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Occupant Tenability in Single Family Homes: Part I—Impact of Structure Type, Fire Location and Interior Doors Prior to Fire Department Arrival

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Abstract. This paper describes an experimental investigation of the impact of structure geometry, fire location, and closed interior doors on occupant tenability in typical single family house geometries using common fuels from twenty-first century fires. Two houses were constructed inside a large fire facility; a one-story, 112 m^2, 3-bedroom, 1-bathroom house with 8 total rooms, and a two-story 297 m^2, 4-bedroom, 2.5-bathroom house with 12 total rooms. Seventeen experiments were conducted with varying fire locations. In all scenarios, two bedrooms had doors remaining open while the door remained closed in a third bedroom immediately adjacent to the open door bedrooms. Temperature and gas measurement at the approximate location of a crawling or crouching trapped occupant (0.9 m from the floor) were utilized with the ISO 13571 fractional effective dose (FED) methodology to characterize occupant tenability up to the point of firefighter intervention. The FED values for the fire room were higher for heat exposure than for toxic gases, while target rooms reached highest FED due to CO/CO_2 exposure. The closed interior door decreased FED significantly, with the worst case scenario resulting in a 2% probability of receiving an incapacitating dose compared to the worst case scenario for an open bedroom of 93% probability of receiving an incapacitating dose. In fact, in 7 of the 17 experiments, the closed interior door resulted in a less than 0.1% chance of an occupant receiving an incapacitating dose prior to firefighter 'intervention.'

Keywords: Fire, Residential fires, Tenability, Heat Exposure, Toxic Gases, Fractional Effective Dose, Firefighting

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1. Introduction

NFPA estimates that from 2009 to 2013 [1], U.S. fire departments responded to an average of 357,000 residential fires annually. These fires caused an estimated annual average of 2470 civilian deaths and 12,890 civilian injuries. More than 70% of the reported home fires and 84% of the fatal home fire injuries occurred in one- or two- family dwellings, with the remainder in apartments or similar properties.

Many contemporary homes are larger than older homes built before 1980. Based on United States Census data [2] homes have increased in average area from approximately 144 m^2 in 1973 to over 247 m^2 in 2014. While the average home size has increased by 71%, newer homes tend to incorporate features such as open floor plans and great rooms [3]. All of these features remove compartmentation and can contribute to rapid smoke and fire spread. While commercial building codes require fire and smoke separations to limit the impact of the fire on occupants, there are minimal requirements for compartmentation in single family homes [4].

The design of installed features in residential structures is a critically important component to ensure a fire-safe home. Great progress has been made in the effectiveness and utility of active detection and suppression systems in the residential market. Recently, significant attention has also been paid to the effectiveness of passive fire compartmentation particularly on the capabilities of interior residential doors as an effective fire safety system within modern homes. Based on both anecdotal evidence and a study by Kerber (2012) [5], public education materials have been produced to encourage families to ensure door closure when sleeping in or exiting a burning structure to help keep the fire and products of combustion compartmentalized [6]. While concerns remain about the impact of door closure on risks for detection (if detector is outside of the compartment of origin) or notification of occupants (if detector is outside of the compartments where occupants are sleeping), additional, quantifiable data on the effectiveness of closed doors can help the general public understand the relative risk and benefits of door closure.

While interior residential doors are not designed specifically as a fire protection system, the ability for such doors to provide temporary protection is important to quantify. Kerber showed that, with a typical living room fire in a one-story house, a fractional effective dose (FED) of 0.3 could be reached at a height of 1.5 m in an adjoining bedroom in approximately 5 min [7]. This FED value corresponds to a probability that the conditions are not tenable for 11% of the population (likely to include young children, elderly, and/or unhealthy occupants). Another bedroom immediately adjacent to this one, with its door closed never reached FED = 0.3. Furthermore, while that study allowed a comparison between times to achieve a typical benchmark FED (0.3 or 1.0), the data did not provide a means of ***quantitatively characterizing improvement*** in tenability for victims who may be in those rooms.

Assessing the risk created by different fire scenarios is paramount to further improving fire safety for building occupants. A recent study looked to analyze the fire risk of residential buildings in China by analyzing the large-scale probabilities of fire frequency, and the effectiveness of automatic suppression systems and firefighting, etc. [8]. Another study analyzed the effectiveness of smoke alarm presence and found that death rates are halved when smoke alarms are present [9]. While these studies supply useful information at the macro-scale of fire risk analysis to help inform and improve fire safety, they do not analyze individual fire risk and the timelines for occupant tenability that can inform firefighters in their risk/benefit analysis when determining best approaches to rescue occupants from structures.

Previous research has been performed to analyze occupant tenability in model fires with typical household furnishings. In 1978, animal models were used to study tenability in room corner tests and found that furniture posed a greater threat than wall insulation materials [10]. Other studies have been performed that have focused on the threat of toxic gases, such as carbon monoxide (CO), carbon dioxide (CO_2) and hydrogen cyanide (HCN), in compartment fires, and found both to have significant impacts on occupant tenability [11–13]. In 2000, Purser [14] used the fractional effective dose methodology to analyze tenability in constructed rigs designed to simulate compartment fires. In particular, the study examined the differences in ventilation on the fire growth and tenability in the different compartments. One of the major findings of the study was that toxic gases contributed more to incapacitation of occupants than heat exposure did.

Many other studies have also implemented the FED methodology used in [14], and later outlined in ISO 13571 [15], to assess the impact of different fires on occupant tenability. These studies include assessing the tenability risk to occupants in numerical simulations of compartment fires [16], one-bedroom apartment fires [17], 1950s legacy residential housing [18], and basement fires [19].

This study will extend the previous work using the FED methodology by studying fires in full-scale modern one- and two-story structures using ISO 13571. This manuscript will focus on the impact of different structure type and different fire location and how that impacts tenability throughout the entire structure. The threat posed by actual residential fires and the typical times to untenability for occupants trapped in such fires will be quantified. Additionally, this data set will provide the ability to quantify the improvement in survivability achieved when an occupant is behind a closed door as compared to an open bedroom in a typical residential structure.

2. Experimental Setup

To examine the impact of common US single family house geometries, two full-size residential structures were constructed inside a large experimental fire facility. Seventeen experiments were conducted varying fire location between living room, bed room and kitchen in one- and two-story structures (Table 1). Experiments in each house were conducted three days apart to allow for ambient conditions inside the houses to be maintained between 15°C and 22°C and below 50% relative humidity prior to ignition.

2.1. One-Story Structure

Nine of the experiments took place in a one-story structure, designed to be representative of a home constructed in the mid-twentieth century with walls and doorways separating all of the rooms and 2.4 m ceilings throughout. The one-story structure had a floor area of 112 m^2; with three bedrooms, one bathroom and eight total rooms (Fig. 1). The house was wood framed and lined with two layers of gypsum board (Base layer 16 mm, Surface layer 13 mm) to protect the structure and allow for multiple experiments. All of the windows were filled with removable inserts so that window failure did not occur in any scenario. The leakage area determined from a blower door test was found to be approximately 0.1 m^2.

