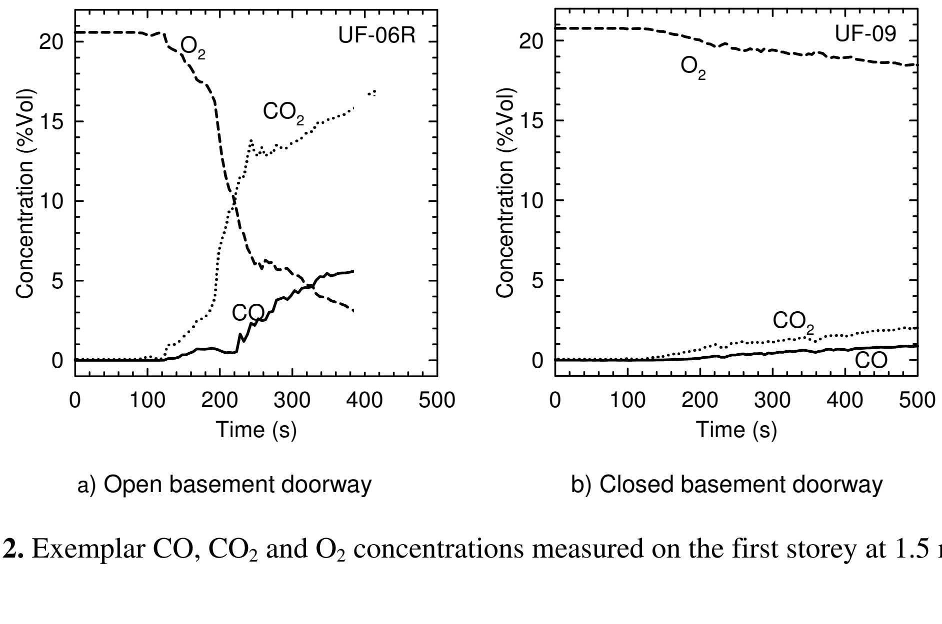



**Figure 2.** Exemplar CO, $CO_2$ and $O_2$ concentrations measured on the first storey at 1.5 m height.

The fractional effective dose for incapacitation due to CO was calculated using ISO 13571 as follows with the $CO_2$-induced hyperventilation factor [10]:

$$FED_{in,CO} = \sum_{t_0}^{t} \frac{[CO]\cdot \Delta t}{35000} \exp\left(\frac{\%CO_2}{5}\right) \quad [1]$$

where *[CO]* is the concentration in *parts per million*, *Δt=0.0833 minute* (data collected at 5 s intervals in the experiments).

Table 1 shows the calculated times for the fractional effective dose to reach two typical values (FED = 1 for healthy adults of average susceptibility, and FED = 0.3 for some susceptible people). The times associated with other FED values can be calculated, if required.

**Table 1.** Time (in seconds) to the specified FED 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 | | | | |
| Solid wood joist | 205 | 235 | 225 | 255 |
| Wood I-joist A | 209 | 240 | 225 | 247 |
| Steel C-joist | 220 | 260 | 245 | 280 |
| Metal-plate wood truss | 206 | 232 | 235 | 260 |
| Wood I-joist B | 198 | 233 | 208 | 241 |
| | 198 | 228 | 207 | 241 |
| | 203 | 233 | 218 | 248 |
| Metal web wood truss | 225 | 265 | 230 | 275 |
| Tests with closed basement doorway | | | | |
| Solid wood joist | 466 | 676 | 362 | 501 |
| Metal web wood truss | 400 | 510 | 375 | 510 |
| Wood I-joist A | 329 | 484 | 364 | 504 |

[a] Calculated based on concentrations at 1.5 m height above the floor.

For the experiments 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 experiment. 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 experiment. Moreover, the time difference between experiments reaching either of the two doses was less than 40 s at any measurement location. These results indicate a consistent time frame for reaching the incapacitation doses for exposure to CO in this fire scenario.

