THE EFFECTS OF FLOOR AREA AND OPENING AREA ON THE DEVELOPMENT OF FIRES IN RESIDENTIAL DWELLINGS

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by

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ABSTRACT

Upholstered furniture fires are responsible for a significant number of deaths in residential dwellings in Canada. How total floor area, total opening area, and flammability of upholstered furniture affect and shape the fire growth profile, time to major events, and tenability levels are assessed in this thesis. The scope of this project includes computational fluid dynamics modeling (using FDS) of two-storey single-family detached homes and townhomes focusing on living room and bedroom fires. The results show that increasing the amount of opening area in a room results in an increase in peak heat release rates, an increase in the time to flashover in detached homes, little or no effect on fire safety device activation, and no increase in available safe egress time (ASET) based on tenability criteria.

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NOMENCLATURE

A	Pre-exponential factor (/s)
A_T	Total compartment surface area (m^2)
A_V	Area of openings (m^2)
c_p	Thermal diffusivity (kJ/kgK)
D	Depth of room (m)
E	Activation Energy (kJ/kmol)
F_V	Ventilation Factor ($m^{0\ 5}$)
ΔHc	Heat of combustion (MJ/kg)
H_k	Effective heat transfer coefficient (kW/m^{o}K)
HRR	Heat release rate (kW)
H_V	Height of openings (m^2)
k	Thermal conductivity (W/mK)
$\dot{m}$	rate of combustion (m in kg/s)
$\dot{Q}$	Rate of heat release (kW)

$\dot{Q}_{FO}$ Heat release rate necessary to cause flashover (kW)

t_o Characteristic time, time after effective ignition (s)

T_{max} Maximum temperature measured in the upper layer (°C)

W Width of room (m)

α Growth rate coefficient (kW/s^2)

Ω Omega ($m^{0.5}$)

1 INTRODUCTION

Research institutes in Canada, the United States, Sweden, and New Zealand have conducted research projects that yielded rich experimental and theoretical benchmark data on the burning characteristics of upholstered furniture [1-6]. The data included the fire growth rates, time to flashover, and production rates of toxic gases. Parameters such as house floor area, size of windows (openings), as well as type of furniture used (upholstered vs. conventional materials) determine the severity profile of the fire that may occur in a house. Literature suggests that a larger floor area translates to a lower fuel load per unit area [7], [8]. This may limit fire growth and help to slow the spread of flames from the first ignited item to adjacent items. When there more combustibles and fresh air from openings, a fire will burn at higher rates and release more heat. In addition, for products such as upholstered furniture, fire can commence and grow in a smouldering fashion. How each of these parameters affect and shape the fire growth profile, time to major events, as well as the tenability levels during the course of fires, is an important issue.

Literature suggests that a better understanding of the impact of the use of upholstered furniture in living and sleeping areas will not only help to increase the life safety of occupants, but will also reduce the high number of deaths and injuries occurring every year, for firefighters. In addition, this will help to reduce property damage.

2 PROBLEM DEFINITION AND METHODOLOGY

The aim of this research is to examine the impact of varying both opening area and total floor area in residential dwelling fires, specifically for fire growth and the time to major fire events. A large number of residential fires are ignited by smoking materials, where the item first ignited is typically upholstered furniture [9]. This fire scenario is evaluated in two locations in a house where it is likely to occur: the living room and bedroom. These two locations were chosen based on high content of upholstered furniture such as sofas and mattresses. In this research, two types of dwellings common to North America are investigated: single-family detached homes and single-family townhomes. In general, detached homes have a greater total floor area and total opening area than townhomes.

The objective of this study was to determine the fire growth profiles, time to major fire events, and times at which tenability criteria are exceeded in critical locations in the house. This was accomplished using a computational fluid dynamics program, Fire Dynamics Simulator (FDS).

3 LITERATURE REVIEW

3.1 The Impact of Upholstered Furniture on an Occupant's Life Safety and Property Damage

Canadian statistics compiled by the Council of Canadian Fire Marshals and Fire Commissioners indicated a decrease in the total number of fires from 1997 to 2002 compared to 1993 to 1996. Similarly, the death and injury rate was also lower during 1997-2002 (Table 3-1). Overall, the number of fires has reduced by over 10,000 per year, fire deaths have decreased by about 100, and injuries are down by 1,000. Despite the fewer number of fires in recent years the total monetary losses were higher than average in 2001 and 2002, nearing $1.5 billion (this value does not account for inflation).

Table 3-1: Canadian Fire Statistics [10]

Year	Estimated Population (Million)	Number of Fires	Losses $ (Billion)	Fire deaths	Death Rate*	Injuries	Injury Rate*
1993	28.7	65,877	1.18	417	1.45	3 463	12.06
1994	29.0	66,719	1.15	377	1.3	3 539	12.19
1995	29.4	64,251	1.11	400	1.36	3 551	12.1
1996	29.7	60,138	1.16	374	1.26	3 152	10.62
1997	30.0	56,292	1.29	416	1.39	3 149	10.5
1998	30.3	57,602	1.76	337	1.11	2 697	8.9
1999	30.5	55,169	1.23	388	1.27	2 287	7.51
2000	30.8	53,720	1.19	327	1.06	2 490	8.1
2001	31.0	55,323	1.42	338	1.09	2 310	7.43
2002	31.5	53,589	1.49	304	0.97	2 547	8.09
10 year Average		59,936	1.22	374	1.25	3 072	10.26

* Total number of deaths/injuries per 100,000 population per year

Table 3-2 provides the estimation of fire losses based on the property types for year 2002. Out of all the fire incidents that happened during 2002, approximately 77% occurred in residential and special properties. Special properties consist mainly of outdoor properties, transportation equipment, and buildings under construction or demolition. The provinces which reported the highest percentages of residential fires were Quebec (67%), Nova Scotia (65%), and New Brunswick (51%) [10].

Table 3-2: Canadian Fire Statistics by Property Type for 2002 [10]

Classification	Fires	% of Total	$ Losses	% $	Injuries		Deaths	
					#	%	#	%
Residential	22,186	41.4	712,209,529	47.83	1,809	71.02	250	82.24
Assembly	1,657	3.09	96,360,073	6.47	53	2.08	-	-
Institutional	455	0.85	18,515,000	1.24	52	2.04	5	1.64
Business and Personal Service	608	1.13	41,329,367	2.78	31	1.22	2	0.66
Mercantile	1,362	2.54	110,773,166	7.44	102	4	-	-
Industrial & Manufacturing Properties	1,381	2.58	189,887,031	12.75	82	3.22	-	-
Storage	1,578	2.94	47,854,782	3.21	78	3.06	-	-
Special	19,396	36.19	137,310,991	9.22	223	8.76	33	10.86
Miscellaneous	4966	9.27	134,772,324	9.05	117	4.59	14	4.61
Total	53,589	100	1,489,012,263	100	2,547	100	304	100

In Canada, residential fires make up 41% of all fires and 48% of the total monetary loss, as cause 71% of the total injuries and 82% of the total deaths [10]. In addition, research also showed an increase in the number of deaths by 9% since 1999, when residential fires accounted for 73% of fires [11]. This shows that residential fires are one of the most costly fires in Canada, both in terms of life and wealth.

Between 1995 and 1998, Ontario reported 95% of fire deaths occurred in residential buildings; with the majority of deaths originating in the living and sleeping areas [9]. Fires starting in the living area made up 11.3% of the residential fires but accounted for 32% of the deaths in residential fires, and fires in sleeping area made up 8.5% of the residential fires, but 15.4% of the residential fire deaths. In most of these fire incidents, upholstered furniture was the leading cause for fire initiation as a result of fatal ignition sources such as lighters, matches, and smoking material [9]. In general, the term "upholstered furniture" relates to household items such as couches and mattresses, containing foam cushioning (usually made from polyurethane) and fabric upholstery. This reiterates the well-accepted worst-case scenario resulting in death due to an upholstered furniture fire being ignited by smoking materials in the main living area.

Therefore having upholstered furniture items in a house increases the possibility of fatalities occurring as a result of a fire, particularly if any of the inhabitants are smokers. Any fire that can grow quickly, such as an upholstered furniture fire, has the capability of causing harm to occupants and creating significant property damage in a short period of time. A significant portion of all residential losses is attributed to upholstered furniture fires (where residential property losses were 5 times greater than any other category of fire by property type [10]).

3.2 Upholstered Furniture Safety Regulations

In an aim to increase consumer protection from smoking related furniture fires, a voluntary program was initiated in 1978 in the United States by the Upholstered Furniture Action Council (UFAC). Later in 1985, the UFAC program was also introduced in Canada. Since its inception, UFAC has developed 'voluntary' standards, which many manufacturers and retailers have agreed to follow. The standards cover fabric classification, furniture construction criteria, labeling and compliance procedures. Products involved in the program may display a hang-tag for consumers which demonstrate that the product meets the UFAC standards. The tag outlines the fire hazards associated with the upholstered furniture, as well as recommends the use of smoke detectors in homes which are essential for reducing residential fire deaths. In the United

States, the UFAC claims partial credit for the 79.3% reduction in the number of upholstered furniture fires started by smouldering cigarettes [12]. Statistics in Canada also show around a 75% reduction in such fires between 1983 and 1986 [13].

In addition to UFAC, the Consumer Product Safety Commission (CPSC) in the United States is also a promoter of voluntary standards for upholstered furniture. Both the CPSC and UFAC standards are derived from the National Fire Protection Association's (NFPA) NFPA 260 [14] and ASTM E 1353 [15] which relate to the cigarette ignition resistance of upholstered furniture. The CPSC also educates the public about fire safety by urging people to:

- Never smoke in bed.
- Not allow children to play with candles, lighters, matches or smoking materials.
- Not to fall asleep while a candle is burning.
- Extinguish candles before leaving the room.
- Have working smoke alarms on each level of the home and inside every bedroom.

California has been a leader in setting stringent standards in the upholstered furniture industry in North America. California Technical Bulletin 116 (TB 116) [16] is a voluntary standard whereas Technical Bulletin 117 (TB 117) [17] is a mandatory regulation for all residential upholstered furniture for sale in the state of California. TB 116 deals with cigarette tests for full-scale pieces of furniture, whereas TB 117 consists of an open flame and a smouldering cigarette test for component materials. All materials in the furniture except the frame must comply with TB 117 to be sold in California. To pass these tests, the burning item cannot display any of the following characteristics in the test room.

1. A temperature increase of 93°C or greater at the ceiling.
2. A temperature increase of 10°C or greater at 1.2 m above the floor
3. Greater than 75% opacity at 1.2 m above the floor
4. Carbon monoxide concentration in the room of 1000 ppm or greater for 5 minutes.
5. Weight loss due to combustion of 3 pounds or greater in the first 10 minutes of the test.

California also has the very strict Technical Bulletin 133 (TB 133) [18], which is a mandatory open flame/room fire test for all upholstered furniture used in public non-residential occupancies.

Historically, mattresses in the United States were known to have very poor fire performance since standards only prescribed resistance against smouldering ignition and not flaming [19]. In contrast, mattresses in the United Kingdom were thought to be safer since they were subjected to more rigorous tests and standards, BS: 5852 [20] that included both smouldering and flaming ignition sources. However, recent changes in the United States are making mattresses safer. In 2006 the CPSC (having federal jurisdiction) brought in a new mandatory regulation, 16 CFR Part 1633 [21], which applies to all new mattresses, mattress sets, and futons manufactured on or after July 1, 2007. In this standard, mattresses must resist ignition to an open flame source which consists of two T-shaped propane burners (resembling flame sources such as a candle, match or cigarette lighter). While, burning freely, the mattress fire must not produce a peak Heat Release Rate (HRR) greater than 200 kW during the first 30 minutes, and the total heat released must not exceed 15 MJ for the first 10 minutes. Here, HRR refers to the rate of heat released per second (typically given in kW).

Currently the California Bureau of Home Furnishings and Thermal Insulation is working on a draft standard for safer bedding products, TB 604 [22], because filled bedding products including comforters, pillows, and mattress pads can act as a significant fuel source and are difficult to extinguish once ignited. After research conducted by Health Canada on reducing the hazard of smouldering ignition caused by cigarettes, it was mandated in 2005 through Cigarette Ignition Propensity Regulations in the Tobacco Act [23] that all cigarettes sold in Canada must have reduced ignition propensity. This made Canada the first country in the world to enact a regulation of this nature. This and other cigarette ignition regulations cite ASTM E2187-04 [24].

3.3 Residential Dwelling Fuel loads

Fuel load relates to the amount of combustible material in a room, such as furniture, books, and decorations. It is difficult to define a residential fuel load because individuals ultimately control the fuel load, distribution and placement of items in their homes, and little information is available due to the private nature of these premises [25]. This is an important issue because the location of the fuel load (for example in the center of a room or in the corner) has a significant effect on fire growth characteristics [26].

In 2004, the National Research Council of Canada (NRC) conducted a survey of 598 homes for combustible contents in Canadian residential living rooms, with a goal of identifying the main types of combustible furniture in use and determining an accurate value for an average fuel load density [7]. Table 3-3 summarizes the findings of the study detailing the most common living room furniture layouts and their fuel load densities. The survey shows that in 80% of homes, after a television, the most likely article in a living room is an upholstered furniture item, such as a sofa, chair, or loveseat, or a combination of these items.

Table 3-3: Example layouts of furniture found in main-floor living rooms [7]

Furniture Arrangement	**Number of homes**	**% (of total sample)**	**Fuel load [1] [MJ]**
TV (any size)	480	80	10
Sofa/chair	355	60	95
Sofa/loveseat	200	33	100
Loveseat/chair	169	28	80
Sofa/loveseat/entertainment unit	139	23	160
Sofas/two chairs	142	23	130
Sofa/loveseat/chair	117	20	140
Sofa/loveseat/bookcase	84	14	160
Sofa/loveseat/chair/coffee table/side table	76	13	190
Sofa/loveseat/chair/coffee table/entertainment unit	59	10	220
Two sofas/loveseat	54	10	160
Two sofas/chair	46	8	150
Sofa/loveseat/chair/coffee table/Ent. unit/bookcase	22	4	310
Two sofas/loveseat/chair	8	1	200

[1] The estimated mean fuel load excluding the contribution of floor and window coverings.

Based on the above furniture configurations, the average fuel load density for a main-floor living room was 410 MJ/m^2. This value can be further refined based on the type of house. Table 3-4 illustrates a summary of the findings for floor and window areas in two-storey single-family detached homes and townhomes. Two-storey townhomes which generally have a smaller total floor area, were found to have the higher average living room fuel load density at 490 MJ/m^2 whereas detached homes had an average of 390 MJ/m^2.

Table 3-4: Two-storey home fuel loads [7]

	Total Area [m^2]	Total Area [ft^2]	Living Room Area [m^2]	Average Fuel load Density [MJ/m^2]
Detached	183	1970	20	390
Townhome	140	1507	17	490

The NRC conducted a similar survey to determine the combustible contents and floor areas in multi-family dwellings (semi-detached homes, townhomes and low-rise apartments) [27]. Their findings included typical areas for different rooms along with corresponding fuel load densities, Table 3-5. For example, in multi-storey dwellings, the living room had the largest area with lowest mean fuel load density. In comparison, the kitchen had the lowest average area but highest mean fuel load density.