2.2. Two-Story Structure

The two-story structure had an area of 297 m^2; with four bedrooms, 2.5 bathrooms and twelve total rooms (Figs. 2, 3). The structure incorporated features common in twenty-first century construction such as an open floor plan, two-story great room, and open foyer. The house was a wood framed structure and lined with two layers of gypsum board (Base layer 16 mm, Surface layer 13 mm). All of the windows in this structure were filled with removable inserts so that window failure did not occur in any scenario prior to fire department intervention (see Part B). The leakage area determined from a blower door test was found to be approximately 0.2 m^2.

2.3. Fuel Load

Figures 1, 2 and 3 include 3-dimensional renderings of the floorplan in each house with ignition and furniture locations (Table 1). The living room in the one-story house as well as the family room and living room in the two-story house were furnished similarly; with television stand, television, end table, lamp with shade, cof-

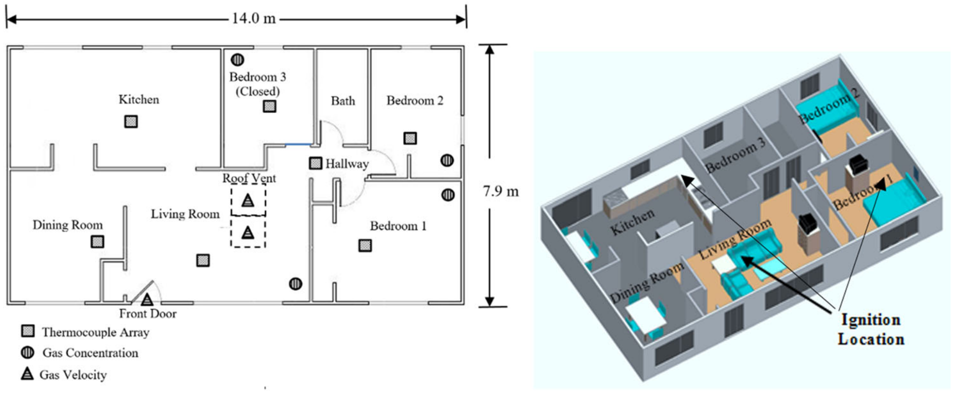

Figure 1. One-story house floor plan and 3D rendering showing furniture and ignition location.

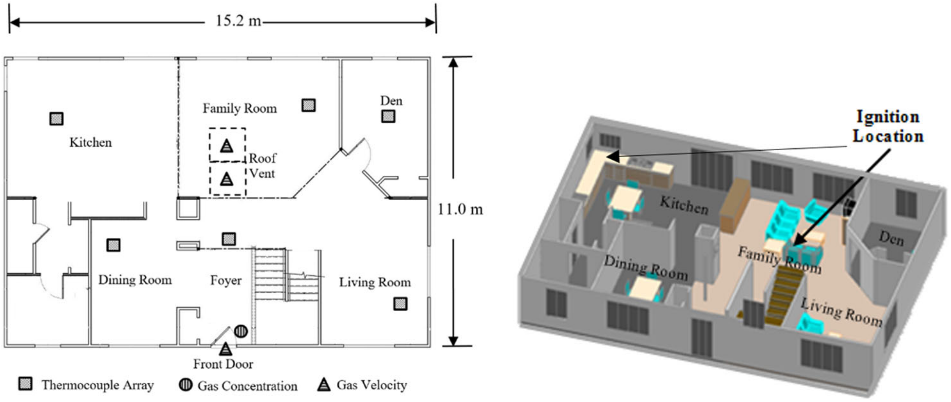

Figure 2. Two-story house first floor plan and 3D rendering showing furniture and ignition location.

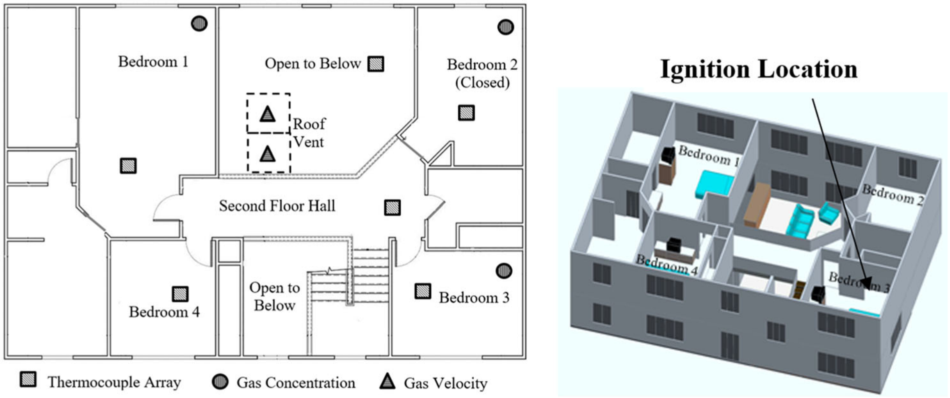

Figure 3. Two-story house second floor plan and 3D rendering showing furniture and ignition location.

fee table, chair, ottoman, two sofas, two pictures, and two curtains. The floor was covered with polyurethane foam padding and polyester carpet. The fuel loading was approximately 29 kg/m^2. To describe the potential energy of the fuel package, a test with the living room furnishings was performed in a compartment with a large opening (6.5 m^2 of ventilation area) under a cone calorimeter resulting in a maximum heat release rate of 8.8 MW and a total of 4060 MJ of heat released [3]. The scenarios reported in Part I of this series are conducted with all windows and door closed, resulting in underventilated conditions and lower heat release rates. This manuscript focuses on occupant exposures from the fire prior to ventilation and flashover did not occur in this timeframe (though flashover did occur after ventilation). Part II will analyze conditions after fire service ventilation [20].

Table 1
Ignition Locations for Each Experiment

Location of ignition	Experiment number
1 Story structure	
Living room	1,3,5,7, 15, 17[†]
Bedroom 1	9, 11
Kitchen	13
2 Story structure	
Family room	2,4,6,8,12
Bedroom 3	10, 14
Kitchen	6

Experiment number is provided to allow the reader to relate to UL Internal Report [3]

[†] Denotes legacy furnishings

Bedroom 1 in both houses was furnished with a queen bed comprised of a mattress, box spring, wood frame, two pillows and comforter. The room also contained a dresser, television stand and television. The floor was covered with polyurethane foam padding and polyester carpet. The remainder of the bedrooms (2 to 4) in both houses were furnished with the same bed, armoire, television and flooring compliment as well as a smaller dresser, headboard, and a framed mirror. A heat release rate experiment was conducted with the bedroom furnishings in a compartment with a large opening (6.5 m^2 of ventilation area) under the cone calorimeter. The maximum heat release rate was 9.4 MW and the total heat released was 3580 MJ [3].The dining room of both houses was furnished with a solid wood table and four upholstered chairs. The kitchens were furnished with the same type of table and chairs as the dining room, as well as a dishwasher, stove, refrigerator and wood upper and base cabinets with cement board counters. The floors of the dining rooms and kitchen were also cement board to simulate a tile floor.