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

The fractional effective doses for incapacitation due to $O_2$ vitiation alone, and due to asphyxiant effect of $CO_2$ alone, were also calculated using the methodology given in the SFPE Handbook of Fire Protection Engineering [11]. Under the experimental conditions of this study, these calculations indicated that the effect of $O_2$ vitiation and the asphyxiant effect of $CO_2$ would cause incapacitation at a later time than the toxic effect of CO.

### 3.2. Exposure to heat

Figure 3 shows exemplar temperature profiles measured on the first and second storeys during the experiments. 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 a 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 the door was breached by the fire, and thereby delayed the onset of untenable thermal conditions on the upper storeys.

Assuming unclothed or lightly clothed subjects, the fractional effective dose for incapacitation due to the convected heat exposure was calculated using the equation in ISO 13571 [10]:

$$FED_{in,heat} = \sum_{t_0}^{t} \frac{T^{3.4}}{5 \times 10^7} \Delta t \qquad [2]$$

where $T$ is the temperature (*°C*), $\Delta t = 0.0833$ *minute*. Since there was temperature stratification, the temperatures at the 1.4 m height on each storey were used for the analysis of convected heat exposure, as this simulated 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 [12]. 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 to be incapacitated for the fire scenarios used.

The convective heat exposure depended on the location in the test house. In the closed bedroom, heat exposure would not cause incapacitation ($FED_{in,heat} < 0.07$ 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 2 for $FED_{in,heat}$ = 0.3 and $FED_{in,heat}$ = 1. 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 experiments with the open basement doorway, the calculated times to reach the heat incapacitation doses on the first storey were comparable to those for CO exposure and, in most cases, 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 one test, the calculated times for heat exposure to reach the incapacitation doses were longer than those for CO exposure.