Table 3-5: Survey results for multi-family dwellings [27]

	Average Area [m^2]	Mean Fuel load Density [MJ/m^2]
Living Room	17.6	412
Kitchen	9.8	807
Primary Bedroom	16.6	534
Secondary Bedroom	10.5	594

Other surveys have been published with similar fuel load density values to those found in the NRC Survey. CIB W14: Fire, a division of the International Council for Research and Innovation in Building and Construction, published a comprehensive list of fuel load data, identifying residential occupancies to have a fuel load density of 500 MJ/m^2 [28]. The New Zealand Building Code currently recommends residential design use a fuel load density of 400 MJ/m^2 [29]. Since the CIB W14 is aimed at an International audience, it provides a more conservative estimate for fuel load density, whereas the New Zealand values are meant to be used by designers in that country and therefore the typical types and uses of furniture are less variable. Table 3-6 summarizes a collection of fuel load densities for residential occupancies from surveys conducted in several countries. Fuel load density is based on the contents that are found inside a typical home and different countries tend to have different customs, different types of furniture, and different room purposes which can dictate the configuration of items in a room and which might explain the variation in values. The values found by the NRC for main-floor living rooms in Canada (410MJ/m^2) are lower than those found in the United States recreation rooms (450-500 MJ/m^2). This difference could be due to the date in which these surveys were undertaken, with the United States survey occurring in 1980 and the NRC survey in 2004. There have been significant advances in fire research in the last 20 years, which might indicate that the recent survey is more representative of modern day home furnishings.

A survey from New Zealand reported a density of 724 MJ/m^2 for bedrooms in apartments. As was previously shown, bedrooms tend to have higher fuel load densities and smaller floor areas. The 400 MJ/m^2 reported in the New Zealand Building Code also applies to the average density of the entire house.

Table 3-6: Published fuel load densities from surveys of residential occupancies [27]

Country	Fuel load density [MJ/m²]	Year	Notes
US	450	1980	Survey of basement recreation rooms in 200 single-family detached homes
US	500	1980	Survey of 70 Residential recreation rooms
Sweden	600	1983	-
New Zealand	724	2000	Four bedrooms in apartments with a mean floor area of 9.3 m^2
Japan	670	1965-1988	Survey of 214 homes
Canada	410 360	2004	NRC Canada, main-floor living rooms NRC Canada, basement living rooms

Kumar and Rao [30] conducted a similar study in India, where fuel loads in residential buildings were also surveyed. It was clear that fuel load density was related to the purpose of each room and that the mean fuel load per room decreased when the number of rooms in the home increased. They found that a drawing room had average area of 17.9 m^2 and a fuel load density of 428 MJ/m^2, similar to the values found for a living room in the NRC study [27]. Their study also found bedrooms average 13.2 m^2 with a mean fuel load density of 495.7 MJ/m^2.

3.4 Code Requirements: Opening Size

The same NRC survey of Canadian residential living rooms also evaluated windows located in living rooms. The survey concluded that in two-storey detached homes there were typically two windows with the largest being 2.6 m^2 in a living room. Similarly two-storey townhome living rooms also had two windows, with the largest being 2.2 m^2 [27].

Opening size is an important factor in determining a potential overall fire size since oxygen is a necessary element in combustion. A room fire can be limited by the amount of oxygen entering the room and hence be ventilation controlled, which results in a lower HRR than if an item were allowed to burn freely in the open. Openings can also permit the movement of smoke and toxic gases out of the room. Likewise stairwells aid in the movement of toxic gases, such as carbon monoxide (CO) and carbon dioxide (CO_2) to the upper floors [24].

For emergency egress purposes, Section A-9.7.1.2. (2) of the 2005 National Building Code of Canada (NBCC) [31] requires at least one window in every bedroom with minimum opening dimensions of at least 380 x 380 mm for both height and width, when sprinklers are not provided. The window dimensions must result in a minimum opening area of 0.35 m^2 and it is recommended that the sill elevation be no higher than 1.5 m above the floor. In an emergency, all parts of a house must provide a safe means of egress, such as a door. These doors must be at least 810 mm wide and 2030 mm high.

The NBCC also has requirements for the amounts of light and ventilation needed in each room. The lighting requirements in the code dictate the amount of necessary unobstructed glass area for a given room as shown in Table 3-7. The area of required glass is a percentage of the area served (the room floor area) and is higher for rooms with no electric lighting. Regardless of electric lighting, living rooms require a glass area equivalent to 10% of the room area. Bedrooms require a glass area equivalent to 5% of the room area.

Table 3-7: Glass Areas for Rooms of Residential Occupancy based on NBCC [31]

Location	Minimum Unobstructed Glass Area	
	With No Electric lighting	**With Electric lighting**
Laundry, basement recreation room, unfinished basement	4% of area served	not required
Water-closet room	0.37 m^2	not required
Kitchen, kitchen space, kitchen above	10% of area served	not required
Living rooms and dining rooms	10% of area served	10% of area
Bedrooms and other finished rooms not mentioned above	5% of area served (1)	5% of area (1)

(1) includes unobstructed openings 0.35 m^2.

Applying these criteria to the NRC survey of Canadian residential living room results, assuming the rooms have electric lighting, the following required window dimensions for typical living rooms are found (see Table 3-8). The largest window area found in the survey is greater than the required glass area for both cases.

Table 3-8: Two-storey home required window area based on NRC survey [27]

	Living Room Area [m^2]	**Minimum Unobstructed Glass Area Required [m^2]**	**Largest Living Room Window Area [m^2]**	**Number of Windows**
Detached	20	2	2.6	2
Townhome	17	1.7	2.2	2

The NBCC also has opening requirements for ventilation when mechanical ventilation is not provided, outlined in Table 3-9. Both living rooms and bedrooms require a minimum of 0.28 m^2 unobstructed natural ventilation areas for use during the non-heating season.

Table 3-9: Natural Ventilation Area for Rooms of Residential Occupancy NBCC *[24]*

Location	**Minimum Unobstructed Area**
Bathrooms or water closet rooms	0.09 m^2
Unfinished basement space	0.2% of the floor area
Dining rooms, living rooms, bedrooms, kitchens, combined rooms, dens, recreation rooms and all other finished rooms	0.28 m^2 per room or combination of rooms

In the NRC multi-family dwelling survey window sizes were also noted. These values were compared to dimensions specified by home builder's construction plans and

Canadian Standards Association (CSA) A440 reference window sizes (not for a specific room), for living room and bedroom windows (Table 3-10). The mean dimensions for windows from these three sources were 1.6 m x 1.4 m high for living rooms, and 1.2 m x 1.2 m high for bedrooms.

Table 3-10: Living room windows for multi-family dwellings [27]

		Mean Width [m]	**Mean Height [m]**	**Mean Area [m^2]**	**Maximum Area [m^2]**	**Minimum Area [m^2]**
Living Room	NRC survey	1.8	1.6	3.1	8.0	1.1
	Construction Plans	1.9	1.3	2.5	5.3	0.84
	CSA A440	1.1	1.2	1.3	2.6	0.4
Bedroom	NRC survey	1.4	1.2	1.7	4.0	0.5
	Construction Plans	1.1	1.3	1.4	2.7	0.6
	CSA A440	1.1	1.2	1.3	2.6	0.4

3.5 Fire Behaviour of Upholstered Furniture

Upholstered furniture fires can develop quickly due to the flammable nature of materials used in their construction. Because of this and its association with a high number of deaths, upholstered furniture has been studied more than any other household furniture item in fire [32]. There are many factors that influence flammability including ignitability, burning behaviour, and furniture construction components.

Upholstered furniture includes couches and mattresses. Couches are made with a frame using wood, metal, thermoplastics or thermosetting materials; however combustible wood frames are the most common type of construction materials. These furniture items generally use polyurethane foam as a cushioning material, which is covered with fabric. Single or multiple layers of covering fabric may be used, as well as, a barrier fabric or interliner. Mattresses use either springs or foam for their structure with an exterior fabric covering; additional foam can be placed on the top surface beneath the exterior fabric covering for added comfort.

After disturbing statistics were published in Europe which implicated upholstered furniture fires as the cause of a large number of deaths, the Combustion Behaviour of Upholstered Furniture (CBUF) programme was initiated as a means to accurately test and predict the burning behaviour of upholstered furniture [33]. CBUF began in 1993 and ran for two years at a cost of $2.8 million involving research facilities from 8 countries [34]. Over 1500 tests were conducted on 72 different types of upholstered furniture, producing the largest collection of upholstered furniture fire data world wide [2]. These tests used the cone calorimeter (ISO 5660) [35] for small-scale testing and the room/corner test (ISO 9705) [36] and furniture calorimeter (NT FIRE 032) [37] for large-scale testing. The furniture calorimeter involves placing an item of furniture beneath an exhaust hood (which measures the heat release rate using the principles of oxygen consumption), igniting it, and allowing it to burn freely under fully-ventilated conditions.

3.5.1 Ignitability of fabrics

Upholstery fabric is likely the first component of furniture to come in direct contact with an ignition source. Therefore, it is important that the fabric be ignition resistant and protect the interior padding from heat [4]. Fabrics need to be resistant particularly to cigarettes, which have been found to be one of the most common ignition sources for furniture fires. The time it takes for an item to ignite depends on properties of the fabric, as well as, the strength of the ignition source [38]. Other furniture construction features, such as decorative fabric additions which do not come in contact with foam can present an added flame hazard [4]. Common test methods gauge ignition resistance against cigarettes (EN 1021-1[20]) and match-like flames (EN 1021-2 [39]).

All samples tested in the CBUF, resisted ignition from cigarettes, even those for which this criterion was not required. A large number of tests also passed the match ignition, which is encouraging.

Broad categories can be used to identify fabrics based on the nature of their fibers; these include natural fibers (cellulosic), which typically char, or synthetic/thermoplastic fibers, which more commonly tend to melt. Natural fibers are thought to perform well in fires, mainly due to their smouldering properties, however they can burn very hot and produce light smoke [40]. Charred fabric can help protect foam from direct fire exposure and can slow fire development [41]. Natural charring fabrics include cotton, viscose, rayon, linen and wool.

Paul and King [38] performed tests to identify the differences in the burning of armchairs with polyurethane foam covered with various fabrics popular in the United Kingdom. They observed that cellulosic fabrics burned slowly and charred until they split. However this is not necessarily true of all natural fabrics. Wool and leather have demonstrated superior fire performance since they are hard to ignite and burn slowly [40]. Wool fabric covering high resilient polyurethane (HRPU) was found in the CBUF to be a highly successful pairing in terms of reducing HRR [2]. The wool fabric delayed the peak HRR of the fire by approximately 10 minutes compared to all other fabrics tested, which included cotton, polyester, and leather with some being fire retardant.

In cigarette ignitability tests conducted on furniture, thermoplastic fabrics resisted ignition better than the cellulosic fabrics [1]. However, once ignited in these tests thermoplastic fabrics had more than double the HRR than cellulosic fabrics and shorter times to reach the peak HRR. Although thermoplastic fabrics have good ignition resistance they can burn quickly, melt, and shrink, which can expose foam directly to flames, intensifying the degree of the fire [4]. These types of fabrics rarely show signs of smouldering. Melting fabrics, such as polyester, nylon, polypropylene, and polyacrylics, expose foam directly to flames and can result in dripping material. Dripping material can create a dangerous pool fire beneath the burning item, permitting faster flame spread. It is important to select non-propagating and ignition resistant fabrics for furniture construction to perform well in fire.

Hshieh and Beeson examined the differences between regular and flame retardant cotton in a cone calorimeter [42]. They observed a reduction in peak and average mass loss and HRR, effective heat of combustion at peak HRR, and propensity to flashover, as would be desired from a flame retarded product, however the flame retardant resulted in a faster time to ignition and increased CO and CO_2 yields.

It is important for all furniture fabrics to meet cigarette ignition resistance guidelines since this fabric can have a noteworthy impact on the early stages of fire growth. It is ideal if the fabric is resistant to both cigarette ignition and flaming ignition. However a fabric that resists well against smouldering ignition will not necessarily perform as well under flaming conditions and vice versa [4]. There is, however, a selection of furniture materials, such as wool fabric and polycholoroprene foam, that do have the benefit of resisting both types of ignition, but they are expensive and therefore are not as common in furniture production [1].

3.5.2 Smouldering and Flaming Ignition

Combustion of materials can either be smouldering or flaming. Flaming ignition is a result of an open flame source, such as a match or cooking flame, whereas smouldering can be initiated by a cigarette. Smouldering fires are slow and can be sustained for long periods of time with a combustion rate around 0.1 g/s (but this can increase depending on conditions such as the density of the item, oxygen supply, and air current directions), whereas flaming combustion is a much faster process at approximately 100 g/s [4]. Although smouldering typically has a low heat output it can produce large amounts of dangerous smoke.

A fire is not necessarily bound to either type of combustion, but it can switch between the two, depending on oxygen availability. Smouldering can transition to flaming anywhere between twenty minutes and several hours [4]. Babrauskas and Krasny [40] noted the mean transition time of 102 published upholstered furniture smouldering tests to be 88 minutes. There is no connection between resistance to smouldering and good fire performance in flaming conditions. For example, furniture items with polyurethane padding and heavy thermoplastic fabrics are resistant to smouldering but demonstrate poor fire performance under flaming conditions since thermoplastic fabrics melt which can result in a pool fire [43]. This implies that the presence of thermoplastic fibers can reduce the tendency to switch from smouldering to flaming [44].

Smouldering ignition is of particular importance when studying upholstered furniture because smoking materials (such as a cigarette or match) are the most likely ignition sources. This scenario typically occurs when an individual falls asleep while smoking and drops a cigarette into a concealed location on the furniture. If a heat source falls between a cushion and chair back, it can be hidden and well insulated. This situation can allow the smouldering to go unnoticed and be permitted to continue burning unhindered for several hours. By the time this type of fire is discovered, occupants will likely encounter untenable conditions as they egress.

Since mattresses lie horizontally and have few crevices they are less likely to ignite from smoking material than a couch [4]. However when a mattress is covered in sheets, smoking materials can more easily ignite the mattress, especially if bed linens readily burn, exposing the mattress to a more significant flame source (as compared to a match) [34].

3.5.3 Flame Propagation

Once ignited, fires can either propagate (progressing until all items are consumed by fire) or not (burning out once ignition sources have been depleted), the former being the more hazardous scenario [45]. Cellulosic fabrics display a much slower fire spread when compared to thermoplastic fabrics [1]. In bench-scale mattress tests performed by the National Institute of Standards and Technology (NIST), it was determined that non-propagating fires produce a HRR less than 100 kW/m^2, whereas propagating fires exhibit HRRs greater than 180 kW/m^2 [45].

3.5.4 Polyurethane Foam

It is important that a furniture item fulfills its function to be comfortable, durable, and aesthetically pleasing. The comfort of an item can be closely tied to its foam cushioning; therefore polyurethane foam is a major component in upholstered furniture and often times it is the main component. Findings in the CBUF suggest that fire performance of an item can be increased solely by reducing the amount of foam in the furniture [2].

While the covering fabric is still in place it should effectively protect the interior foam from ignition; however, once the fabric melts or tears, the foam can be directly exposed to flames. A high density foam will be stronger, more expensive, and have a higher HRR [2], whereas a low density foam will be cheaper and exhibit a fast flame propagation rate [46]. Polyurethane foam is highly resistant to smouldering [44].

In tests performed by Babrauskas involved the burning of 13 chairs, loveseats and sofas in the furniture calorimeter, the effects of fabric, padding, and frame types were studied [1]. Of all the items tested, the fastest fire development occurred for a polyurethane foam and thermoplastic fabric combination. Much slower developments were observed for combinations containing cellulosic fabrics, the slowest fire development occurred when all the cellulosic materials were used. Also interestingly, the type of foam used did not affect the time to reach peak HRR.