The same make and model of all of these fuels (with the exception of Experiment 17) were purchased from the same supplier and stored in an environmentally controlled warehouse before they were used in an identical layout in the structure for each experiment. Experiment 17 was conducted using a different fuel package than the remaining experiments. While the room layout was the same, the natural fiber furnishings are intended to provide a relative risk from a common structure fire of 50+ years ago.

2.4. Instrumentation

While significant amounts of instrumentation were included in each of these structures (Figs. 1, 2, 3), this manuscript will focus on gas temperature and concentration data collected in the fire rooms and bedrooms at a height of 0.9 m from the floor. Gas temperature was measured with bare-bead, type K thermocouples, with a 0.5 mm nominal diameter in locations shown in Figs. 1, 2 and 3. The uncertainty in type K thermocouple measurements is less than 1% to 2% of the measured value for temperatures up to 1250 K [21].

Gas concentrations of oxygen, carbon monoxide, and carbon dioxide were measured using Ultramat 23 NDIR from Siemens at 0.9 m from the floor adjacent to the front door and in bedrooms 1, 2 and 3 for both houses. The uncertainty of the measured concentration is 1% of the maximum concentration measurement. The maximum concentration measurements were 1% by volume for CO and 10% by volume for CO_2. The gases were extracted from the corners of rooms to minimize transport length from sample location to the sensor and reduce the risk of damage during firefighting operations. All data was collected at a frequency of 1 Hz.

For this study, tenability was calculated based on the measurements of air temperature and CO/CO_2. Other factors could contribute to increased FED values and lower times to untenability, including the effect of radiant heat (particularly in the fire room) and the presence of HCN and other gases in the structure. However, due to experimental limitations, these factors are not considered here. The FED values from HCN should scale with CO/CO_2. So although are values may be conservative, there is consistency in the comparisons.

2.5. Experimental Methodology

All of the experiments started with the exterior doors and windows closed, the roof vents closed, and all of the interior doors open except for Bedroom 3 in the one-story and Bedroom 2 in the two-story structure. The fire was ignited on a sofa in the living room (one-story) or family room (two-story), in a trash can next to the bed, or in a coffee maker on the kitchen countertop (Figs. 1, 2, 3). The ignition of each experiment was performed with a set of matches that were spark ignited on a fuel source (couch in the living/family room, trash can next to the bed in the bedrooms, and towels under a cabinet in the kitchen) in the room of interest [3].

A flaming fire was allowed to grow until ventilation operations were simulated. Fire service ventilation for each scenario was determined based on three factors; time to achieve ventilation limited conditions in the house, potential response and intervention times of the fire service, and window failure times from previous window failure experiments [5]. Times to arrival on-scene vary greatly based on fire department capabilities and response distance. NFA 1710 suggests that departments should provide for the first arriving engine company to be on-scene within approximately five minutes (80 s for turnout, 240 s for travel time) after alarm handling (which includes 15 s for alarm handling [95% of the time], and 64 s for processing [90% of the time]) [22]. According to NFPA 1720, the goal for fire emergency response for volunteer departments is to arrive at the scene **at a maximum** of 9 min in an urban area ($\sim$384 people/km^2), 10 min in a suburban area (192 people/km^2 to 384 people/km^2), 14 min in a rural area ($\sim$192 people/km^2) and directly related to driving distance for remote areas greater than 8 miles from the closest fire station [22]. Of course, these times do not include the time to detection and notification, which can also vary greatly (60 s to 310 s [23]). To account for this variation, while still achieving objectives for other components of this study, firefighter intervention was largely determined on achieving ventilation limited conditions for each scenario, within the realistic timeframes provided by NFPA standards. In all cases, temperatures were relatively stable (see Fig. 4) such that accumulation of additional exposure and increased FED is estimated to be constant. Therefore, to allow estimation of changes in FED if ventilation were delayed beyond the intervention time used here, the instantaneous rate of FED per second will be reported at the time when initial ventilation was provided.

For living room fires in the one-story structure, ventilation began at 8 min after ignition for most experiments (to simulate quick fire department arrival and due to the fire stabilizing under ventilation-limited conditions). The two exceptions were Experiment 15 at 6 min (ventilated to study the impact of flow path and fire spread) and Experiment 17 at 24 min (to allow for the legacy fire to become ventilation-limited), while the two-story house was ventilated 10 min after ignition for the family room fires. The additional time in the two-story structure enabled ventilation limited conditions, as more time is needed for oxygen to be consumed in a larger volume. In all bedroom scenarios, ventilation occurred at 6 min after ignition due to the smaller fire room compartment and simulated window failure, while kitchen fires were ventilated 10 min after ignition (to allow for ventilation-limited conditions). As an example, Fig. 4 shows a typical evolution of temperature with time in the one-story structure from Experiment 3, collected at a height of 0.9 m. This experiment began with ignition on the couch in the living room, which grew until the fire became ventilation-limited. The temperatures then began to decrease until 8 min into the experiment when an initial ventilation opening was created, in this case, by opening the front door. The data analyzed here focuses on tenability prior to Fire Service intervention, and will largely consider temperature and gas concentrations up to the times listed above. However, for

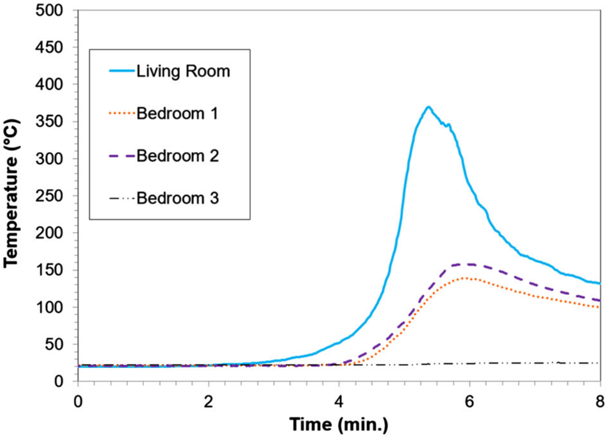

Figure 4. Temperature 0.9 m above the floor in experiment 3. Ignition was located in the living room. This study will focus on the time prior to fire department intervention (in this case, prior to 8 min).

reference and to contextualize this data, some of the following tables do include exposures after fire department intervention (Tables 2, 3).