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

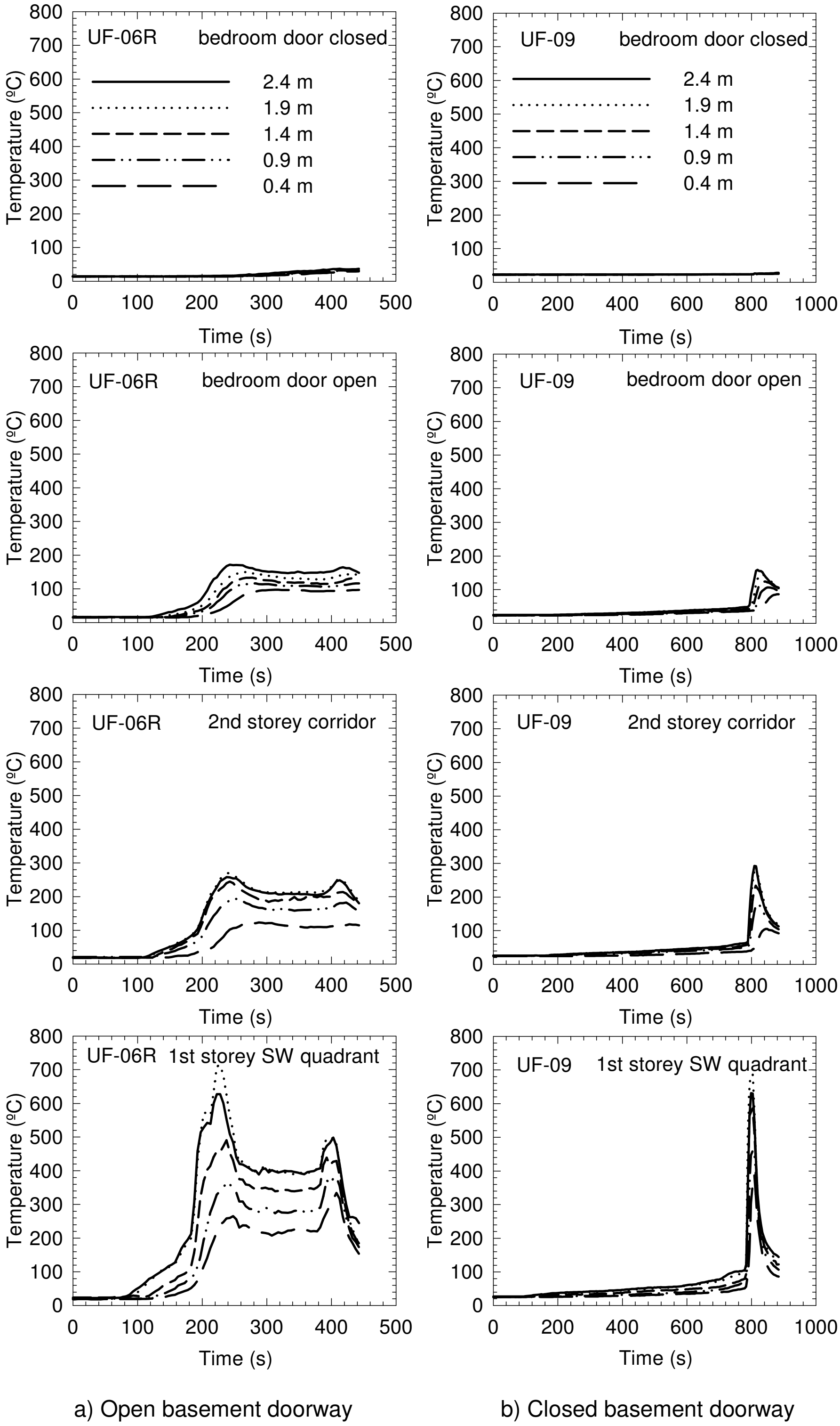



**Figure 3.** Exemplar temperature profiles on upper storeys.

**Table 2.** Time (in seconds) to the specified FED 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 | | | | | | |
| Solid wood joist | 230 | 280 | 320 | 435 | 455 | 690 |
| Wood I-joist A | 205 | 213 | 252 | 330 | 370 | (FED<0.8) |
| Steel C-joist | 207 | 215 | 250 | 290 | 325 | 460 |
| Metal-plate wood truss | 220 | 240 | 270 | 320 | 345 | 500 |
| Wood I-joist B | 202 | 211 | 229 | 254 | 315 | (FED<0.8) |
| | 193 | 199 | 217 | 238 | 293 | (FED<0.8) |
| | 209 | 216 | 234 | 298 | 393 | (FED<0.4) |
| Metal web wood truss | 192 | 207 | 225 | 255 | 305 | (FED<0.9) |
| Tests with closed basement doorway | | | | | | |
| Solid wood joist | 1086 | 1196 | 1171 | 1241 | 1263 | (FED<0.5) |
| Metal web wood truss | 482 | 486 | 507 | (FED<0.5) | (FED<0.1) | (FED<0.1) |
| Wood I-joist A | 786 | 796 | (FED<0.2) | (FED<0.2) | (FED<0.1) | (FED<0.1) |

[a] Calculated based on temperatures at 1.4 m height above the floor.