3.5.4.1 Foam Flame Retardants

The goal of using flame retardants is to reduce the risk of flame propagation and reduce the amount of heat released in a fire. Higher concentrations of flame retardant can result in a lower peak HRR [47]. There are currently no requirements for the use of retardants in polyurethane foam in Canada, however many manufacturers voluntarily use products with flame retardants. It is believed that retardants, which use toxic chemicals in their production, might increase the amount of smoke and gases released by burning items, although more research still needs to be done in this area. A wide variety of fire retarding methods are available. Some of the typical types of polyurethane foams used are:

1. SPU: Standard Polyurethane

2. FRPU: Fire Retardant Polyurethane
3. HDPU: High Density Polyurethane
4. HRPU: High Resilient Polyurethane
5. CMHRPU: Combustion Modified High Resilient Polyurethane

Foams can also be fully impregnated with latex containing high levels of alumina trihydrate or other retardants. These foams are reserved for prison mattresses due to their low combustibility and high cost. A layer of impregnated foam can be placed above SPU foam to increase comfort and ignition resistance [2].

Using an high grade retardant foam, such as CMHRPU over SPU or HRPU will improve the fire resistance as demonstrated in Figure 3-1. The polyether foam, similar to SPU, has the fastest time to peak, as well as, the highest peak HRR. The retarded HRPU and CMHRPU both perform better, with longer times to peak and slightly reduced HRR values.

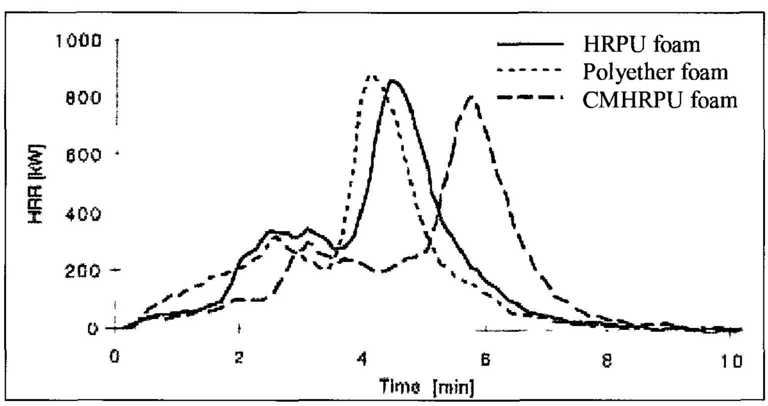


Figure 3-1: Effects of different foams on HRR [2]

The HRR of two armchairs using two different types of foam (HRPU and CMHRPU) covered with cotton fabric were compared during the CBUF, as shown in Figure 3-2. It is apparent that both chairs had a similar peak HRR of less than 700 kW; however the time to reach this peak was delayed for the CMHRPU foam. This would be expected since the CMHRPU foam had the highest level of ignition resistance of all those tested in the CBUF [2]. This illustrates that the presence of flame-retardants can delay the growth of a fire, in this case by 2 minutes. In the CBUF a fire was said to be detectable when it reached 50 kW, which occurred at approximately 30 s in these tests. This implies that the use of fire retardant products could prolong the Available Safe Evacuation Time (ASET), giving occupants a greater opportunity to evacuate the premises safely. The typical fire department response time in Ontario is five minutes from the time a fire station receives a distress call [9], so it is important to delaying fire growth as much as possible in the first few minutes.

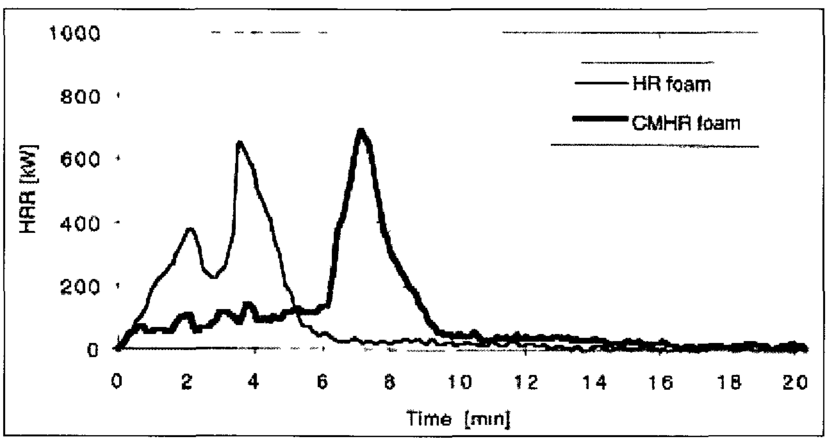


Figure 3-2: HRR of armchairs covered with cotton fabric filled with foam [2]

Paul and King conducted 18 upholstered chair tests examining different types of foam (e.g. SPU, HRPU, and CMHRPU). They used various fabrics, while the chair design was kept constant, to eliminate construction variables from affecting the fire. They demonstrated that HRPU has a slower burn rate and a 70% reduced HRR than SPU (when a similar design and fabric are tested), but it produced more smoke and a higher peak CO concentration [41].

3.5.4.2 Interliners

Another practice used to improve the fire performance of upholstered furniture is interliners. An interliner is a construction technique that uses a textile with flame retardant composition to separate the covering fabric from the foam and can provide adequate fire resistance by limiting the exposure of the foam to flames. Interliners can effectively improve fire performance by reducing peak burning rates and delaying fire development [2].

As the PU foam in furniture melts, the upper surface steadily moves downward away from the interliner. For this reason interliners may exhibit a greater benefit beneath thermoplastic fabrics, due to their melting properties when exposed to heat [1]. In this case the interliner acts like a thermal shield and reduces the amount of heat radiating to the foam [2]. Melting fabric above the interliner is blocked from reaching the foam, ultimately slowing PU melting and reducing the HRR, or at least delaying the time to peak HRR. This is demonstrated in Figure 3-3, where the cotton-interliner combination over PU shows a peak HRR at approximately 16 minutes, 12 minutes after the virgin cotton over PU. The wool-interliner combination is effective in reducing the peak HRR from approximately 900 kW to 100 kW.

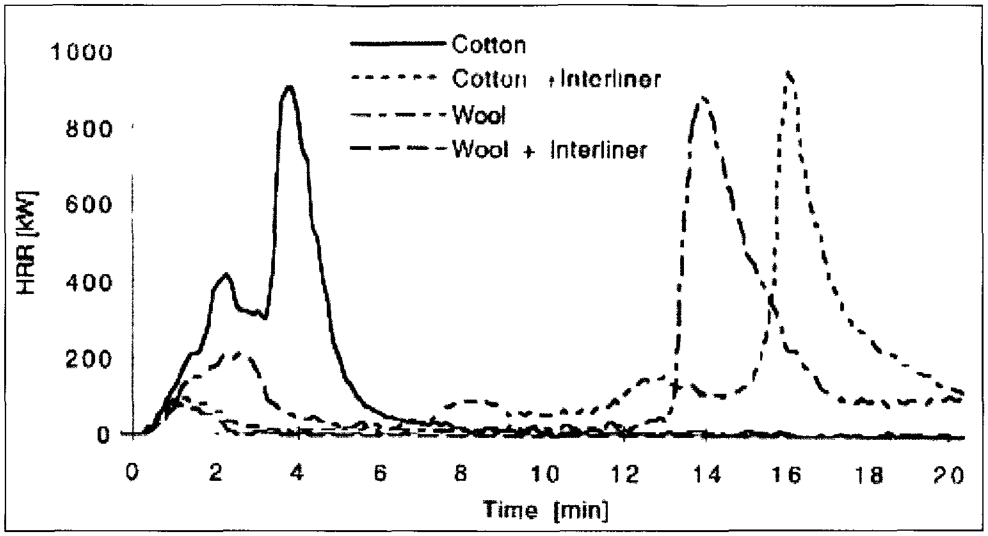


Figure 3-3: Effect of an interliner on HRR [2]

Eggestad and Johnsen [48] tested eight different interliners with 5 different covering fabrics and two filling materials to examine the effects that interliners had on the ignitability of upholstered furniture. They found that interliners did not cause any substantial changes to furniture ignitability, but the use of HRPU foam instead of SPU, particularly when a cigarette was used as the ignition source, had better capabilities of reducing ignitability. When a flame was used for ignition the covering fabric seemed to be the most important factor in reducing ignitability.

3.6 Fire Growth

If a fire is permitted to grow uncontrolled in a compartment, provided there is ample fuel and oxygen, the fire can be described by four distinct phases starting at ignition: growth, flashover, fully-developed and decay as illustrated in Figure 3-4. The vertical axis can represent temperature or HRR.

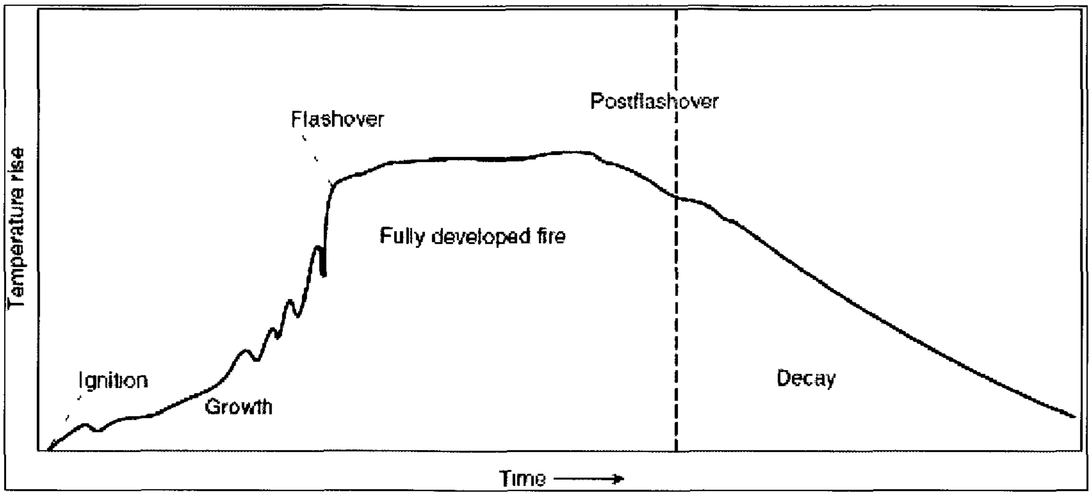


Figure 3-4: Fire Growth Stages *[47]*

The time it takes for the first item in a room to ignite depends on the item itself, but also the ignition source and the manner in which it is applied. The value t_o is used to define the time from ignition of the source until flaming of the item occurs (i.e. when significant energy starts to be released). This value depends on the material and the manner in which the ignition source is applied. A collection of ignition times from furniture calorimeter tests are given in Table 3-11 for various upholstered furniture items. The fastest times to ignition occurred when a foam cushion was present.

Table 3-11: Ignition time for various chairs and mattresses [49]

Description	**t_o (s)**	**α (kW/s^2)**
Chair F33 (trial loveseat) 39.2 kg	140	0.0066
Chair F31, (loveseat) 39.6kg	145	0.2931
Chair F31, (loveseat) 40.4kg	100	0.1648
Chair, adjustable back metal frame, foam cushion, 20.8kg	30	0.0365
Chair metal frame w/padded seat and back 15.5kg	50	0.0086
Loveseat metal frame w/foam cushions 27.26 kg	210	0.0042
Loveseat wood frame w/foam cushions, 11.2kg	50	0.0042
mattress and box spring, 62.36kg (initial fire growth)	400	0.0086
mattress and box spring, 62.36kg (initial fire growth)	90	0.0009

Once an item has ignited, the fire enters the growth phase where the HRR generally follows an exponential t^2 curve defined by [49]:

$$\dot{Q} = \alpha t^2 \qquad \text{Equation 3-1}$$

Where $\dot{Q}$ is the heat released in kW, t is time from ignition in seconds and α is a growth rate coefficient given in kW/s^2. According to the t-squared equation, fire growth is proportional to the square of time that has elapsed since ignition. The growth rate coefficient characterizes whether the fire will develop in a slow, medium, fast, or ultra-fast manner. An ultra-fast growth will result in the fastest time to flashover [50],[51]. Karlsson and Quintiere provide a general definition for these types of growth in Table 3-12 below [49]. Experimentally found growth rates using a furniture calorimeter for a selection of items can be found in Table 3-11. For example, using the Fast growth rate which is listed as 0.0466 kW/s^2 (Table 3-12), a fire that has been ignited for 2 minutes (or 120 s) will produce a HRR of 670 kW. After 5 minutes (or 300 s) have elapsed the fire will have reached a HRR of nearly 4200 kW.

Table 3-12: Growth Rate Coefficient Values [49]

Growth Rate	**Design Fire Scenario**	**Value of α**	**Time to reach 1055 kW (s)**
Slow	Floor Coverings	0.00293	600
Medium	Shop counters, office furniture	0.0117	300
Fast	Bedding, displays and padded work-station partitioning	0.0466	150
Ultra-Fast	Upholstered furniture and stack furniture near combustible linings, lightweight furnishings, packing material in rubbish pile, non-fire-retarded plastic foam storage, cardboard of plastic boxes in vertical storage arrangement	0.1874	75

When comparing the experimental to the theoretical values, it is seen that the theoretical values, which are used in design, are higher and therefore conservative in most cases. For example, the theoretical fast growth rate (for bedding) is 0.0466 kW/s^2 whereas the experimental value for a mattress and box spring is 0.0086 kW/s^2. This suggests that a higher theoretical value will result in higher release rates resulting in a more severe fire which will grow more quickly. In comparison, the ultra-fast growth rate (commonly used for upholstered furniture) was 0.1874 kW/s^2, which was exceeded by the experimental values for a loveseat at 0.2931 kW/s^2.

The values from Table 3-12 are plotted in Figure 3-5. The graph demonstrates how an ultra-fast fire is capable of releasing a large rate of heat, in a very short period of time, for example 2 MW after 2 minutes.

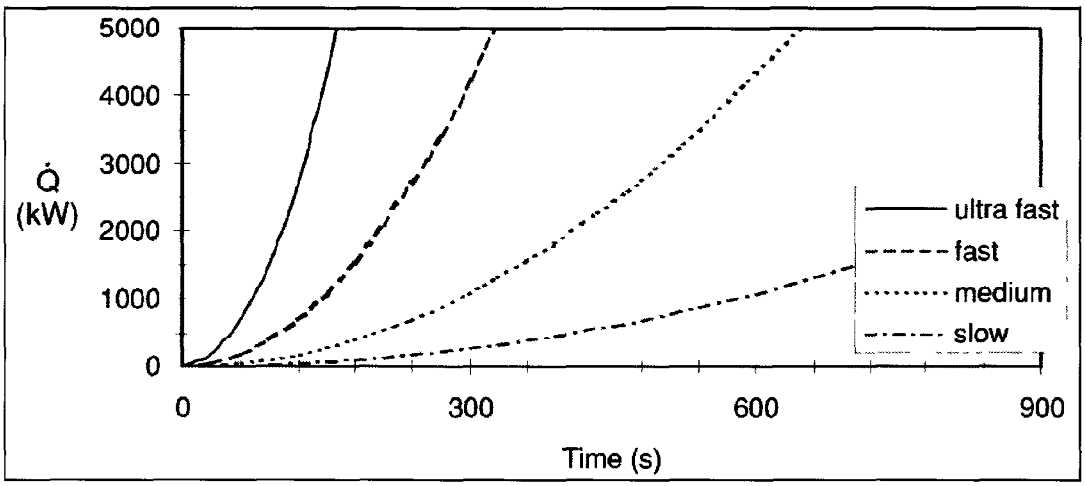


Figure 3-5: Growth rate effects on HRR [49]

In a study comparing numerical predictions and HRR from experiments, the NRC demonstrated that using a fast t^2 growth for modeling produces an accurate representation of couch fires [52].