2.6. Occupant Tenability

Occupant tenability, which is the survivability of occupants in the fire environment, is a primary concern for any firefighting operation. Two standard measures of occupant tenability were used during these experiments—temperature and gas concentration-based upon the fractional effective dose methodology (FED) from ISO 13571 [15]. This methodology provides a method to calculate the time to incapacitation based on an accumulated exposure to either toxic gases:

$$\upsilon_{CO_2} = exp\left(\frac{\varphi_{CO_2}}{5}\right) \tag{1}$$

$$FED_{CO} = \sum\left[\frac{\varphi_{CO}}{3.5} \cdot \upsilon_{CO_2} \cdot \Delta t\right] \tag{2}$$

or local ambient air temperature

$$FED_{temp} = \sum\left[\left(\frac{T^{3.61}}{4.1 \cdot 10^8}\right) \cdot \Delta t\right] \tag{3}$$

where υ_{CO_2} is a frequency factor to account for the increased rate of breathing due to carbon dioxide, φ_{CO_2} and φ_{CO} are the mole fractions (%) of carbon dioxide and carbon monoxide, T is the temperature near the occupant (°C), and Δt is the time increment of the measurements made in the experiments in minutes (1/60 in these experiments). According to ISO 13571, the uncertainty in Eq. 1 is ±20% and the uncertainty in Eq. 2 is ±35%. Equation 3 only applies for temperatures greater than 120°C, which is taken as the lower limit to this method. Gas concentration measurements did become saturated for some of the experiments (1% by volume for CO and 10% by volume for CO_2), so the FED values that we report are conservative estimates. Tables 2, 3, 4 and 5 will indicate which specific samples were saturated.

FED relates to the probability of the conditions being non-tenable for a certain percent of the population through a lognormal distribution. For reference, FED = 0.3 is the criterion used to determine the time of incapacitation for susceptible individuals (young children, elderly, and/or unhealthy occupants) and corresponds to untenability for 11% of the population, and FED = 1.0 is the value at which 50% of the population would experience untenable conditions.

FED's were calculated at an elevation of 0.9 m above the floor for both houses, representative of exposures that would be experienced by a person crawling on the floor. The time to exceed the thresholds for all of the experiments in each house for both heat (only convection considered as no radiant heat flux measurements were made) and carbon monoxide/carbon dioxide are calculated for both houses in living rooms and bedrooms, both with doors open and closed. It should be noted that the values assume the occupant was in that location for the duration of the experiment up to ventilation. These estimates may be considered lower bound scenarios as additional thermal risks may be present from exposure to large radiant heat exposures or from the additive effects of exposure to a variety of different hazardous gases.

While these measurements estimate exposures for the most likely case of an occupant crawling in smoky conditions, it is acknowledged that both heat exposure and toxic gas exposure will be larger with increasing elevation in the structure. If an occupant is standing or attempting to walk out of the structure, higher FED values and lower times to untenability will likely result.

3. Results

Calculations for FED = 0.3 and total FED at firefighter intervention are provided in Tables 2 and 3 for the one-story structure and in Tables 4 and 5 for the two story structure.

Table 2
Time to Untenability in One-Story Experiments for FED = 0.3 at 0.9 m Above the Floor

Location of the fire, experiment #			Living room (mm:ss)	Bedroom 1 (mm:ss)	Bedroom 2 (mm:ss)	Bedroom 3 (closed door) (mm:ss)
Living room (FD intervention at 8:00, except #15 @ 6:00 and #17 @ 24:00)	1	CO	**05:29**[a]	06:14[a]	05:32[a]	–
		Temp	**05:08**	(11:29)	07:00	–
	3	CO	**05:30**[a]	06:44[a]	05:29[a]	–
		Temp	**05:06**	(14:27)	07:17	–
	5	CO	**04:40**[a]	06:02[a]	EM	–
		Temp	**04:18**	(11:12)	05:57	–
	7	CO	**05:06**[a]	06:24[a]	05:57[a]	–
		Temp	**04:46**	(10:55)	06:18	–
	15	CO	**05:39**[a]	05:32[a]	05:24[a]	***(13:41)***
		Temp	**04:29**	–	05:19	–
	17[†]	CO	**(27:10)**	(23:14)	(23:06)	–
		Temp	**(27:43)**	(33:17)	(29:13)	–
Bedroom 1 (FD intervention at 6:00)	9	CO	05:37[a]	**04:01**[a]	04:40[a]	***(11:16)***
		Temp	–	**03:10**	(16:16)	–
	11	CO	06:06[a]	**EM**	05:09[a]	–
		Temp	–	**03:13**	07:29	–
Kitchen (FD intervention at 10:00)	13	CO	(12:38)[a]	(10:37)[a]	(09:48)[a]	***(19:06)***
		Temp	(13:08)	–	–	–

Bold values indicate fire room, while the bold italicised value highlights the bedroom behind closed doors. For reference, times when FED = 0.3 after fire department intervention are included in parentheses

– not achieved, *EM* equipment malfunction

[†] Denotes legacy (>50 years ago) furnishings

[a] The calculated time to attain untenable conditions in the one-story structure are longer than the actual times (conservative) because the CO and CO_2 gas concentration exceeded the measurement limits (1% and 10% respectively) of the instruments used

Table 3
FED Values at Initial Firefighter Intervention in One-Story Structure

Location of the fire, experiment #			Living room (%)	Bedroom 1(%)	Bedroom 2	Bedroom 3 (closed door) (%)
Living Room (FD intervention at 8:00, except #15 @ 6:00 and #17 @ 24:00)	1	CO	**3.27 (88)**	2.21 (79)	4.41 (93%)	***0.01 (< 0.1)***
		Temp	**4.21 (92)**	0.18 (4)	0.33 (13%)	*<0.01 (< 0.1)*
	3	CO	**3.17 (88)**	0.80 (41)	4.51 (93%)	***0.11 (1)***
		Temp	**4.01 (92)**	0.14 (2)	0.31 (12%)	*<0.01 (< 0.1)*
	5	CO	**3.72 (91)**	1.85 (73)	EM	***0.05 (0.1)***
		Temp	**4.45 (93)**	0.21 (6)	0.41 (19%)	*<0.01 (< 0.1)*
	7	CO	**4.53 (93)**	1.84 (73)	1.79 (72%)	*<0.01 (< 0.1)*
		Temp	**6.82 (97)**	0.22 (6)	0.44 (21%)	*<0.01 (< 0.1)*
	15	CO	**1.02 (50)**	1.17 (56)	1.17 (56%)	***0.01 (< 0.1)***
		Temp	**16.3 (>99)**	0.16 (3)	0.50 (24%)	*<0.01 (<0.1)*
	17†	CO	**0.23 (7)**	0.36 (15)	0.37 (16%)	***0.01 (<0.1)***
		Temp	*<0.01 (<0.1)*	*<0.01 (<0.1)*	*<0.01 (<0.1%)*	*<0.01 (<0.1)*
Bedroom 1 (FD intervention at 6:00)	9	CO	3.57 (90)	**9.81 (99)**	6.06 (96%)	***0.08 (0.5)***
		Temp	*<0.01 (<0.1)*	**37.1 (>99)**	0.21 (6%)	*<0.01 (<0.1)*
	11	CO	0.18 (4)	**0.24 (8)**	0.46 (22%)	***0.01 (<0.1)***
		Temp	*<0.01 (<0.1)*	**31.1 (100)**	0.11 (1%)	*<0.01 (<0.1)*
Kitchen (FD intervention at 10:00)	13	CO	0.16 (3)	0.18 (4)	0.51 (25%)	***0.07 (0.4)***
		Temp	*<0.01 (0)*	*<0.01 (0)*	*<0.01 (0)*	*<0.01 (<0.1)*