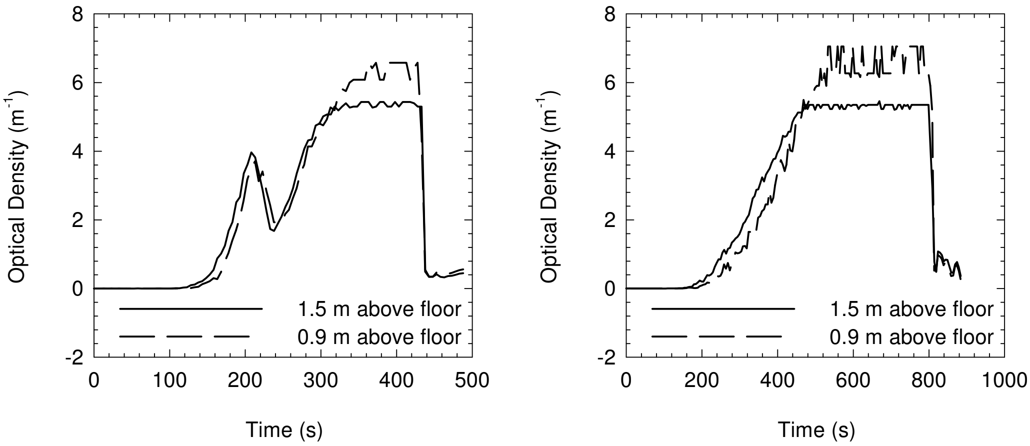
### 3.3. Visual obscuration by smoke

Visual obscuration by the optically dense smoke tended to be the first hazard to arise that could impede evacuation by the occupants. Visibility through smoke and the optical density of smoke are related (e.g. the visibility is proportional to the reciprocal of the *OD* for non-irritating smoke) [13]. The smoke obscuration can be expressed as the optical density per meter (*OD* in $m^{-1}$):

$$OD = \frac{1}{L}\log_{10}\left(\frac{I_0}{I}\right) \quad [3]$$

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 $OD = k/2.303$.

In ISO 13571, the minimum visible brightness difference between an object and its background is used to estimate the smoke obscuration limit at which occupants cannot see their hands in front of their faces (a distance of 0.5 m or less). 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 with impaired vision, this can happen at an optical density of 2 $m^{-1}$ or lower. Possible reduction of time to untenable smoke level due to psychological effect is not addressed in the calculations. A tenability limit of $OD_{Limit}$ = 2 $m^{-1}$ is used in this study.




a) Test UF-06RR with open basement doorway    b) Test UF-09 with closed basement doorway

**Figure 4.** Exemplar data of smoke optical density (in the corridor on the second storey).

Figure 4 shows exemplar optical density-time profiles. 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). 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, and then increased again.

Table 3 shows the times to reach various optical density levels at the 1.5 m height, which were very similar from one experiment to another. The increase in the optical density was faster with the open basement doorway than with the closed basement doorway. It must be pointed out that the smoke density meters used for the first storey had a narrow working range and could not measure the smoke obscuration of OD = 2 $m^{-1}$ 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 1 and Table 3 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.

**Table 3.** Time (in seconds) to the specified smoke optical density.

| | 1st storey SW quadrant | | 2nd storey corridor | | | |
|---|---|---|---|---|---|---|
| **OD =** | **1 $m^{-1}$** | **1.7 $m^{-1}$** | **1 $m^{-1}$** | **1.7 $m^{-1}$** | **2 $m^{-1}$** | **3.4 $m^{-1}$** |
| Tests with open basement doorway | | | | | | |
| Solid wood joist | 155 | 170 | 170 | 185 | 185 | 200 |
| Wood I-joist A | 158 | 168 | 173 | 178 | 183 | 198 |
| Steel C-joist | 160 | n.a. | 180 | 190 | 195 | 210 |
| Metal-plate wood truss | 160 | n.a. | 175 | 186 | 190 | 200 |
| Wood I-joist B | 147 | 155 | 160 | 167 | 170 | 185 |
| | 133 | 153 | 150 | 158 | 161 | 178 |
| | 168 | n.a. | 168 | 178 | 184 | 198 |
| Metal web wood truss | 134 | 140 | 155 | 165 | 170 | 330 |
| Tests with closed basement doorway | | | | | | |
| Solid wood joist | 187 | n.a. | 247 | 277 | 297 | 377 |
| Metal web wood truss | 220 | 325 | 265 | 330 | 360 | 450 |
| Wood I-joist A | 186 | n.a. | 254 | 304 | 319 | 374 |

[a] Determined based on optical density measurements at 1.5 m height above the floor.
[b] n.a. – not available due to limited measurement range of the smoke meters used for the first storey.

## 4. SUMMARY

Table 4 summarizes the estimated times to the onset of various conditions. Smoke obscuration was the first hazard to arise in all of the experiments. 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 smoke obscuration limit ($OD_{Limit}$ = 2 $m^{-1}$) was consistently reached around 180 s. With the closed basement doorway, this time was significantly increased.

The calculated times 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, are listed in Table 4. Heat exposure tended to be more severe on the first storey than on the second storey. In most cases, the time difference for heat exposure and CO exposure to reach the specific FED was not significant with the open basement doorway.