3.6.1 Heat Release Rates

A high HRR corresponds to large flames and can be linked to faster rates of fire growth due to high temperatures which can increase fire spread [14],[45]. The greater the mass of a combustible specimen the higher the potential HRR can be. For example a typical HRR will be higher for a sofa than a loveseat or chair [1]. A significant portion of the heat released by upholstered furniture can be attributed to the polyurethane foam; this amount of heat can be reduced through the use of flame retarded polyurethane foam and by limiting flame exposure of the foam by using a barrier layer or interliner [2]. In studies performed by NIST, 27 material combinations (7 fabrics, 4 barriers, and 2 polyurethane foams) were fire tested in cushion mock-ups (conforming to TB 133) using the furniture calorimeter. It was observed that the peak HRR occurred after the failure of an interliner [53].

A single piece of typical upholstered furniture can release heat at a rate as high as 1 MW within the first few minutes of a fire [54]. Sundstrom reports maximum HRRs for the following two chairs [2] (refer to Figure 3-2):

Chair: wooden frame, HRPU foam, cotton fabric	650 kW
Chair: wooden frame, CMHRPU foam, cotton fabric	700 kW

In a study conducted by the NRC examining the combustion of non-open-flame resistant Canadian mattresses in a room fire environment, HRRs between 1500 kW and 3500 kW were observed [55]. Of the five mattresses tested, four were capable of bringing the room to flashover.

From the numerous furniture calorimeter tests (NT FIRE 032) of upholstered furniture and mattresses conducted during the CBUF, four typical HRR curves were observed: very limited burning, quickly developing, delayed fire development, and slowly developing (Figure 3-6). The very limited burning fires did not last long and had a low peak HRR; slowly developing fires also had a low peak HRR, which occurred late in the fire allowing for a long period of growth. The more severe fires had a delayed fire development with a moderate peak HRR and the worst case quickly developed to a high peak HRR. The quickly developing fire had a peak HRR approximately 100 times greater than the very limited burning. Overall, the typical time for these large fires to develop varied from 2 to 20 minutes.

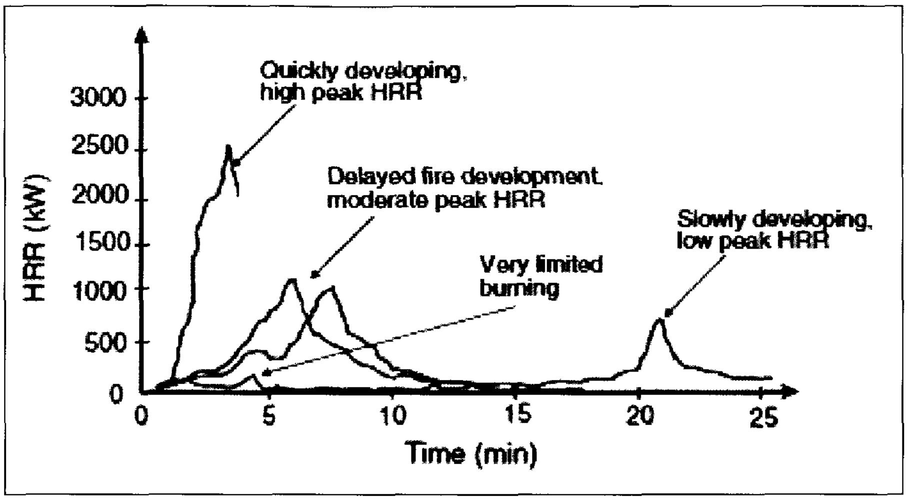


Figure 3-6: Typical HRRs as a function of time measured in the furniture calorimeter for a selection of European upholstered furniture and mattresses [32]

The maximum HRR of a compartment fire is related to the windows in the room. The theoretical maximum HRR can be estimated using Equation 3-2, assuming the maximum amount of fuel that can be burned is based on the amount of air entering the room [56]:

$$\dot{Q} = 1500 A_V \sqrt{H_V} \qquad \text{Equation 3-2}$$

where A_V is the area of the openings (m^2) and H_V is the height of the openings (m). When there are multiple windows of different heights the weighted average of all the heights can be used.

3.6.2 Room Fire Dynamics

The plume from a fire consists of hot gas and soot. The plume will rise to the ceiling due to buoyancy and will entrain air from the surrounding environment as it rises. When these hot gases reach the ceiling they spread out radially, resulting in what is known as the ceiling jet, seen in Figure 3-7. The temperature and velocity of a ceiling jet are related to the heat release of the fire (Q in kW), the height of the ceiling (H in m), and the distance radially from the fire (r in m) [57]. Smoke detectors, heat detectors, and sprinklers are installed on the ceiling so that they will come in contact with the ceiling jet. As the ceiling jet flows away from the fire the hot layer grows thicker by entraining cooler air from below and because the air cools and is therefore less buoyant [57].

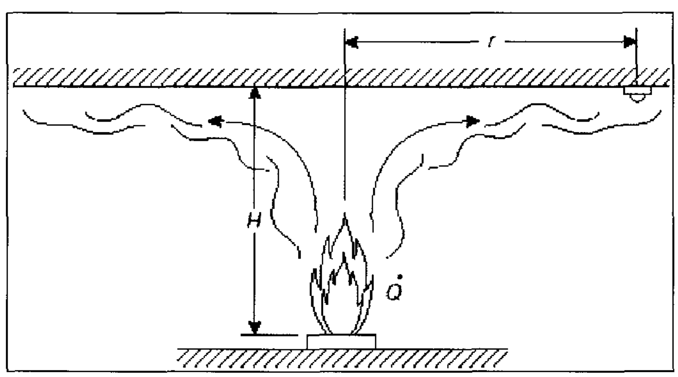


Figure 3-7: Ceiling Jet [57]

When the ceiling jet reaches a wall, it can no longer travel horizontally and is forced downward, resulting in a wall jet. This high temperature and low density wall jet, will again try to rise due to buoyancy, causing turbulence in the corners, further entraining more cool air, as demonstrated in Figure 3-8. As more smoke is being expelled by the fire it accumulates at the ceiling. A clear division begins to form between the hot upper layer (smoke layer) and the cool lower layer (ambient air), known as the smoke layer interface. The smoke layer interface will continue to descend as the smoke concentration and temperature in the upper layer increase [58].

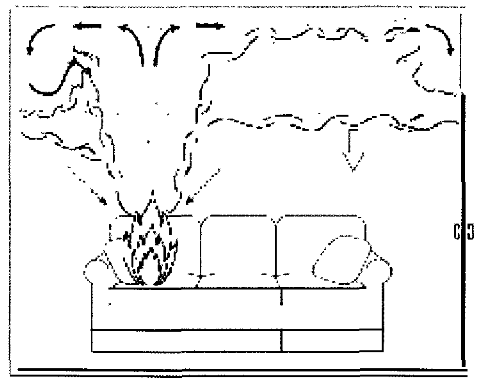


Figure 3-8: Formation of hot upper layer [58]

3.6.2.1 Flashover

A single item of upholstered furniture can bring a room to flashover, which seems likely given the quickly developing high peak HRR seen in Figure 3-6. Several methods exist to determine the minimum HRR, at which flashover will occur. Three of such methods are detailed below. The first and simplest was developed by Babrauskas [59] (Equation 3-3) and the second by McCaffrey, Quintiere, and Harkleroad (MQH) [60] (Equation 3-4). The third, Equation 3-5, is 'Thomas's flashover criterion', developed from experimental fires, which only applies to a room with one window [29].

$$\dot{Q}_{FO} = 750 A_V \sqrt{H_V} \qquad \text{Equation 3-3}$$

$$\dot{Q}_{FO} = 610(h_k A_T A_V \sqrt{H_V})^{1/2} \qquad \text{Equation 3-4}$$

$$\dot{Q}_{FO} = 7.8 A_t + 378 A_V \sqrt{H_V} \qquad \text{Equation 3-5}$$

where h_k is the effective heat transfer coefficient (kW/m^{2}K), A_t is the total compartment surface area (m^2), A_V is the opening area (m^2), and H_V is the height of the opening (m). From these equations it is apparent that the opening area and the height of the opening play a role in determining when flashover will occur. The MQH and Thomas methods take into account the total compartment surface area. According to these methods, which are based on the conservation of energy in the hot upper layer of a compartment, when opening height and area are increased a greater heat release will be required to bring a room to flashover.

Flashover can be characterized as the transition from the growth stage to a fully-developed fire. This phenomenon occurs once a critical amount of heat is radiated from the hot upper layer so as to ignite all of the combustibles in the room with gas temperatures reaching 800-1000°C, or when a fire reaches about 1000 kW in a small room [2]. It is commonly accepted that flashover occurs when the hot upper layer temperature is around 600°C (and sometimes at 500°C). Kim and Lilley equate flashover to a heat flux of 20 to 25 kW/m^2 at floor level [50], whereas Karlsson and Quintiere present a more conservative value of 15-20 kW/m^2 [49]. In furniture calorimeter tests of armchairs and loveseats conducted by Babrauskas, flashover was reached for all the specimens between 302 and 410 s, where flashover was taken as irradiance at the floor of 20 kW/m^2 [59]. Whether or not flashover occurs, is dependent on several variables including the fire growth rate, ventilation openings, wall/ceiling materials, and room geometry among other things. A single flaming upholstered furniture item can have the capability of causing fire to engulf a room and bring it to flashover [11],[27] .

Kim and Lilley [50] also studied geometric parameter effects on the time to reach flashover using the computer program FASTLite. It was determined that vent height above the floor, the ceiling height, fire location, fire radiation/heat loss fraction all had little to no effect on the time to flashover. Factors that had a significant impact on time to flashover included: vent width, vent height, and area. Temperatures were reduced when larger vents were present since they allowed large amounts of hot gases to be vented from the room. In addition, a larger floor area permits more mixing between the hot upper and cold lower layer [50]. These tests also revealed a shorter time to flashover when the burning item is against the wall, or even worse in the corner. This is a result of less cool air being entrained into the fire plume from all sides [50]. When the maximum HRR was 2 MW or greater, flashover occurred much sooner than when the item released only 1 MW.

Three tests were conducted during the 'Home Fire Project' in 1975, to determine the growth of a fire in a full-scale, fully furnished bedroom [61]. The room was 2.4 x 3.7 x 2.4 m and the door was open. Flashover was reached at 1055, 429, and 391 s for the three tests. The significant difference in the results of the first test was attributed to using old worn furniture (new items were used in the other two tests), and moisture (it was raining on the day of the test). The size of openings affects how much hot air can flow out and how much cool air can flow in. This influences the rate of burning and fire spread [61].

Once flashover has occurred the fire will be fully-developed, and all combustible items in the room will be burning. This fire will have an approximately constant temperature and HRR which is dependent on the fuel and oxygen available. As the fuel source depletes due to combustion, the fire will eventually begin to decay, releasing lower amounts of heat.

In tests designed to assess fire hazards on ships, it was shown that a polyurethane fire will extinguish in a volume fraction of oxygen between 14-18% [62]. In the tests a sudden drop in heat release rate was associated with oxygen depletion.

3.6.3 Room Size Effects

As was previously mentioned, the size of a room can impact the growth of a fire. Room size can be an indication of the fuel load and spacing between combustible items. Therefore since the CBUF was a comprehensive research programme, not only was the flammability of upholstered furniture studied but also the effects of room size on fire growth. They studied the effects of room size by using the ISO Standard 9705 room [36] (measuring 3.6 m x 2.4 m x 2.4 m high) and a room with larger volume (7.4 m x 5.7 m x 4.0 m high). In typical ISO room tests specimens are subjected to a 100 kW burner for the first 10 minutes and then a 300 kW burner for the next 20 minutes. Combustion gases are collected through a hood where heat release rate and smoke production values are measured. In the CBUF tests, higher average mass loss rates were observed in the smaller room, as would be expected from the large amounts of heat being radiated from the walls and hot upper layer (the heat flux measured at the floor was much higher in the smaller room) [59]. This implies that smaller rooms reach flashover conditions more quickly.

Experimental results were compared for the burning of an identical upholstered chair in a furniture calorimeter (allowing free burning) versus in the ISO room to examine the effect of the enclosure [63]. The peak HRR was found to be 2.25 times higher in the ISO room than when allowed to burn freely, since heat feedback from the walls and ceiling of the enclosure accelerated the burning and heat release rate.

3.6.4 Ventilation Effects

The size and locations of openings in a fire can have a large impact on fire dynamics, especially when a fire is ventilation controlled. When there is insufficient oxygen, all of the combustible gases in a room will not be able to burn. This is called a ventilation controlled fire. The converse to this would be a fuel controlled fire.

The amount of ventilation in a room is typically described by a ventilation factor, F_V ($m^{0.5}$), Equation 3-6. It relates to opening area (A_v), the height of openings (H_v), and the total area of internal surfaces of the compartment (A_t), all in m.

$$F_V = \frac{A_V \sqrt{H_V}}{A_t} \qquad \text{Equation 3-6}$$

According to Law, the rate of combustion ($\dot{m}$ in kg/s) for a post-flashover compartment fire is dependent on A_V, H_V, A_t, and the width (W) and depth (D) of the room, demonstrated in Equation 3-7 and Equation 3-8 [29]. These equations are derived from small-scale compartment fires using wood cribs, and can only be applied when windows are on one wall. However, a weighted average window height, H_V, can be used when more than one window is present.

$$\dot{m} = 0.18 A_V \sqrt{\frac{H_V W}{D}} (1 - e^{-0.036\Omega}) \qquad \text{Equation 3-7}$$

where $$\Omega = \frac{A_t - A_V}{A_V \sqrt{H_V}}$$ Equation 3-8

This can also be useful in estimating the maximum temperatures (T_{max} in ^{o}C) in a compartment, Equation 3-9 [29].

$$T_{max} = 6000(1 - e^{-0.1\Omega}) / \sqrt{\Omega}$$ Equation 3-9

In the ISO 9705 room fire tests conducted during the CBUF, the effects of varying ventilation openings were studied. The cases that were examined were a fully open and 12.5% door opening. The latter case yielded lower mass loss and HRRs. For fast burning chairs the reduced opening resulted in a 30% mass loss rate reduction and a peak HRR reduction of 60%. A smaller opening also resulted in a thicker hot smoke layer, increased smoke obscuration (through total smoke production, smoke yield, and peak smoke production rate), higher concentrations of CO and hydrogen cyanide (HCN), and reduced concentrations of oxygen (O_2) [59]. This demonstrates that the fire size was limited by reducing ventilation openings, but the ventilation controlled fire reached life threatening smoke tenability levels faster. It was also observed that when air supply in the room is reduced the smoke layer descends more quickly [2].

The NRC conducted 11 CFD simulations to determine the effects of different ventilation sizes in a medium sized residential room [26]. They found that window size has a significant effect on the fire characteristics for two scenarios: when the room contains a window located opposite a door or the room only contains a window. Window size had little effect when it was located on the same wall as a door.

3.6.5 Window Breakage

A compartment fire can subject windows to extreme temperatures and pressures. It is difficult to estimate the time at which windows (glass) will break since there are a large variety of window products available to consumers. In experimental tests performed by Joshi [52], a large variation in the breaking strength of glass of nearly identical specimens was observed which demonstrates the difficulty in determining a generalized breaking temperature for all windows. Criteria that are commonly used to assess time to breakage include temperature differentials between different points on the glass which induce stresses that result in cracking and ultimately fall-out.