Bold values indicate fire room, while the bold italicised values highlights the bedroom behind closed doors. Percent of the population that would experience untenable conditions is included in parentheses

Italic values indicate <0.01 (<0.1%)

† Denotes legacy furnishings

In the one-story structure, where ignition occurred in the bedroom or living room, untenable conditions for susceptible populations (FED = 0.3) were reached in every room (except for the closed door room) before Fire Service intervention (Table 2). The average time to FED = 0.3 in the living room, bedroom 1, and bedroom 2 was 5 min 32 s. Thus, depending on firefighter response times, susceptible occupants inside the structure (and outside of closed rooms or compartments) are likely to have experienced untenable conditions prior to fire department intervention.

In the two-story structure, experiments with initial ignition in the family room (2, 4, 6, 8, 12), resulted in average times to untenability of 9 min 36 s for a FED criterion of 0.3 in open bedrooms and at the front door (Table 4). Additionally, FED values at the time of firefighter intervention (Table 5) outside of the fire room typically remain below 1. The exception to this trend was for the scenarios where the fire was ignited on the second floor bedroom. In those cases, FED values in the open bedroom on the same level were remarkably high for CO exposure.

Table 4
Time to Untenability in Two-Story Experiments for FED = 0.3 at 0.9 m Above the Floor

Experiment #			Family Room (mm:ss)	Bedroom 1 (mm:ss)	Bedroom 2 (mm:ss)	Bedroom 3 (mm:ss)
Family room (FD intervention at 10:00)	2	CO	**07:55**	09:43	–	09:06
		Temp	**05:36**	(13:52)	–	07:34
	4	CO	**09:28**	(10:43)	–	(10:25)
		Temp	**07:12**	(17:21)	–	09:04
	6	CO	**08:49**	(10:08)	–	10:00
		Temp	**06:18**	(13:29)	–	08:23
	8	CO	**09:51**	(10:48)	–	(10:36)
		Temp	**07:10**	(11:55)	–	08:34
	12	CO	**09:29**	08:42	–	08:21
		Temp	**05:57**	(10:54)	–	07:31
Bedroom 3 (FD intervention at 6:00)	10	CO	–	05:07[a]	***(17:31)***	**03:56**[a]
		Temp	–	–	–	**03:03**
	14	CO	–	05:14[a]	***(12:37)***	**04:00**[a]
		Temp	–	–	–	**03:19**
Kitchen (FD intervention at 17:00)	16	CO	(17:08)	(15:39)	***(22:19)***	(16:02)
		Temp	(26:05)	(28:33)	–	(27:05)

Bold values indicate fire room, while the bold italicised values highlights the bedroom behind closed doors. For reference, times when FED = 0.3 after fire department intervention are included in parentheses. Family room CO measurements were made at the front door of the structure

– not achieved

[a] The calculated time to attain untenable conditions in the bedroom 3 fire scenarios in the two-story structure are longer than the actual times (conservative) because the CO and CO_2 gas concentration exceeded the measurement limits (1% and 10% respectively) of the instruments used

Table 5
FED Values at Initial Firefighter Intervention in Two-Story Structure

Experiment #			Family Room[a] (%)	Bedroom 1(%)	Bedroom 2 (closed door) (%)	Bedroom 3 (%)
Family Room (FD intervention at 10:00)	2	CO	**0.68 (35)**	0.29 (11)	*<0.01 (<0.1)*	0.44 (21)
		Temp	**2.39 (81)**	*<0.01 (<0.1)*	*<0.01 (<0.1)*	0.64 (33)
	4	CO	**0.34 (14)**	0.16 (3)	*<0.01 (<0.1)*	0.19 (5)
		Temp	**3.77 (91)**	*<0.01 (<0.1)*	*<0.01 (<0.1)*	0.46 (22)
	6	CO	**0.47 (23)**	0.23 (7)	***0.05 (0.1)***	0.26 (9)
		Temp	**5.84 (96)**	*<0.01 (<0.1)*	*<0.01 (<0.1)*	0.55 (28)
	8	CO	**0.49 (24)**	0.21 (6)	***0.04 (0.1)***	0.27 (10)
		Temp	**9.77 (99)**	0.14 (2)	*<0.01 (<0.1)*	0.70 (36)
	12	CO	**0.09 (1)**	0.13 (2)	***0.03 (0.1)***	0.17 (4)
		Temp	**3.74 (91)**	0.03 (0.1)	*<0.01 (<0.1)*	0.42 (19)
Bedroom 3 (FD intervention at 10:00 for #10 & 8:35 for #14)	10	CO	*<0.01 (<0.1)*	8.5 (98)	***0.05 (0.1)***	**10.5 (99)**
		Temp	*<0.01 (<0.1)*	*<0.01 (<0.1)*	*<0.01 (<0.1)*	**137 (>99)**
	14	CO	*<0.01 (<0.1)*	5.5 (96)	***0.03 (0.1)***	**9.2 (99)**
		Temp	*<0.01 (<0.1)*	*<0.01 (<0.1)*	*<0.01 (<0.1)*	**100 (>99)**
Kitchen (FD intervention at 17:00)	16	CO	0.27 (10)	0.54 (27)	***0.13 (2)***	0.47 (23)
		Temp	*<0.01 (<0.1)*	*<0.01 (<0.1)*	*<0.01 (<0.1)*	*<0.01 (0.1)*

Bold values indicate fire room, while the bold italicised values highlights the bedroom behind closed doors. Percent untenable is in parentheses

Italic values indicate <0.01 (<0.1%)

4. Discussion

The results from the 17 experiments show that both heat and toxic gases present a significant threat to trapped occupants in residential fires. And while heat is typically considered the more serious concern very near the fire, as distance from the seat of the fire increases, i.e. the adjacent non-fire rooms, CO production begins to become the more serious threat to trapped occupants. For the timelines investigated in this study, the total FED for CO and temperature were very similar in the single story structure, while temperature affects dominated the larger two-story structure. This affect is attributed to the fires more rapidly becoming ventilated limited in the smaller structure as well as the reduced volume for diluting the effluent gases.