For the experiments with the open basement doorway, the time for FED to change from 0.3 to 1 was no more than 40 s. The times to reach each FED level were also very consistent for the different experiments. The tenability data indicates that, regardless what test floor assemblies were used, the untenable conditions (for incapacitation) were reached in a consistent timeframe soon after smoke obscuration. Depending on the susceptibility and location of occupants, the untenable conditions generally occurred within 180 to 240 s after ignition under this fire scenario.

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. The ASET 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.

In the second storey bedroom where the door to the bedroom was kept closed, untenable conditions were not reached in any of the experiments.

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

Table 4 also summarizes the chronological sequence of the fire events in the full-scale experiments — fire initiation, smoke alarm activation, onset of untenable conditions, and structural failure of the test floor assembly. In all experiments except one, fire events followed a chronological sequence: initiation and growth of the fire, activation of smoke alarms, loss of tenable conditions in open areas on upper storeys, and finally structural failure of the test floor assembly over the basement (loss of the main egress route on first storey). However, 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. In the closed basement doorway scenario, one engineered floor assembly experienced structural failure before untenable conditions (FED=1) were reached in the open areas on the upper storeys.

The FED and ASET calculations, along with this timeline approach, enabled the establishment of the key sequence of the fire events in the experiments to better understand the impact of the basement fires on the ability of occupants on the upper storeys to escape in houses with alternative floor construction.

**Table 4.** 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 |

[a] Values determined using the measurements at 1.5 m height (for gas concentrations and OD) or 1.4 m height (for temperatures).
[b] The number in *Italic* 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.

## ACKNOWLEDGMENTS

The authors would like to acknowledge the following partner organizations that provided valuable financial support and technical input to the research: Canada Mortgage and Housing Corporation, Canadian Automatic Sprinkler Association, Canadian Wood Council, Cement Association of Canada, City of Calgary, FPInnovations-Forintek Division, North American Insulation Manufacturers Association, Ontario Ministry of Community Safety and Correctional Services/Office of the Fire Marshal, Ontario Ministry of Municipal Affairs and Housing, and Wood I-Joist Manufacturers Association. The authors would also like to acknowledge G. Proulx, A. Kashef, J.R. Thomas, D. Carpenter, G. Crampton, E. Gibbs, C. McCartney, M. Ryan, M. Wright, M. Kanabus-Kaminska, J. Henrie, R. Monette and R. Rombough for their contributions in the project planning, construction of the test facility and conducting the fire tests.

## REFERENCES

1. Bénichou, N., Su, J.Z., Bwalya, A.C., Lougheed, G.D., Taber, B.C., Leroux, P., Kashef, A., McCartney, C., Thomas, J.R. (2009) Fire Performance of Houses, Phase I, Study of Unprotected Floor Assemblies in Basement Fire Scenarios, Part 1 - Results of Tests UF-01 and UF-02 (Solid Wood Joists), Research Report 246, Institute for Research in Construction, National Research Council of Canada, Ottawa, ON, http://www.nrc-cnrc.gc.ca/obj/irc/doc/pubs/rr/rr246/rr246.pdf
2. Su, J.Z., Bénichou, N., Bwalya, A.C., Lougheed, G.D., Taber, B.C., Leroux, P., Kashef, A., Thomas, J.R. (2009) Fire Performance of Houses, Phase I, Study of Unprotected Floor Assemblies in Basement Fire Scenarios, Part 2 - Results of Tests UF-03 and UF-09 (Wood I-Joists A), Research Report 247, Institute for Research in Construction, National Research Council of Canada, Ottawa, ON, http://www.nrc-cnrc.gc.ca/obj/irc/doc/pubs/rr/rr247/rr247.pdf
3. Bénichou, N., Su, J.Z., Bwalya, A.C., Lougheed, G.D., Taber, B.C., Leroux, P., Kashef, A., Thomas, J.R. (2009) Fire Performance of Houses, Phase I, Study of Unprotected Floor Assemblies in Basement Fire Scenarios, Part 3 - Results of Test UF-04 (Light-Gauge Steel C-Joists), Research Report 248, Institute for Research in Construction, National Research Council of Canada, Ottawa, ON, http://www.nrc-cnrc.gc.ca/obj/irc/doc/pubs/rr/rr248/rr248.pdf