In tests performed by Collier, a garbage bin filled with paper was used to ignite an upholstered furniture sofa in a living room [51]. The first window in the room shattered once the upper layer temperature reached approximately 275°C, with others following shortly after. At this time the layer interface had descended to around 0.5 m from the floor.

While studying fire exposed window assemblies protected by sprinklers, Richardson and Oleszkiewicz observed window breakage (when no sprinklers were present) when the temperature of the centre of the exposed side reached 380°C, the lower half of the glass was 290°C [64]. Manzello *et al.* studied the fire performance of non-load bearing glass wall assemblies consisting of four glass panes [65]. All four sections fell out at exposed face temperatures between 400°C–500°C. Heat fluxes at the exposed face were measured to be between 50-70 kW/m^2. Shields *et al.* performed similar tests and reported the average exposed glass surface temperatures at major glass fall out was 447°C and the average total heat flux incident on the glass panels was 35 kW/m^2 [66].

In CFD tests performed by the NRC evaluating life safety of a fire in a living area in residential dwellings, a temperature of 300°C on the exposed glass face was used as the criteria for window breakage, which appears to agree, or at least be conservative with the values presented above.

3.7 Tenability

Harmful emissions from fires have two effects on occupants: asphyxiation and irritation. Smoke and soot present in the environment can further intensify the effects of these gases by causing swelling of the respiratory tract, effectively speeding up the process of asphyxiation [32]. Asphyxiants include fire gases such as CO, CO_2, HCN, and O_2 deficiency. Irritants often found in the combustion gases from upholstered furniture include hydrogen chloride (HCl), hydrogen bromide (HBr), hydrogen fluoride (HF), sulfuric acid (H_2SO_4), nitrous oxide (NO_2), and acrolein.

Different stages during the fire will result in different production rates and types of toxic gases. When an item smoulders, large amounts of smoke are produced where toxicity can be very high [44], which is common of upholstered furniture.

CBUF tests showed CO, HCN and HCl (a byproduct of PVC based covering fabrics) were key gases being the first to reach tenability levels [2]. Wool fabrics demonstrated the largest concentration of HCN.

3.7.1 Tenability Limits

Tenability limits relate to temperatures, visibility, radiation, and toxicity that would cause an occupant to become incapacitated and unable to egress. The size and geometry of a room as well as ventilation conditions (i.e. open windows) dictate how quickly conditions may become untenable in a fire. If a room is small with little or no ventilation, tenability limits may be reached even before a fire reaches a detectable size (50 kW) [2]. The time at which tenability limits are reached is dependent on the characteristics of the occupant and the growth rate of the fire and the production of toxic gases [67].

The hot upper layer - smoke interface can be used as a deciding factor for the ability of an individual to escape since the hot upper layer can be assumed to be immediately untenable but not immediately lethal [33]. The interface height is important as tenability limits are reached later in the lower layer; this height is dependent on the mass balance of the upper layer (accounting for gas flow out the doorway and gases traveling into the upper layer) which is closely related to the HRR [68]. In a CFD study performed by NRC visibility and gases were measured 1.5 m from the floor (on the first and second stories of a house) to determine the effects on occupants, as this was taken as the height under which one was thought to be able to escape [69]. Incapacitation has also been identified as the time that the first hazard was inflicted on a person at 1 m from the floor [70].

During the CBUF it was determined that the time between a fire HRR of 50 to 400 kW in the furniture and room calorimeter provides a good indication of the ASET, because at 50 kW the fire is detectable and the hot upper layer is descending from 1.5 m to 1 m (in the ISO 9705 room) [2]. The CBUF defined a 100°C isotherm of the smoke layer interface as a good indicator of the heights under which individuals could still escape [2]. A person will experience pain due to radiant exposure once the upper layer temperatures reach 183°C [70]. An individual exposed to 120°C dry air will experience skin burns, temperatures slightly lower than this can lead to hyperthermia [67]. Also an upper layer temperature of 200°C or a radiative heat flux of 2.5 kW/m^2 corresponds to painful exposure and will cause harm to an individual [67].

Tenability limits for CO, CO_2, and visibility published in the New Zealand Fire Engineering Design Guide are the following: [34]

a. CO $\geq$ 1400 ppm

b. $CO_2 \geq$ 0.05 mol/mol (5%)

c. Visibility $\leq$ 2m

CO will cause harmful effects to humans in concentrations greater than 1400 ppm. In smouldering fires, typical of upholstered furniture, carbon monoxide intoxication occurs slowly as the concentration gradually increases. This can be difficult for occupants to detect and as a result they may not attempt to evacuate until they are no longer able [71].

CO_2 is one of the main products of combustion and it can cause incapacitation in concentrations upwards of 5%. At concentrations exceeding 5%, exposure to carbon dioxide causes dizziness, headache and fatigue, followed by unconsciousness [67]. Once the 2% threshold has been exceeded an individual can experience hyperventilation (i.e. increased rate of respiration), which encourages the uptake of other toxic products and can result in a faster time to incapacitation [72].

Deprivation of oxygen can also cause harm to occupants. As a fire grows it requires more oxygen for combustion to occur, therefore removing oxygen from the environment and reducing the amount available for breathing. Severe incapacitation occurs between 11.8 to 9.6% O_2 with critical hypoxia (i.e. unconsciousness and death) occurring at between 9.6 to 7.8% O_2 [67].

Fractional Effective Dose (FED) is a technique used to assess human incapacitation due to the combustion gases. FDS uses concentrations of CO, CO_2, and O_2 to calculate FED [73]. This calculation is outlined in depth in Appendix A. An FED value of 0.3 can cause incapacitation for a more susceptible person (such as a child or the elderly); a value of 1 has sub-lethal effects making occupants incapable of egress [67].

The primary threats that occupants will encounter in a fire include incapacitation due to the high concentrations of narcotic gases or exposure to high temperatures due to both radiative and convective heat [2]. However, if visibility drops below 2 m in the relevant layer, individuals can become disoriented making it difficult for an occupant to safely egress [52].

3.8 Detection Devices

3.8.1 Smoke Detectors

Smoke detectors have played a key role in reducing the number of fire deaths over the last 30 years in North America. The time to smoke alarm activation is dependent on the fire size, the geometry of the room, the location of the detector and type of detector. Two factors mainly affect the activation of smoke detectors: particle size and fire-induced velocities [74].

As prescribed by Section 2.13 of the Ontario Fire Code [75], at least one smoke alarm should be installed on each storey of a home, and they should be located outside all sleeping areas. Detectors should always be placed on ceilings or high on a wall so as to detect the first traces of smoke, due to the fact that smoke and heat rise.

In recent years there has been an increase in the variety of smoke detectors available to consumers, the two most common being ionization and photoelectric, the former being more common in Ontario [76]. Photoelectric alarms are activated when smoke particles enter the detector and alter the path of a light sensor. Ionization detectors are activated when smoke particles enter the device which disrupts the conductance of the air. Ionization detectors may detect flaming fires slightly faster, whereas photoelectric alarms tend to react faster to smouldering fires. The National Fire Code of Canada requires all residential smoke alarms comply with the ULC Standard CAN/ULC-S531. The sensitivity of smoke and heat detectors is described by their response time index (RTI). A higher RTI value translates to an increase in activation time.

3.8.2 Heat Detectors

Historically heat detectors have been in use to alert occupants to fires for much longer time than smoke detectors. Heat detectors are activated once a specified temperature has been reached, typically from 54 to 74°C or when the rate of temperature change increases to a given point, generally around 7 to 8°C/min.

As the distance between the fire and a heat detector increases a higher heat release rate is required to activate the device, as would be expected [77]. This reiterates the importance of having multiple alarms throughout a house, placed in locations of higher fire probability, to reduce the time to fire detection.

Smoke detectors generally activate first, followed by heat detectors, and finally sprinklers. This was observed in the Kemano room fire tests performed by the NRC [78].

3.8.3 Sprinklers

The use of sprinklers in residential buildings has become more widespread in recent years. Although sprinklers are the last to activate of the three most common residential fire detection devices, they are the most effective in controlling fire spread and reducing fire deaths, injuries and property damage [77].

As of April 1, 2010 all new construction in Ontario of multiple-unit residential buildings over three storeys in height (including additions, floors of existing buildings that undergo a change of major occupancy to residential, and floor areas that undergo substantial renovation) will require sprinkler systems as stated in O. Reg. 205/08 [79]. This regulation will set a new standard for fire safety. As a result some smaller construction projects may choose to also adhere to this regulation therefore it is important to also study the use of sprinklers in single-family homes.

The activation of a sprinkler depends on gas temperature (quick response sprinklers used in the Kemano fire tests were rated at 68.3°C [78]). Thermal response of sprinklers is characterized using the Response Time Index (RTI) and is determined experimentally based on gas temperature and flow rate. The RTI describes the delay between the actual gas temperature and the temperature measured by the sprinkler bulb. The lower the RTI the faster a sprinkler will respond [80]. When sprinklers are installed in one to two family dwellings they should follow NFPA 13D [81].

3.9 Modelling

No computer model can ever be perfect for several reasons, there is always a random aspect to how a fire behaves therefore no two fires are ever identical. However, models can be very effective at providing information on an expected outcome. The benefits and draw backs of network, zone, and computational fluid dynamics (CFD) models are herein summarized and evaluated for the purpose of this research.

3.9.1 Network Models

Simple network models calculate flow through buildings. Each compartment is represented by a node and nodes are connected via a link. The properties of each room can be defined at a node. Flow is generated based on pressure differences, moving from areas of high to low pressure (such as stack effect). These models can determine smoke concentrations due to the conservation of species. Since network models are inherently simple using generalized geometries, calculations are efficient and fast, however fires and smoke movement cannot be modeled. CONTAM is an example of a network model [82].

3.9.2 Zone Models

Zone models usually consist of 2 zones: a hot upper layer (created by the fire plume) and a cold lower layer. This type of model is capable of calculating combustion, heat transfer, flow through openings, interface heights (the horizontal line at which these two zones meet), and HRRs. Each of the layers is assumed to have uniform properties that change with time. Zone models are limited to locations where the two zone assumption is valid (i.e. not applicable in tunnels), and geometries with a few small compartments. CFAST is an example of a two zone model [83].

Collier conducted a study comparing experimental data for a fire in a residential building to predictions made using CFAST [51]. He concluded that windows rarely break to create an opening equivalent to 100% of their area (pieces remain intact), open vents can be modeled reliably, and the temperature rise in the upper layer is accurate for activating heat detectors and sprinklers.

The CBUF project demonstrated that hazard analysis can be conducted using experimental methods or two zone models, and that these two zone models can directly use data collected in a furniture calorimeter [68]. These models are important in predicting the depth and temperatures of the two layers. Information that needs to be known to run these models is room geometry, as well as, the history of fire growth [68]. There are also limitations to using zone models, such as assuming a discontinuous temperature profile, assuming the fire is small in comparison to the compartment (not representative of rapidly growing fires), and this type of model best applies to compartments whose width and depth are not very different [68].

3.9.3 Computational Fluid Dynamics

CFD models divide a given space into control volumes where conservation of mass, momentum, and energy equations are numerically solved for each volume. CFD models allow a user to define a geometry (including openings and obstacles), boundary conditions, and a fire location and heat release rate. A CFD model that is commonly used for fire modeling is the Fire Dynamics Simulator (FDS) developed by NIST [73].

The truth is that real upholstered furniture cannot be fully described by a model due to several uncertainties, specifically the properties of component materials. But accurate approximations and estimates which are representative and meaningful can still be developed. In an NRC study comparing HRR data from sofa mock-up experiments to FDS numerical predictions, the peak HRR predicted by FDS was typically less than the experimentally measured values, however the shape of the HRR curve was well predicted [52]. It was believed that this was due to an inaccurate representation of the thermal boundary conditions and the polyurethane pyrolysis process [52]. This illustrates the difficultly in determining accurate properties for component materials.

3.9.3.1 FDS material property values

Matala studied pyrolysis of different materials (including wood) to determine kinetic parameters using thermogravimetric analysis data and thermal parameters from cone calorimeter data for the purpose of fire simulation [84] She found that using a simple one step reaction for wood pyrolysis was adequate for fire engineering purposes. Her results for input values to be used in FDS are shown in Table 3-13.

In a study on numerical simulation of flame spread on polyurethane foam slabs, when the values for polyurethane, listed in Table 3-13, were used in FDS they provided a good prediction of the results [85].

Table 3-13: Thermal material properties for use in FDS simulations

	Wood [84]	**Polyurethane** [85]
k	0.1 W/mK	0.8 W/mK
c_p	1.7 kJ/kgK	1.6 kJ/kgK
ΔH_c	19 MJ/kg	30 MJ/kg
ΔH_l	400 kJ/kg	1 500 kJ/kg
A	1.0E15 /s	1.686E08 /s
E	2.0E05 kJ/kmol	1.35E05 kJ/kmol
A_2		8.746E9 /s
E_2		175000 kJ/kmol

A list of common heat of combustion (ΔH_c) values for upholstered furniture is found in Table 3-14. The highest quoted value is 35 MJ/kg for a polypropylene frame sofa, which is likely related to the high ΔH_c value of polypropylene around 43.2MJ/kg [1].

Table 3-14: ΔH_c values for polyurethane or upholstered furniture

ΔH_c (MJ/kg)	***Reference***
28	NRC residential fire simulations [86]
23	*Eurocode 1* [29]
23	Average of cone calorimeter data for CBUF predictions [5]
Varied 15-30	Chair F21: wood frame, PU foam padding and polyolefin fabric [4]
35.1	Polypropylene framed sofa [1][4]

3.10 Full Scale Experiments

3.10.1 Dalmarnock

Recently an apartment living room fire test was conducted in the UK by the University of Edinburgh, known as the Dalmarnock fire tests [87]. The purpose of the test was to simulate real fire conditions by using realistic fuel packages. A round-robin exercise was then undertaken for fire safety teams around the world to model the fire in whatever method they saw best fit. The results were very interesting in that they showed a large variation between the different models, and also between different users of the same model. However, the experimental component is useful as a comparison.

The dimensions of the living room were 6.4 x 4.0 x 2.7 m. A smoke alarm was located on the ceiling in the centre of the room, which was set to activate at the lower criteria of 0.21%/m and the heat detector at 54°C [88]. The ignition source was a plastic waste paper bin filled with crumpled newspaper and 500 ml of heptane, which was intended to spread to a sofa placed near the centre of the room.

The ionization smoke detector activated after 16 s and the optical detector at 25 s. The heat detector activated after 40 s.

3.10.2 Kemano

A number of tests were conducted in by Forintek in Kemano, British Columbia [89]. Six tests were completed in a series to test a wide range of variables, but of importance to this research was the monitoring of fire growth and smoke movement throughout the house. A waste paper basket was the ignition source, followed by either an upholstered sofa or mattress.

In a specific test that was designed to assess the performance of gypsum board in a fire, a fire was started in a living room with a window partially open and the door closed. The test was conducted in two very similar rooms with the only difference being the gypsum board on the walls. Test 1 used regular gypsum board and Test 2 used fire rated gypsum board. The room measured 3.4 x 4.8 x 2.5 m high. The sole window in the room consisted of three panes, with the top of the window 0.57 m below the ceiling. The two outer panes measured 0.55 x 1.42 m high and were open at the beginning of the fire; the central pane was 1.47 x 1.42 m high and closed. The fire grew very quickly and experienced flashover in the first few minutes. Test 1 reached flashover at 2.7 minutes and Test 2 at 4.3 minutes. Upper layer temperatures data for Test 2 was translated into equivalent HRR data using the MQH method for the pre-flashover fire and the Japanese Parametric Model for the post-flashover fire, Figure 3-9. In a pre-flashover fire the average compartment temperature is low, the fire is localized to the room of fire origin, and the interaction with the compartment boundaries becomes significant, whereas in a post-flashover fire all of the combustible items in a room are burning, the room is filled with flames, and temperatures are high [90]. Therefore separate equations are necessary to determine the HRR during each stage of the fire.