The selected ventilation times represent, for the most part, best case scenarios of fire department arrival (based on rapid fire detection) given the recommended NFPA standard alarm processing and response times. However, if the time of initial ventilation were further delayed, additional FED accumulation (FED/s) can be estimated since the temperature and gas concentration conditions were relatively stable upon ventilation. These estimates are shown in Tables 6 and 7. For example, if ventilation were delayed in Experiment 1 from 8 min to 10 min the values in Table 3 (e.g. $\mathrm{FED}_{\mathrm{Temp}} = 4.21$) would be increased by approximately 0.96 ($\mathrm{FED}_{\mathrm{Temp}}/\mathrm{s} = 0.008 \times 120$ s). It is clear from these tables that at this point in the fire development, the additional threat from thermal exposure is typically less than the threat due to toxic gases, even in the fire rooms for the one-story structure.

Based on the results presented here and typical response times that may be expected by the fire service it is likely that susceptible individuals who remain stationary (sleeping or otherwise unable to self-evacuate) at these locations will have experienced untenability in all parts of the one-story structure that have direct connection to the fire room. The high FED levels achieved over relatively short duration (typically 6 min to 10 min) also raises a concern for those who may be attempting to evacuate from the structure, particularly if exiting through the main living room or family room areas. Tables 2 and 4 highlight the times to untenability for susceptible individuals, which can be compared to the required safe egress time (RSET). In 2006, the National Research Council Canada published a report reviewing the available information on egress times from single family from residential structures and found that the time for egress can range from 2 min to 16 min [23]. This fact points to the critical need for active detection to reduce the detection time and suppression systems installed in these structures to control the fires allowing egress. This data also suggests additional consideration for the importance of "design for tenability" in residential structures, e.g. through compartmentalization.

The fire department interventions times utilized in these studies remained fairly constant for all of the living room and family room fires. While these intervention time are similar to the NFPA 1720 recommendations, variations in the response times are likely to have a relatively small impact on the outcomes for these ventilation limited fires. As seen in Fig. 4, the temperatures at the fire service interven-

Table 6
FED Instantaneous Exposure at the Time of Ventilation in the One-Story Experiments

Location of the fire, experiment #			Living room (FED/s)	Bedroom 1 (FED/s)	Bedroom 2 (FED/s)	Bedroom 3 (closed door) (FED/s)
Living Room (FD intervention at 8:00, except #15 @ 6:00 and #17 @ 24:00)	1	CO	**0.0145**	0.0236	0.0288	***0.0001***
		Temp	**0.0018**	0.0006	0.0009	***0***
	3	CO	**0.0094**	0.0179	0.0290	***0.0001***
		Temp	**0.0018**	0.0007	0.0009	***0***
	5	CO	**0.0092**	0.0253	EM	***0.0003***
		Temp	**0.0014**	0.0005	0.0007	***0***
	7	CO	**0.0210**	0.0254	0.0264	***0***
		Temp	**0.0018**	0.0006	0.0009	***0***
	15	CO	**0.0348**	0.0273	0.0352	***0.0001***
		Temp	**0.0102**	0.0017	0.0031	***0***
	17†	CO	**0.0010**	0.0014	0.0014	***0***
		Temp	**0.0002**	0.0001	0.0001	***0***
Bedroom 1 (FD intervention at 6:00)	9	CO	0.0319	**0.0308**	0.0352	***0.0007***
		Temp	0.0007	**0.0260**	0.0012	***0***
	11	CO	0.0048	**0.0032**	0.0144	***0.0001***
		Temp	0.0007	**0.1623**	0.0020	***0***
Kitchen (FD intervention at 10:00)	13	CO	0.0010	0.0029	0.0031	***0.0001***
		Temp	0.0001	0	0.0001	***0***

Bold values indicate fire room, while the bold italicised values highlights the bedroom behind closed doors

tion times were on a gradual decline and often even below the 120°C threshold for which heat is an imminent threat for the trapped victim. On the other hand, the accumulation of FED due to CO exposure was usually at the maximum measurable value (due to saturation of the CO and CO_2 measurement equipment) at 0.035 FED/s at both 6 and 8 min after ignition. Thus, the longer the victims remain within these ventilation-limited fire scenarios, the more important the gas exposures to the victims become. Were these fires conducted with a different ventilation profile, such as one that would be caused by an open door or after window failure, results may be different. Such scenarios will be the subject of future study.

The FED methodology predicts that susceptible victims in the fire room will reach a critical thermal exposure prior to reaching a similar critical gas exposure. In most cases, this difference is only 20 s to 30 s, even with utilizing the simple two gas (CO & CO2) model. It is possible that if temperature and concentration sampling were taken at a vertical location higher in the room, this discrepancy would be larger. Victims' proximity to the flaming fire would also have a significant impact on these values, increasing the thermal FED closer to the seat of the fire. Furthermore, including the effect of exposure to radiant heat would increase thermal FED in the fire room. For the sampling locations in non-fire (but connected) rooms, critical levels of exposure were reached for CO exposure, typically well before critical exposure to elevated temperatures.

Table 7
FED Instantaneous Exposure at the Time of Ventilation in the Two-Story Experiments

Experiment #			Family room[a] (FED/s)	Bedroom 1 (FED/s)	Bedroom 2 (closed door) (FED/s)	Bedroom 3 (FED/s)
Family Room (FD intervention at 10:00)	2	CO	**0.0035**	0.0034	***0***	0.0044
		Temp	**0.0009**	0.0008	***0***	0.0018
	4	CO	**0.0034**	0.0020	***0***	0.0026
		Temp	**0.0093**	0.0010	***0***	0.0026
	6	CO	**0.0038**	0.0028	***0.0001***	0.0031
		Temp	**0.0070**	0.0010	***0***	0.0024
	8	CO	**0.0053**	0.0041	***0.0002***	0.0052
		Temp	**0.0096**	0.0016	***0***	0.0034
	12	CO	**0.0014**	0.0023	***0.0001***	0.0188
		Temp	**0.0136**	0.0014	***0***	0.0036
Bedroom 3 (FD intervention at 10:00 for #10 & 8:35 for #14)	10	CO	0	0.0310	***0.0003***	**0.0032**
		Temp	0	0.0003	***0***	**0.0027**
	14	CO	0	0.0352	***0.0004***	**0.0313**
		Temp	0	0.0006	***0***	**0.0275**
Kitchen (FD intervention at 17:00)	16	CO	0.0027	0.0049	***0.0003***	0.0040
		Temp	0.0007	0.0004	***0***	0.0010

Bold values indicate fire room, while the bold italicised values highlights the bedroom behind closed doors

As we conducted four experiments that were identical pre-ventilation in both the one-story (1, 3, 5, 7) and two-story (2, 4, 6, 8) structures, it is possible to quantify the repeatability in tenability for identical fuel loads and fires. Table 8 shows the average accumulated FED value at ventilation in each room as well as the sample standard deviation for both the heat and toxic gases exposure. The largest variability was seen in the fire room of the two-story structure. However, for the most part, the standard deviation was ±25% of the mean.