4. Su, J.Z., Bénichou, N., Bwalya, A.C., Lougheed, G.D., Taber, B.C., Leroux, P., Kashef, A., Thomas, J.R. (2009) Fire Performance of Houses, Phase I, Study of Unprotected Floor Assemblies in Basement Fire Scenarios, Part 4 - Results of Test UF-05 (Metal-Plate-Connected Wood Trusses), Research Report 249, Institute for Research in Construction, National Research Council of Canada, Ottawa, ON, http://www.nrc-cnrc.gc.ca/obj/irc/doc/pubs/rr/rr249/rr249.pdf
5. Bénichou, N., Su, J.Z., Bwalya, A.C., Lougheed, G.D., Taber, B.C., Leroux, P., Thomas, J.R. (2009) Fire Performance of Houses, Phase I, Study of Unprotected Floor Assemblies in Basement Fire Scenarios, Part 5 - Results of Tests UF-06, UF-06R and UF-06RR (Wood I-Joists B), Research Report 250, Institute for Research in Construction, National Research Council of Canada, Ottawa, ON, http://www.nrc-cnrc.gc.ca/obj/irc/doc/pubs/rr/rr250/rr250.pdf
6. Su, J.Z., Bénichou, N., Bwalya, A.C., Lougheed, G.D., Taber, B.C., Leroux, P., Thomas, J.R. (2009) Fire Performance of Houses, Phase I, Study of Unprotected Floor Assemblies in Basement Fire Scenarios, Part 6 - Results of Tests UF-07 and UF-08 (Metal-Web-Connected Wood Trusses), Research Report 251, Institute for Research in Construction, National Research Council of Canada, Ottawa, ON, http://www.nrc-cnrc.gc.ca/obj/irc/doc/pubs/rr/rr251/rr251.pdf
7. Bwalya, A.C., Lougheed, G.D., Su, J.Z., Taber, B.C., Bénichou, N., Kashef, A. (2007) Development of a fuel package for use in the fire performance of houses project. In: Fire and Materials Conference, San Francisco, CA, January 29, 2007
8. Su, J.Z., Bwalya, A.C., Lougheed, G.D., Bénichou, N., Taber, B.C., Thomas, J.R. (2007) Fire Scenario Tests in Fire Performance of Houses Test Facility - Data Analysis, Research Report 210, Institute for Research in Construction, National Research Council of Canada, Ottawa, ON, http://www.nrc-cnrc.gc.ca/obj/irc/doc/pubs/rr/rr210/rr210.pdf
9. American Society for Testing and Materials (2002) Standard Test Method for Fire Testing of Upholstered Furniture, ASTM E1537-02a, ASTM, West Conshohoken, PA
10. ISO 13571 (2007) Life-threatening Components of Fire—Guidelines for the Estimation of Time Available for Escape Using Fire Data, International Organization for Standardization, Geneva
11. Purser, D.A. (2008) Assessment of Hazards to Occupants from Smoke, Toxic Gases, and Heat. In: DiNenno PJ, Drysdale D, Beyler CL, Walton WD, Custer RLP, Hall JR, Watts JM (ed) The SFPE Handbook of Fire Protection Engineering, 4th edition, Society of Fire Protection Engineers /National Fire Protection Association, Quincy, Massachusetts, Section 2, Chapter 6
12. Wieczorek, C.J., Dembsey, N.A. (2001) Human Variability Correction Factors for Use with Simplified Engineering Tools for Predicting Pain and Second Degree Skin Burns, Journal of Fire Protection Engineering, 11: 88-111
13. Jin, T. (2008) Visibility and Human Behavior in Fire Smoke. In: DiNenno PJ, Drysdale D, Beyler CL, Walton WD, Custer RLP, Hall JR, Watts JM (ed) The SFPE Handbook of Fire Protection Engineering, 4th edition, Society of Fire Protection Engineers /National Fire Protection Association, Quincy, Massachusetts, Section 2, Chapter 4