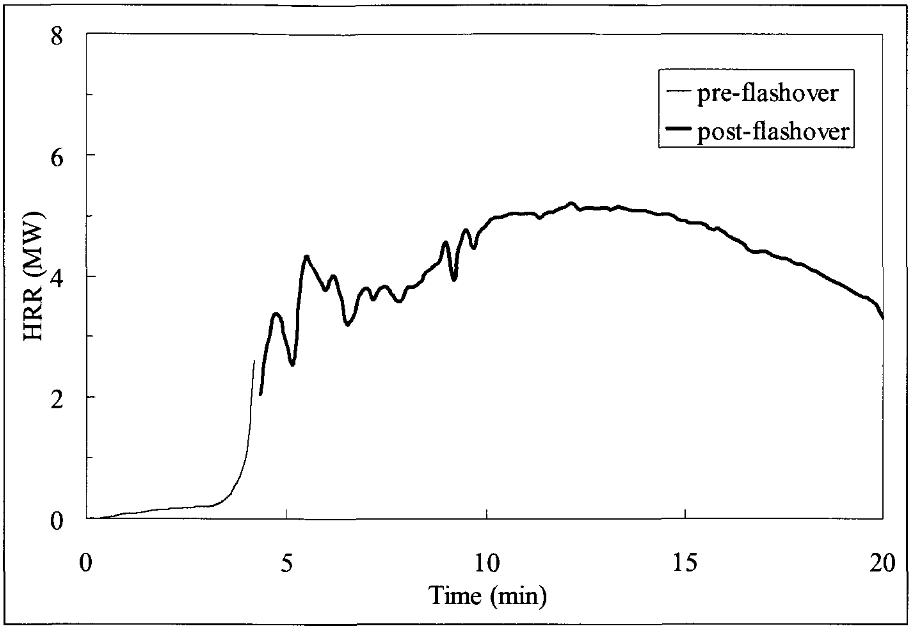


Figure 3-9: HRR of fast t-squared and Kemano Fire [89]

The window cracked shortly after flashover, at 4.5 minutes and fell out at 5.2 minutes. Applying Equation 3-2 the maximum possible heat release rate is 2,800 kW and after window fallout 6,600 kW, therefore this fire was fuel surface controlled. From this series of tests it was concluded that upholstered furniture items posed a higher fire safety threat than the wood frame structure. It was also noted that untenable conditions always developed before the structure was involved in the fire.

Another aspect of the Kemano project, which was conducted by the NRC, was to determine the activation of sprinklers in a residential setting, for this a separate series of tests were conducted [78]. A similar living room fire layout was used in a room measuring 7.2 x 3.7 x 2.4 m high which connected to a dining room measuring 4.0 x 3.14 m. It was outfitted with a sofa, leather chair, television, and a wood end table, where the ignition source was a fuel pan in front of the sofa. The sprinklers used were fast response sprinkler heads with a temperature rating of 68.3°C. The first sprinkler activated at 59 s and controlled the fire.

3.10.2.1 Bedroom Experiments

Chen developed fire curves for bedrooms in motels and hotels [91]. In his experiments the bedroom furniture consisted of a double bed (including bedding), an upholstered chair, nightstands, a desk and a dresser which was determined through an extensive survey. The room had one window measuring 1.5 m x 1.5 m. He suggested two design curves: the first simply following the HRR of the fire and the second being conservative for fire protection design with a safety factor of 1.15 applied to the fully-developed stage. The burner used follows a fast t-squared growth curve until it reaches 3.61 MW, shown in Figure 3-10. It maintains this HRR for 12.8 minutes, after this the HRR decays linearly to zero, reached at 33 minutes. The burner is placed close to the centre of the room, but generally more away from the doorway as this is the likely location of the majority of the fuel load.

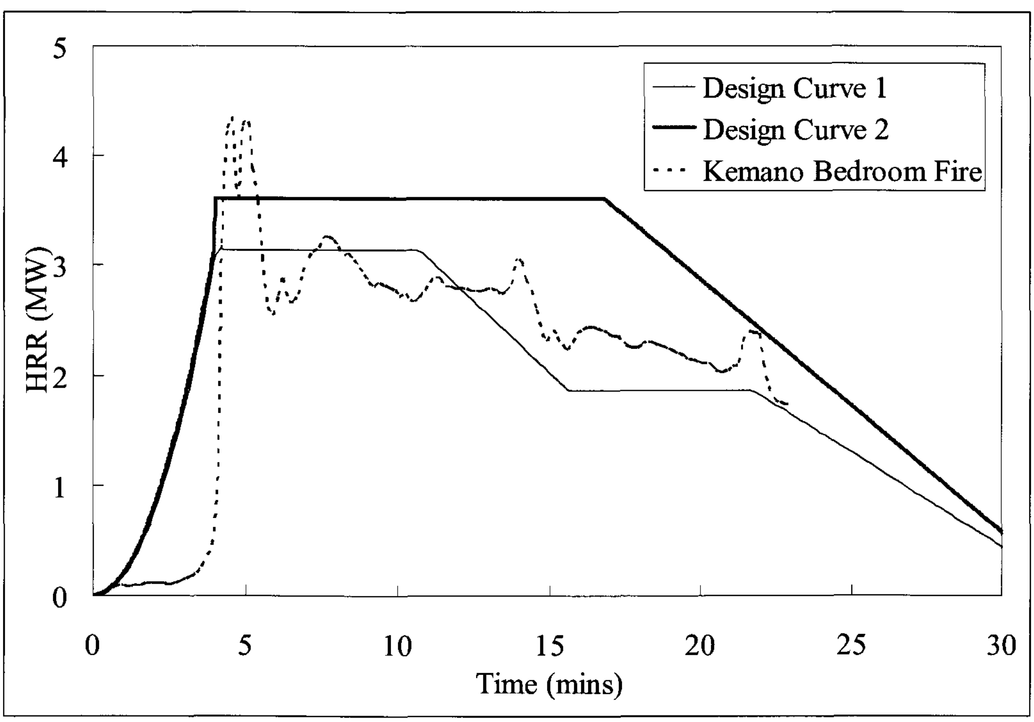


Figure 3-10 HRR from bedroom design fire curve and Kemano Fire [91],[92]

These design curves are also compared to the experimental work conducted by Forintek during the Kemano series of experiments [92]. In this test, thermocouples were used to measure temperature data in a bedroom fire outfitted in a similar manner to the tests conducted by Chen. The window measured 0.76 m x 1.27 m. This data was then translated into equivalent HRR data using the same method as was used in Figure 3-9 [89]. Design Curve 2 is more severe than the Kemano fire (except for the initial peak), as would be expected since it is a conservative curve.

As previously discussed, sprinkler activation was part of the research interest of the NRC in the Kemano fires. One of the bedroom tests, in a room 3.9 x 3.2 x 2.4 m high, had one sprinkler head in the room. The door was initially open during the experiment. The room had a queen size bed and a small dresser. The ignition source was a fuel pan under the bed, with the bedspread touching the pan. A sprinkler was activated in a bedroom fire after 84 s [78].

3.11 Significance of Research

A significant amount of work has been done to study the behaviour of upholstered furniture in fires. However, most of the work that has been done involves small-scale testing to examine individual component materials. It is important to study the influence these items have on fire growth and tenability in dwelling fires. Several correlations exist for room fire dynamics equations, but few specifically relate to fires involving upholstered furniture.

This study aims to provide information that is currently missing for residential home designers. Examining how an upholstered furniture item will affect fire growth and the time to major events will provide valuable data for performance based code designers.

By simulating residential fires in bedrooms and living rooms, the specific times that tenability criteria will be exceeded can be evaluated at critical locations throughout a house (in the room of fire origin, at the base of the staircase, and at the top of the staircase).

4 RESEARCH AND METHODOLOGY

This study uses the Computational Fluid Dynamics model, Fire Dynamics Simulator 5 (FDS) [73], developed by the National Institute of Standards and Technology, to simulate fires in conventional houses furnished with upholstered products. The aim is to demonstrate the impact that varying the total floor area and the total opening area in the room of fire origin has on time to major events, smoke movement, and tenability. Fire scenarios included a living room and a bedroom fire in a residential house. Two types of two-storey houses were examined: single-family detached and single-family townhomes. A detached home is a stand alone unit, whereas the townhomes examined are row houses, sharing both side exterior walls with other units. Detached homes are typically larger and have more windows than townhomes.

The model considered the house geometry including number of rooms and stories, furniture (material and arrangement), ventilation conditions (doors and windows), ignition of upholstery items (sofa or mattress), and fire growth rate and heat release rate. Expected outputs include time to major fire events (e.g., fire alarm and sprinkler activation, window breakage, and time to flashover), smoke movement inside the house and leakage to the outside, toxic gases (production rates and total production), and time to untenable conditions and risk to life (e.g. visibility, thermal effect, toxicity levels).

4.1 Fire Dynamics Simulator

FDS was chosen as the model to use for this research since this study is interested in the movement of heat and smoke in a complex geometry. FDS is also the most commonly used CFD model for fire research since it is widely available (offered free to the public by NIST). Because the software is widely available there have been numerous studies to show the validity of the model for complex fire scenarios. Specifically for this research, a vertical temperature profile would be a very useful tool when determining the effect of the fire on occupants and to verify when flashover has occurred. Evaluating species concentrations and temperatures at different heights allows for an in-depth analysis to determine the ability of an occupant to egress.

FDS is a very powerful research tool and it produces an overwhelming amount of data. For all of the graphs presented in the results section, data values were averaged over ten seconds to reduce the number of data points for ease of presentation. This smoothed the curves by eliminating any outliers and noise.

4.2 Description of the Houses

The building geometries were created using actual residential home building plans for two-storey single-family detached homes and townhomes (found in Appendix B) [93-98]. Three different floor plans were used for each of these types of houses, totaling six, all with different total floor areas. The sizes examined for the detached home were 297 m^2, 260 m^2, and 223 m^2, and the sizes for the townhome were 186 m^2, 167 m^2, and 149 m^2. House floor plans are typically given in imperial units, as shown in Table 4-1. The listed total floor area of a house can be slightly exaggerated and can also include the floor area of the basement. For this reason an actual size calculated from the drawings of each house is included in the table to accurately represent the total floor area of the first and second floor. Throughout the rest of this work, the houses will be referred to by their listed size in metric units.

Table 4-1: Total Floor area of selected houses

	Listed size (m^2)	Listed size (ft^2)	Actual size (ft^2)
Detached homes	297	3200	2850
	260	2800	2200
	223	2400	1700
Townhomes	186	2000	1400
	167	1800	1250
	149	1600	1150

The details of how floor area is allocated in the main living area (living room, kitchen, and breakfast area (including dining room in the townhomes)) are summarized in Table 4-2. This study is looking at the main living area in homes that are 'open concept'. Some of the larger homes have specific rooms for different purposes (i.e. a dining room or office) which are included in the living area. But the smaller townhomes combine the living room, dining room and kitchen into one smaller open area. The living room, kitchen, and breakfast area all decrease as the total floor area of the homes decreases. The total living area decreases for each of the types of homes, but there is a discrepancy between the detached and townhomes due to the inclusion of the dining area in the townhomes.

Table 4-2: Ground Floor room sizes

Total Floor Area (m^2)	Living Room (m^2)	Kitchen (m^2)	Breakfast (m^2)	Dining (m^2)	Living Area (m^2)
297	32.3	17.9	17.6	-	67.8
260	22.4	14.8	11.8	-	49.0
223	24.0	11.5	7.2	-	42.7
186	19.6	10.8	7.3	12.6	50.3
167	17.6	7.4	6.8	11	31.8
149	14.9	7	3.2	7.4	25.2

4.3 Generating the FDS Model

A grid size of 0.15 m was used for the fire room and area of interest, while the remainder of the building had a grid size of 0.3 m to reduce the overall computational duration. This resolution is in accordance with values that are recommended based on the HRR and diameter of the fire [73],[63],[99],[100]; see Appendix C for sample calculations. Larger and smaller grid sizes than those specified above were assessed by means of a sensitivity analysis. Little difference was seen when the grid size in the room of fire origin varied between 0.1 and 0.15 m. A grid of 0.3 m produced somewhat different results.

Walls and ceilings were modeled as gypsum board and the floor as yellow pine, using default material values from FDS [73]. Any upholstered items (consisting of polyurethane) were modeled using the same thermal properties as those found in a study evaluating the flame spread on a polyurethane foam slab in compartment fires [85], listed previously in Table 3-13. The wood furniture (e.g., kitchen cabinets, dining room table) items were modeled using pine properties derived by Matala, also found in Table 3-13 [84]. The heat of combustion (ΔH_c) used for wood was 19 MJ/kg [29] and 30 MJ/kg for polyurethane. The value of 30 MJ/kg for polyurethane was chosen for these simulations as an upper limit of accepted values.

The burner, whose HRR is specified for each of the room fires in subsequent sections, was modeled to emulate the reactions of a polyurethane fire, with a soot yield of 0.1.

Since this study is mainly concerned with the fire growth and the time to major fire events, FDS simulations were only run until all major events had occurred. Major events include alarm activation, flashover, window breakage and reaching tenability criteria which all occur in the early stages of a fire.

A sample FDS input file for a living room fire in a 297-m^2 home with 11.2-m^2 openings is presented in Appendix D.

4.3.1 Determining flashover

Flashover is a phenomenon where any combustible item in a room will ignite; this is in part due to heat being radiated back down to combustible items from the upper layer. It is widely accepted that flashover occurs when heat fluxes at the floor reach 20 kW/m^2 [59] and/or when the upper layer in the room reaches between 500 and 600°C [58]. FDS is capable of calculating the layer interface height and estimating both upper and lower layer temperatures at any specified location.

To determine when flashover had occurred in the simulations, the upper layer temperature values were averaged from two measurement locations inside the room of fire origin, shown in Appendix E. These two locations were chosen to be close to the main location of the fire so that the exact same configuration could also be applied in the bedroom simulations. At the same two locations heat flux measurements were taken at floor level (it is common to refer to FDS device locations as measurement locations, however no physical measurements are actually being taken, these are merely 'virtual measurements'). FDS results demonstrated that the times to flashover in all six dwellings are very similar when the criteria of 600°C and 20 kW/m^2 are used. Another method that was employed to verify the time of flashover was a temperature slice profile taken along the length of the room. Once a 600°C temperature isotherm consistently spanned the room, approximately 0.3 m from the ceiling, flashover was said to have occurred; once this happened the upper layer rapidly dropped and all items in the room ignited. For the first few simulations all three methods were used to asses each method's accuracy. For the last few simulations only the upper layer temperatures and the isotherm method are used.

4.3.2 Alarm Activation

Ionization smoke detectors are modelled, with an obscuration threshold of 3.28 %/m. Heat detectors have an RTI of 100 $m^{1/2}s^{1/2}$, with an activation temperature of 57°C. Sprinklers have an RTI of 100 $m^{1/2}s^{1/2}$, with an activation temperature of 74°C. Sprinklers locations were determined following NFPA 13D, where residential houses are described to have a light hazard in terms of fuel load. A light hazard building is limited to coverage of each sprinkler head to 20.1 m^2 (225 ft^2) or 15.6 m^2 (168 ft^2) for buildings of combustible construction [81]. Therefore the proximity of the nearest sprinkler to the initial ignition source depends on the room geometry and the placement of the ignition source, which varied for all the simulations.