Table 8
Repeatability of FED Accumulation for Identical Experiments (Values in Table Written in Mean ± Standard Deviation)

Structure	Exposure type	Living room/family room	Master bedroom	Target bedroom with open door	Target bedroom with closed door
One-story	CO	3.67 ± 0.62	1.68 ± 0.61	3.57 ± 1.54	0.045 ± 0.047
	Temp	4.87 ± 1.31	0.19 ± 0.04	0.37 ± 0.06	0 ± 0
Two-story	CO	0.50 ± 0.14	0.22 ± 0.05	0.29 ± 0.11	0.022 ± 0.026
	Temp	5.44 ± 3.21	0.035 ± 0.07	0.59 ± 0.11	0 ± 0

4.1. One-Story versus Two Story Structure: Living Room Fires

Four experiments in the single story structure (Experiments 1, 3, 5, and 7) are all identical in terms of structure and fuel package layout and materials, ignition location (Living Room), and ventilation conditions up to the 8 min where firefighters intervened. Environmental conditions were held to a high level of repeatability in terms of temperature, moisture and air velocity (basically still). However, outside of the closed bedrooms, FED values ranged dramatically. For the fire room (living room), FED_{temp} ranged from 4.0 to 6.8, while FED_{CO} in Bedroom 2 ranged from 1.2 to 4.5. For the two-story structure, a similar series of experiments were run with the Family Room as the ignition location. Nearly identical fuel packages were ignited in experiments 2,4,6,8, and 12. For the fire room, FED_{temp} ranged from 2.4 to 9.8, while FED_{CO} in Bedroom 3 ranged from 0.2 to 0.5.

Time to untenability for these ‘room and contents’ fires with limited ventilation is much improved on the second floor of the two story structure compared to the one-story structure, largely due to the increased volume of the structure. If the same volume of CO is generated by these fires, the two-story structure will have a smaller CO concentration because of the increased dilution with air in the enclosed space. Additionally, carbon monoxide generation typically increases as the fire becomes oxygen-limited. Since the two-story structure has more oxygen available inside the enclosed space at the start of the fire, CO generation is likely to increase more slowly than in the one-story structure. Importantly, while the second floor bedrooms are more tenable than the first floor spaces, egress through the interior of the structure would likely require exposure to the highly untenable conditions on the first floor. Firefighters should consider this fact in the risk–benefit analysis when employing vent-enter-isolate-search techniques to rapidly access victims on the second floor from the exterior as opposed to attempting rescue through the high temperature environment on the interior of the first floor.

For the single story structure, the FED_{CO} values in the target bedrooms with open doors were consistently higher in Bedroom 2 compared to Bedroom 1. The trend for FED_{temp} was not as clear, though the values were higher in Bedroom 2 compared to Bedroom 1 for two experiments and similar in the remaining three living room fire experiments. This affect could possibly be attributed to the smaller volume of Bedroom 2, the orientation of the door at the end of the hallway, or the distance from the heat source which results in lower temperatures further from the heat source and thus less stratification of the gas layer. For the two-story structure, FED_{CO} was similar in Bedroom 1 and 3. However, FED_{temp} was significantly higher in Bedroom 3, exceeding 0.3 for all 5 scenarios while never exceeding 0.2 in Bedroom 1 for any scenarios. Interestingly, the largest FED in the second floor bedrooms was due to thermal effects for Bedroom 3, but due to CO in Bedroom 1. Again, this may be due to the distance from the heat source resulting in lower temperatures but also less stratification of the gas layer. Additional research would be required to fully understand and decouple these potentially interacting effects.

4.2. Impact of Fire Location and Fuel Source

The bedroom fire scenarios each transition to ventilation limited conditions more rapidly than the Living Room fires, and result in higher fire compartment temperatures. FED at the time of fire department intervention for the bedroom scenarios was well in excess of 30, suggesting that more than 99.9% of the population would be incapacitated. These fires are ignited in smaller compartments providing significant re-radiation and more rapid growth. For the single story structure, FED_{CO} values produced by the bedroom scenarios were similar to or larger than those produced by the Living Room fire despite fire department 'intervention' 2 min earlier than the Living Room scenarios. At the same time, the temperature increase in the non-fire rooms is relatively small, with the maximum $FED_{temp} = 0.21$ in the adjacent bedroom.

For the two story scenarios, where the fire was ignited in the second floor bedrooms, the FED_{temp} values are almost three times higher than similar fires in the single story structure, even with identical furnishings and similar room size. However, this is partially attributed to the longer times to firefighter 'intervention' in those experiments. Additionally, for open bedrooms on the second floor, the FED_{CO} values were 20× to 30× higher in the bedroom fires than those measured during the family room fires. As with the living room/family room scenarios, the largest risk for remote victims is again gas exposures, but the risk is relatively more elevated in the bedroom fire scenarios because the fires become locally ventilation-limited due to their confined nature. It is also likely that since these scenarios resulted in higher ambient fire room temperatures more rapidly, they were able to sustain the combustion process even at lower oxygen concentrations, producing relatively larger amounts of CO. On the first floor of the structure, there was little measureable impact on tenability, most likely due to the buoyant nature of the combustion products. Furthermore, without a ventilation location for combustion products to escape, air from the first floor is not as easily entrained into the oxygen-limited fire on the second floor.

The kitchen fuel package (Experiments 13 and 16) resulted in low FED compared to the living room and bedroom fuel packages in both structures. For the kitchen fire scenarios—and typical of common structures in the US—the majority of the fuel is wood cabinets and countertop appliances of hard plastic. Fewer soft and/or foamed polymers are typically found in the kitchen. At the time of fire department intervention (even delayed to 10 min), $FED_{temp} < 0.01$ in all target rooms. The worst case bedroom $FED_{CO} = 0.5$, which is equivalent to the lowest value measured for the living room fire. The fuel sources in the kitchen fires consisted mostly of wood cabinets and countertops that burn slower and take longer for the structure to reach ventilation-limited conditions. CO production increases significantly when the fire reaches ventilation-limited conditions [24], and thus there is more CO produced by the bedroom and living room fires. Kitchen fires are the most common source of residential fires (43%), but fortunately appear to be the most survivable based on results from this study.