4.3.3 Assessing Tenability Criteria

To evaluate the risk posed to life safety, tenability criteria were evaluated at three critical measurement locations for each of the fires. Measurements to assess untenable conditions included: carbon monoxide (CO) and carbon dioxide (CO_2) concentrations, oxygen (O_2) depletion, the Fractional Effective Dose index (FED), visibility, lower layer temperatures and radiative heat fluxes. The following values were used to judge when it would become difficult for an occupant to evacuate the premises:

a. CO $\geq$ 1400 ppm [52]

b. CO_2 $\geq$ 0.05 mol/mol [52]

c. O_2 $\leq$ 11.8% (severe incapacitation) [67]

An FED value of 0.5 is used in these simulations as the criteria to roughly assess tenability [67]. FDS calculates FED based on the concentrations of CO, CO_2, and O_2.

If visibility drops below 2 m in the relevant layer, individuals can become disoriented making it difficult for an occupant to safely egress [52].

An individual exposed to 120°C dry air will experience skin burns, whereas temperatures slightly lower than this can lead to hyperthermia [67]. Also an upper layer temperature of 200°C or a radiative heat flux of 2.5 kW/m^2 corresponds to painful exposure and will cause harm to an individual [67]. The CBUF defined a 100°C isotherm of the smoke layer interface as a good indicator of the heights under which individuals could still escape [2].

Heat detector, smoke detector and sprinkler activation data were also collected. Heat detectors and sprinklers are triggered by temperatures exceeding 57°C and 74°C, respectively, both using a Response Time Index of 100 $m^{1/2}s^{1/2}$. Ionization smoke detectors are activated at an obscuration threshold of 3.28 %/m.

Glass breakage of windows was determined through the use of heat detectors placed slightly above the centre of the window. These surfaces were set to open (simulating breakage) when a temperature of 250°C was reached by the individual heat detectors for each pane. Since there has been shown to be a large variation in the breaking temperatures of windows (Section 3.6.5), 250°C was chosen as a conservative value. When the heat detector location reaches 250°C, the top of the window will be exposed to higher temperatures inducing stresses due to temperature differences in the glass which will result in window breakage.

4.4 Description of the Living Room Model

These simulations assume a fire starts in the living area; the fire is modeled using a 5 m^2 burner which follows a fast t-squared growth curve until it reaches 5 MW, shown in Figure 4-1. The burner maintains a 5 MW HRR for 30 minutes. This fire is specifically modeled after a living room test that was conducted by Forintek in Kemano, British Columbia [89]. This data was then translated into equivalent HRR data using the Japanese Parametric Model, Figure 4-1. The materials in the room for a fire of this nature would likely consist of a sofa, chair, end tables, entertainment unit, and a coffee table as found in the NRC survey of the fuel loads [7]. The burner used is more severe than the Kemano fire, but this will help give conservative estimates of the times to major fire events.

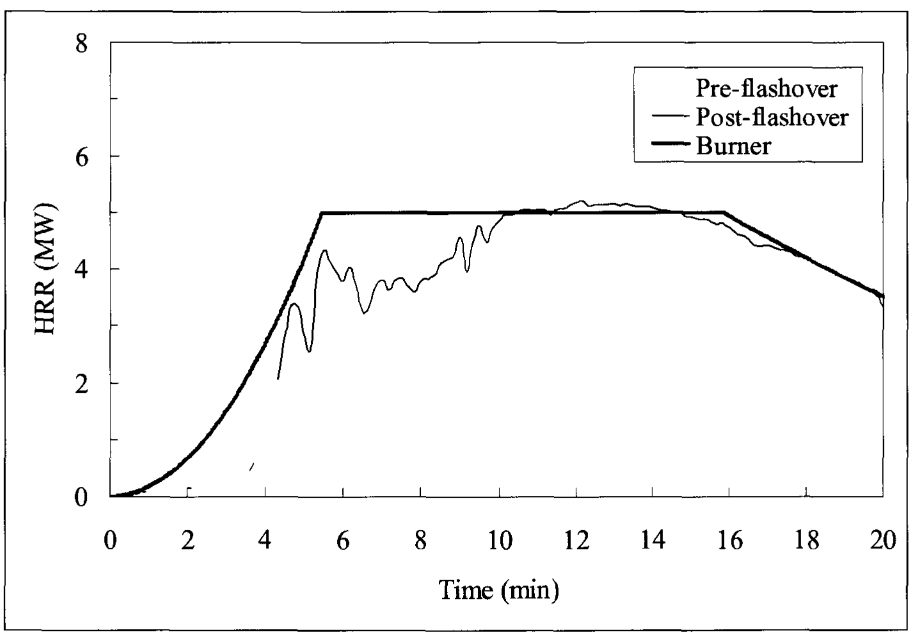


Figure 4-1: HRR of fast t-squared burner and Kemano Fire

A small upholstered chair (~6 kg) and a wood table (~15 kg) are placed in close proximity to the burner, as a method to determine fire spread; this configuration is detailed in Appendix E. If the house was large enough to have space for a breakfast area, a second table was placed in that area. The burner was placed close to the centre of the living area, with the shorter edge of the burner being 1.05 m from the windows in the detached homes. To maintain the same furniture configuration in the townhomes the edge of the burner was 1.1 m, 1.0 m and 1.6 m from the windows for the 2000, 1800, and 1600 m^2 homes respectively. The 1600 m^2 townhome was the smallest house examined; in this case the orientation of the furniture configuration was rotated 90° to be able to fit in the space.

The kitchen was furnished with wood cabinets, the size and number of cabinets was essentially equal for all simulations. This resulted in an average 881 MJ/m^2 fuel load density for the townhomes, which is more conservative than the 807 MJ/m^2 value found in the NRC survey [27]. This same fuel package was used in the detached homes giving an average fuel load density of 500 MJ/m^2, which is higher than the average of 390 MJ/m^2 for the whole home found in the NRC study [7] but equivalent to the value recommended by CIBW14 [28]. The main part of the kitchen fuel load (upper and lower cabinets, an island, and a breakfast table) was kept constant for all of the homes, however some of the larger homes had a second table since there was ample space. The fuel load density in the kitchen for the 297-m^2 home was 400 MJ/m^2; the 260-m^2 home was 480 MJ/m^2, and 620 MJ/m^2 for the 223-m^2. The fuel load in the kitchen area in the townhomes was: 186-m^2: 663 MJ/m^2, 167-m^2: 963 MJ/m^2, and 149-m^2: 1017 MJ/m^2.

The other case that was examined involved keeping the total floor area constant (for all 6 geometries) while varying the total opening area in the room of interest. 8.4 m^2 provides a good representation of window openings in the living area for detached homes and 6.5 m^2 is representative of townhomes similar to those studied in this research. Some simulations were conducted to examine the effects of increasing the window area throughout the house, but little differences were seen. Therefore to clearly illustrate the effects of window areas in the detached home, the typical value was doubled and halved. Due to the narrow nature of townhomes, the maximum amount of windows are typical, therefore this value was halved twice to amplify the effects of changing window size. The simulations involving the detached homes used opening areas of 11.2, 8.4, and 5.6 m^2; the townhome simulations used 6.6, 4.9, and 3.3 m^2.

These simulations considered all of the doors on the second level to be closed, which significantly limits the spread of heat and smoke to the bedrooms upstairs. With these doors closed, the windows in the bedroom do not impact fire growth so they are not considered in the total opening area for the homes, which are listed in Table 4-3 for detached homes and in Table 4-4 for townhomes. The total opening areas were constant for the townhomes since their geometry only allowed one additional window at the front of the house.

Table 4-3: Total house opening area for living room fires in detached homes

	Living Room Opening Area (m^2)		
Total Floor Area (m^2)	**11.2**	**8.4**	**5.6**
297	20.8	18.0	15.5
260	18.3	15.5	13.0
223	18.9	16.1	13.6

Table 4-4: Total house opening area for living room fires in townhomes

	Living Room Opening Area (m^2)		
Total Floor Area (m^2)	**6.6**	**4.9**	**3.3**
186	6.8	5.1	3.5
167	6.8	5.1	3.5
149	6.8	5.1	3.5

The three locations where tenability criteria were assessed are: inside the room of fire origin (Location A), in the hallway at the bottom of the stairs (Location B), and at the top of the stairs (Location C). Tenability criteria were assessed at 1.5 m from the floor to represent the nose-height of an average adult, which provides a good indication of the effect of gases on the occupants [52]. Smoke and heat detectors were located at all three measurement locations. Location A was the main detector of interest as it was centrally located between the living room and kitchen, where one might typically find a smoke detector in a home.

All of the living rooms would be considered 'open concept', having no wall separation between the living room and kitchen, therefore opening area was distributed along the exterior walls of this space. In the living area windows were divided into panes, each measured 0.7 x 1.2 m high. For the detached homes kitchen window panes measured 0.5 m x 1.0 m high. Townhomes did not have any windows in the kitchen since openings were only located on the main front and back wall. All homes had sliding patio doors leading to the backyard, which consisted of two panes of glass measuring 0.8 m x 2 m high.

4.5 Description of the Bedroom Model

The same six house geometries used in the living room fire simulations (detached homes with 297 m^2, 260 m^2, and 223 m^2 floor area; and the townhomes with 186 m^2, 167 m^2, and 149 m^2 floor area) were also used to examine the bedroom fires where upholstered furniture (i.e., a mattress) was the main item burning in the fire. The sizes of the primary and secondary bedrooms for each house are given in Table 4-5. It should be noted that the bedroom dimensions of the townhome with 149-m^2 floor area closely resemble the dimensions of multi-family dwellings from the NRC survey [27].

Table 4-5: Bedroom areas in detached homes and townhomes

Total Floor Area (m^2)	**297**	**260**	**223**	**186**	**167**	**149**
Primary Bedroom (m^2)	33.4	31.1	27.0	21.7	18.7	16.1
Secondary Bedroom (m^2)	19.3	20.1	17.8	13.7	11.0	10.2

These simulations assume that a fire starts in the primary (master) bedroom. The fire is modeled using a 5 m^2 burner with a fast t-squared growth curve, which continues to grow over the course of the simulation. The burner is placed in a location that is common to the placement of a mattress, since the mattress is the most likely item of first ignition and the majority of furniture in a bedroom is typically concentrated near the bed. The burner was placed at the centre of the longest wall if space permitted; otherwise it was located at the centre of the wall containing windows. The burner and measurement location layouts for each of the houses can be found in Appendix F. Since the dimensions of the bedroom varied for each of the houses, the distance between the burner and windows was not constant. The distance between the two decreased for the smaller houses, listed in Table 4-6. A small wooden piece of furniture (~25 kg) was also placed on the wall opposite the burner, to assess when combustibles in the room would start to burn.

Table 4-6: Burner distance to window in bedroom fires

Total Floor Area (m^2)	**297**	**260**	**223**	**186**	**167**	**149**
Distance to window (m)	1	0.75	0.5	0.45	0.45	0.3

The total opening area in the bedroom for detached homes varied between 3.6, 2.4, and 1.8 m^2 and townhomes between 2.4, 1.8, and 1.2 m^2. According to the building plans used, an opening area of 2.4 m^2 provided a good representation of bedroom window openings for detached homes. For townhomes, an opening area of 1.8 m^2 was realistic and similar to those studied in this research [27]. Table 4-7 lists the total possible opening area in each house, if all of the windows break. The detached homes have about 2 times the total amount of windows than the townhomes do. Windows outside the room of fire origin are more likely to break later in the fire and may not necessarily have any impact on the growth of the fire.

Table 4-7: Total opening area in entire house for bedroom fire simulations

		Total opening area (m^2)			
Bedroom opening area (m^2)		**3.6**	**2.4**	**1.8**	**1.2**
Total Floor Area (m^2)	**297**	29.8	28.6	28.0	-
	260	26.1	24.9	24.3	-
	223	26.1	24.9	24.3	-
	186	-	12.6	12.0	11.4
	167	-	12.0	11.4	10.8
	149	-	12.6	12.0	11.4

Since this study is mainly concerned with the fire growth and the time to major fire events, simulations were only long enough to observe the early stages of the fire.

4.5.1 Assessing Tenability Criteria

To evaluate the risk posed to life safety, tenability criteria were evaluated at four critical locations, Location A: inside the room of fire origin (1.1 m from the burner towards the doorway, in line with the centre of the burner); Location B: at the top of the stairs; Location C: at the bottom of the stairs; Location D: near the doorway inside an adjacent secondary bedroom. These locations are all representative of critical locations that are likely occupied during a fire, or routes that would need to be accessed during egress. Tenability criteria are assessed at 1.5 m from the floor to represent the nose-height of an average adult, which provides a good indication of the effect of gases on the occupants [52].

5 Results and Discussion: Effects of Varying Opening Area

5.1 Living Room Fires

5.1.1 Detached Homes

5.1.1.1 Heat Release Rate Histories

Heat release rates for a fire in a detached home are shown in Figure 5-1, Figure 5-2, and Figure 5-3 each representing a different total floor area (297, 260, and 223 m^2 respectively).