Finally, experiment 17 was added to the test series to provide a comparison with furnishings constructed from mostly natural materials (sometimes referred to as legacy furniture [5]) as opposed to the largely polymer based furnishings that are currently common in US households. The average times to achieve untenable conditions for Experiment 17 were well beyond the timeframe of initial fire service intervention (24:30 for FEC criteria of 0.3). This is an increase of approximately 20 min compared to the experiments with living room furnishings common in the twenty-first century in the one-story structure. Compared to the NFPA 1710 and 1720 based response timeframes, it is apparent that firefighters of the past responding to fires with these fuels were likely to find survivable victims more readily than fires involving fuel loads typical of today's structures. At the same time, fire-related occupant fatalities have continued to decline over the past several decades in apparent contrast to the tenability data presented here. Thanks to progress in public education, fire safety initiatives, widespread use of smoke detectors, and increasing installation of active fire sprinkler system, fire protection engineers have been successful at not only keeping pace with this increasing tenability risk, but actually affecting an improvement in life safety.

4.3. Behind Closed Doors

While improved detection, suppression and public education have helped to drive down fire related injuries and fatalities, a complimentary initiative can be supported by the notable tenability levels in Bedroom 3 of the one-story structure and Bedroom 2 of the two-story structure. Both of these rooms had the interior doors closed for the duration of the experiments, physically separating these spaces from the fire room. Importantly, the times to untenability found in Tables 2 and 4 suggest that occupants in compartments with closed doors never receive an FED > 0.3, even though an immediately adjacent bedroom may reach FED $= 0.3$ in approximately 5 min or less. In every case, thermal FED in the bedroom behind closed doors remained less than 0.01. The maximum FED based on CO exposure in these rooms was measured for living room fires at 0.11, which would be considered untenable for 1.4% of the population. For this same scenario, the adjacent bedroom with open door resulted in a measured $\text{FED}_{\text{CO}} = 4.51$, which would be untenable for 93% of the population.

In order to quantitatively characterize the improvement in tenability behind closed doors, FED ratios at the time of firefighter intervention were calculated and they are reported in Tables 9 and 10. The FED ratio is calculated for the nearest bedroom of the same dimensions compared to the closed door bedroom (BR2/BR3 for one-story and BR3/BR2 for two-story). Two scenarios for the two-story structure utilized bedroom 3 as the fire room, so in this case, the bedroom 1 is the open bedroom control. This bedroom is farther away from the fire room than bedroom 2 and larger, so should provide a conservative FED estimate. In some scenarios, the FED behind closed doors is very small, so a lower limit of FED $= 0.01$ is utilized for these calculations to bound the calculation. In all cases, the maximum FED—based on either temperature or gas—is utilized for each room.

Due to the relatively small FED in the closed bedroom, the FED ratio varies widely even for the same ignition location. However, for the single story structure,

Table 9
Maximum FED Values and FED Ratios Comparing Open and Closed Bedroom FED in the Single Story House

Experiment #		Bedroom 2	Bedroom 3 (closed door)	FED Ratio
Living Room	1	4.41 CO	0.01 CO	441
	3	4.51 CO	0.11 CO	41
	5	1.85 (CO, BR1)	0.05 CO	37
	7	1.79 CO	0.01 CO	179
	15	0.50 Temp	0.01 CO	50
	17[†]	0.37 < CO	0.01 CO	37
Bedroom 1	9	6.06 CO	0.08 CO	179
	11	0.46 CO	0.01 CO	46
Kitchen	13	0.51 CO	0.07 CO	7.3

For closed bedroom where the measured FED < 0.01, the value of 0.01 was assumed to provide lower bound estimate

Table 10
Maximum FED Values and FED Ratios Comparing Open and Closed Bedroom FED in the Two Story House

Experiment #		Bedroom 2 (closed door)	Bedroom 3	FED Ratio
Family room	2	0.01 CO/Temp	0.64 Temp	64
	4	0.01 CO/Temp	0.46 Temp	46
	6	0.05 CO	0.55 Temp	11
	8	0.04 CO	0.70 Temp	17.5
	12	0.03 CO	0.42 Temp	14
Bedroom 3	10	0.05 CO	8.5 (BR1) CO	170
	14	0.03 CO	5.5 (BR1) CO	183
Kitchen	16	0.13 CO	0.47 CO	3.6

For closed bedroom where the measured FED < 0.01, the value of 0.01 was assumed to provide lower bound estimate the FED ratio ranged from 7.3 for the kitchen scenario (which resulted in FED <0.5 throughout the structure) to over 400 for a Living Room scenario. The median value (for all 17 experiments) was 46—a potential trapped victim behind a closed door would be exposed to a 46× lower FED than those in a bedroom with an open door.

In both cases, the lowest FED ratio behind closed doors was for the Kitchen scenarios, which were significantly longer and had relatively low temperatures compared to the other tests. For the two story structure, the largest FED ratio was found for the Bedroom fires, which occurred on the same level as the other bedrooms. For the one story structure, there was little difference in the FED ratio from the Bedroom to Living Room fires.

Once again, this data suggests the importance of teaching the public the value of a comprehensive fire safety plan in residential structures. As mentioned earlier, the rapid accumulation of an incapacitating FED in a timeframe that is well within the 2 min to 16 min RSET analysis of Proulx et al. [22] highlights the need for rapid fire detection and notification throughout a structure as well as active suppression systems that can control the fire. At the same time, certain individuals will not feasibly be able to respond rapidly enough to self-evacuate, in which case the critical message of sheltering behind a closed door should be shared. The tables included in this manuscript show the unequivocal improvement in tenability behind closed doors, particularly for those who may be susceptible to smoke exposure and also have a long RSET (young, elderly, mobility impaired). Furthermore, for those individuals whose means of egress may be cut off by the progression of a fire, the value of sheltering behind closed doors should be reinforced based on this data.

5. Conclusions

Using the ISO 13571 tenability criteria for occupant exposure to heat and toxic gases, tenability conditions were determined throughout a series of 17 experiments. It was observed that prior to firefighter intervention, fires in the one-story structure result in a larger threat to occupant tenability for similar fires due to the lower amounts of available oxygen and smaller volume for the toxic gases to fill. These two factors lead to increased carbon monoxide and carbon dioxide concentrations. In many of the one-story experiments, the FED values prior to firefighter intervention were larger than 1 even in the non-fire rooms. In the single story structure, gas exposure was the highest risk for target rooms, while thermal exposure was the largest risk in the same rooms in the larger two-story structure. However, it was also observed that for rooms where the door was closed during the development of the fire, the FED values remained below 0.1 in all cases prior to firefighter intervention. Importantly, the median FED value was 46× higher for occupants in open bedrooms than for occupants behind closed doors, significantly reducing the risk the occupant faces.

This study provides further understanding of the timelines for tenability for common residential structure fires. It is important to note that the effect of radiant heat in the fire room and the impact of other toxic gases, especially HCN, was not measured. As a result, the presented FED values may be lower and times to untenability higher than if the combined effects were included. Future research should expand upon this data by incorporating those additional measurements (heat flux and HCN concentration) as well as other types of construction common in different parts of the world.

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