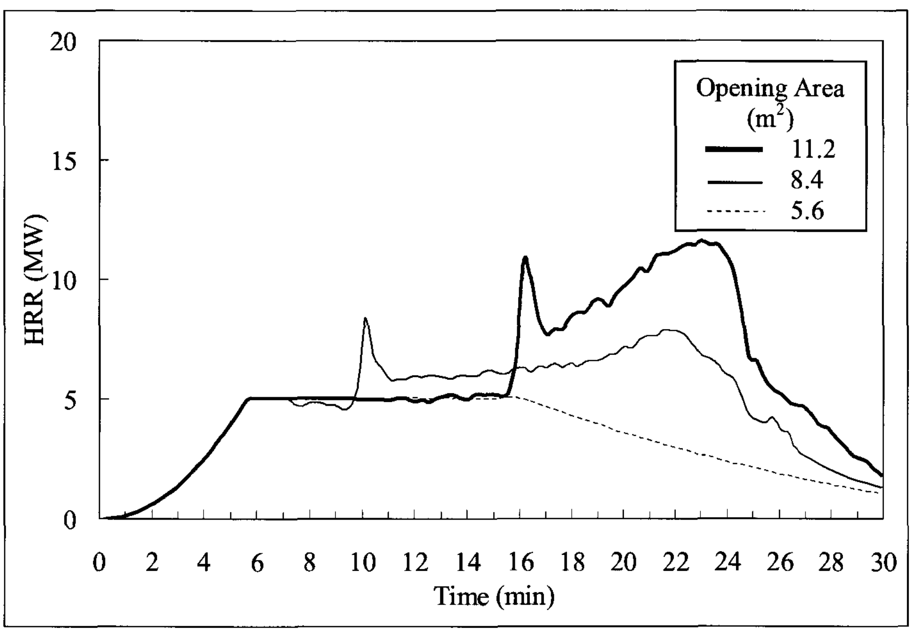


Figure 5-1: Heat release rates for living room fires in a 297-m^2 detached home

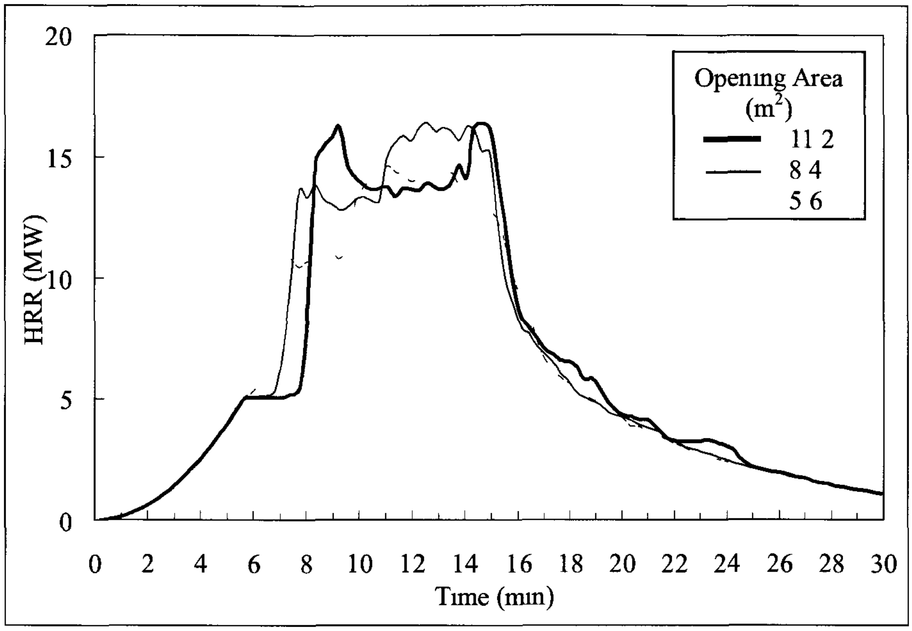


Figure 5-2: Heat release rates for living room fires in a 260-m^2 detached home

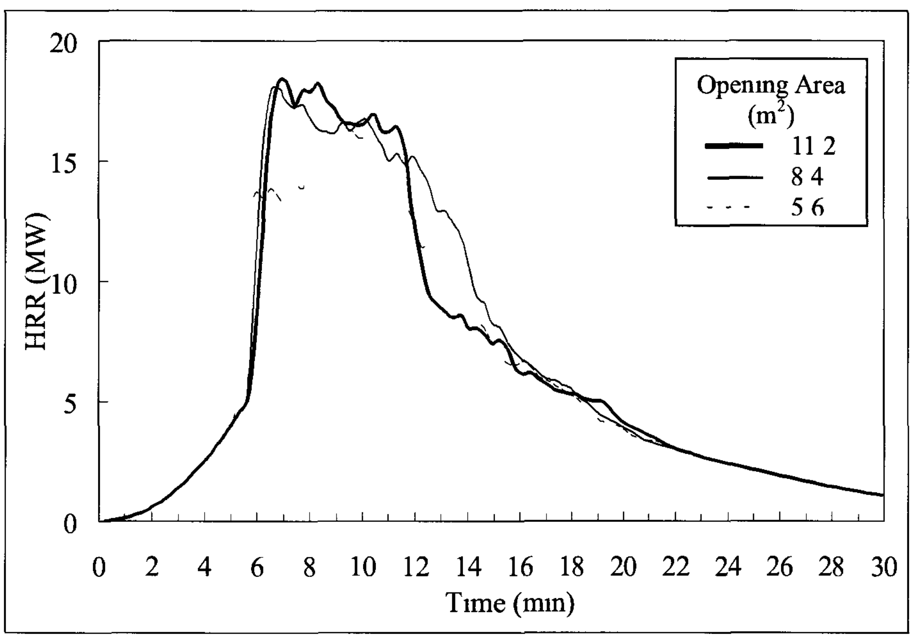


Figure 5-3: Heat release rates for living room fires in a 223-m^2 detached home

For all of the detached houses the HRR curves initially follow the growth of the burner until the fire spreads. These plots demonstrate that an increase in opening area produces higher HRRs yet delays fire growth. The fact that changing the amount of opening area alters the HRR illustrates that the fire is ventilation controlled (apparent in

Figure 5-1 and Figure 5-2), which is typical of enclosure fires. Figure 5-3 shows less variation in the HRRs when opening area is varied which would indicate a fuel surface controlled fire. As windows throughout the house begin to break, more oxygen enters the home and allows the fire to grow and release heat at a faster rate. Times of window breakage are listed in Table 5-1. Since the fire is ventilation controlled, flames typically concentrated near the openings.

Table 5-1: Window breakage in room of fire origin for detached homes living room fires

Total Floor Area (m^2)	**Opening Area (m^2)**					
	11.2		**8.4**		**5.6**	
	Window (min)	**Door (min)**	**Window (min)**	**Door (min)**	**Window (min)**	**Door (min)**
297	2.3	3.5	2.4	3.6	2.4	3.3
260	2.3	3.1	2.3	3.4	2.3	2.7
223	2.1	3.1	2.0	3.3	2.1	2.9

Windows breaking in a fire translates to increased opening area allowing cool fresh air to enter the room and hot smoke to escape, increasing the interaction between the upper and lower layers. The first window always breaks at about the same time in each house despite the opening area: 2.4, 2.3, and 2.1 minutes respectively from the largest to smallest home. The only factor that might alter the time of first window breakage is presence of more window panes due to increased opening area; thus resulting in some glass being closer to the initial fire source. The time at which the kitchen glass door breaks, is also important, as it increases the amount of opening area in the room by 3.2 m^2. However, there is little impact of this occurring in the detached homes. On the other hand, in townhomes the patio doors account for a large percentage of opening area, thus their breakage has a prominent effect.

In the house with 297 m^2 floor area, the fire takes longer to spread. This is because combustible items in the kitchen are at a greater distance from the ignition source, as well as, the room size is much larger than the other homes. The impact of opening area is most significant in the 297-m^2 home, but the fire did not spread to other items when there were 5.6-m^2 openings. Due to larger room area, the smoke and heat spread out which results in a longer time for the interface height to drop below 1 m (i.e. thinner hot upper layer); thereby reducing heat fluxes and making it difficult for other items to ignite.

The fire does spread to other items more quickly in the 260-m^2 house; however increased opening area has less drastic effects in delaying fire spread compared to the 297-m^2 home. It is evident that the fire has spread when there is a rapid increase in HRR, which occurs earlier in the homes with the smaller opening area. In the 223-m^2 house the division between the HRR graphs due to opening area is less prominent.

The times that the first windows break outside the living area are listed in Table 5-2. These windows break once flashover has occurred, since temperatures are increasing rapidly and the fire is spreading outside the room of fire origin. For the two smaller homes other windows begin to break earlier when less opening area is present in the room of fire origin. This was not the case in the 297-m^2 home because the fire did not spread to other items.

Table 5-2: First window breakage outside the living area in detached homes

Total Floor Area (m^2)	Opening Area (m^2)		
	11.2	8.4	5.6
	Window (min)	Window (min)	Window (min)
297	-	1179	1435
260	490	432	383
223	369	353	324

5.1.1.2 Temperatures

FDS is capable of calculating the layer interface height and estimating both upper and lower layer temperatures at a given location. These values are averaged from two locations in the room of fire origin for each of the three detached homes (measurement locations described in Appendix E) and illustrated in Figure 5-4, Figure 5-5, and Figure 5-6. The three upper layer temperature curves resulting from different opening areas initially follow the exact same line until window breakage begins to occur at approximately 2.4 minutes (Table 5-1). At this point, slightly higher temperatures are associated with the smaller opening areas, where hot air is trapped inside the room with less hot air able to move out through the openings.

The 297-m^2 house had very different temperatures than the other two houses, primarily because not all of the other items ignited during the fire resulting in lower temperatures.

The fire spread is delayed in the larger homes, but there is a lack of increase in upper layer temperatures once the fire does spread, as seem in Figure 5-4. In Figure 5-1 HRRs significantly increase for the 11.2-m^2 openings around 16 minutes, but this is not apparent when examining the corresponding upper layer temperature curve (Figure 5-4). This is because upper layer temperatures are measured in the living room and at this point in time the burner fire is decaying, but the fire has moved to the contents of the kitchen. For this reason higher upper layer temperatures are not seen in the living room, but would be in the kitchen.

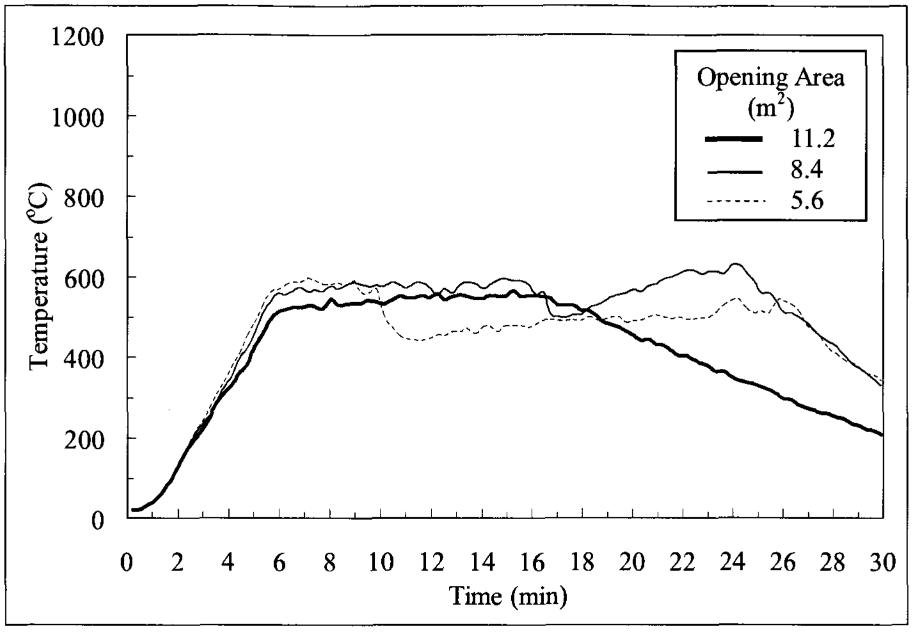


Figure 5-4: Upper layer temperatures for living room fires in a 297-m^2 detached home

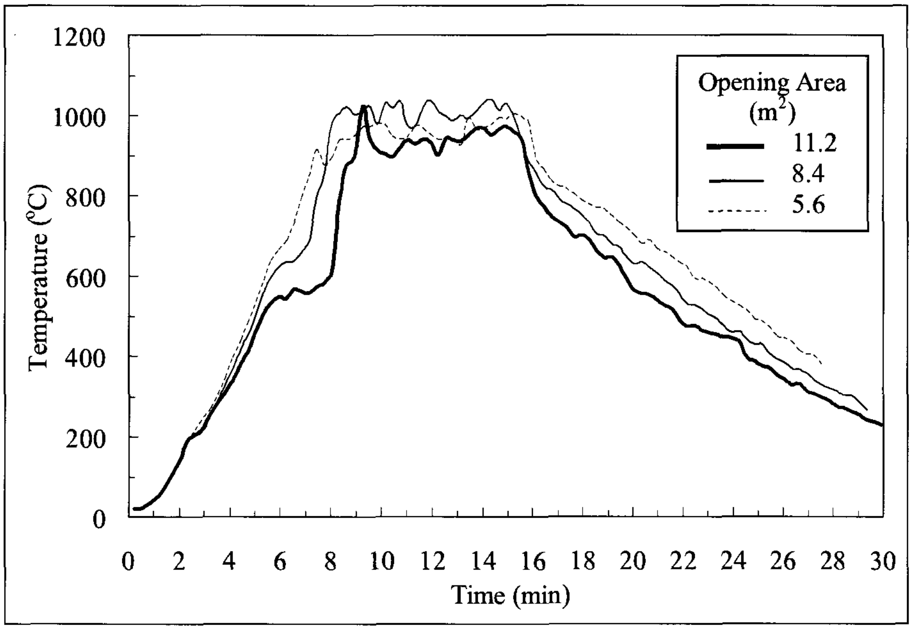


Figure 5-5: Upper layer temperatures for living room fires in a 260-m^2 detached home

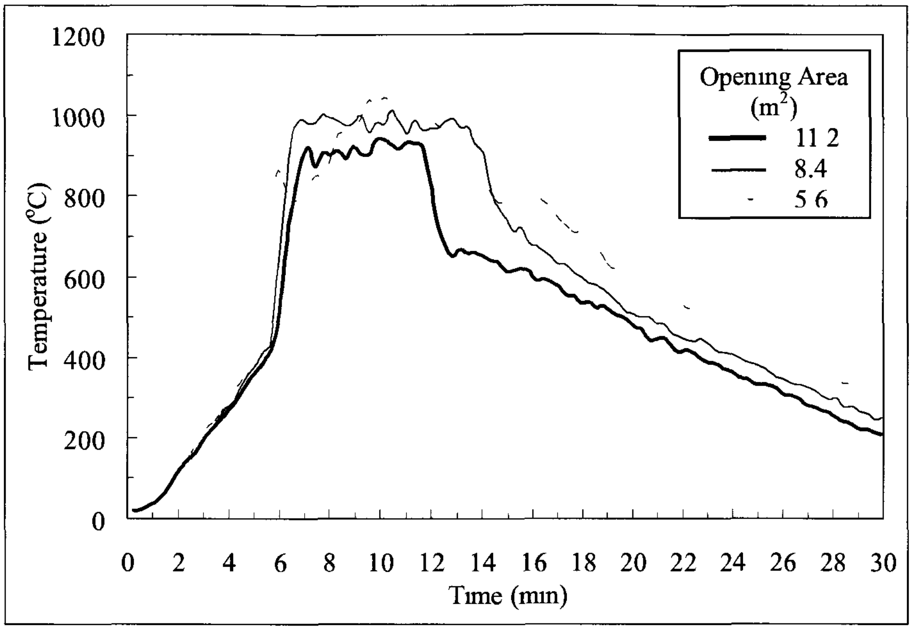


Figure 5-6: Upper layer temperatures for living room fires in a 223-m^2 detached home

It is apparent from the Figure 5-5 for a 260-m^2 house, that when the total opening area increases, the upper layer temperatures are generally lower. It is also evident that once upper layer temperatures reach the flashover point, 600°C, they continue to increase rapidly due to the spread of fire to other items. Peak temperatures for the two smaller houses were relatively similar at just under 1000°C for all the opening areas. Peak temperatures in the 297-m^2 home were under 600°C.

As windows begin to break, they allow hot upper layer gases to leave the room, thus resulting in lower average upper layer temperatures. When gases leave the upper layer, more energy is required to increase the temperature of that layer. This is because essentially a greater volume of air needs to be heated; therefore it takes longer for the fire to increase temperatures in the upper layer. Larger windows also allow cool air to enter the room, which can become entrained into the upper layer, and thus further reducing temperatures. When smaller windows are present, less smoke is able to escape and therefore temperatures are higher in the upper layer. In this case the thicker upper layer radiates heat perpetuating higher temperatures. Table 5-3 lists the times at which windows break in other rooms throughout the 260-m^2 house with 11.2 m^2 of openings in the living room. There is clearly a significant increase in temperatures around 8.1 minutes when windows in both the dining room and formal living room break, associated with flashover occurring in the living room.

Table 5-3: Time of window breakage in other rooms in 260-m^2 home, 11.2 m^2 openings

Room	**Time (min)**
Dining Room	8.2
Den	-
Formal Living Room	8.2
Loft (2nd floor)	14.0

Similar trends are observed in the lower layer temperatures, as seen in Figure 5-7, Figure 5-8, and Figure 5-9, which show higher temperatures when fewer openings are present. Lower layer temperatures were averaged at the same two locations as were the upper layer temperatures. The 11.2-m^2 opening always resulted in the lowest temperatures between 100-400°C. The other two opening areas resulted in similar temperatures, with peaks between 400 and 700°C. When windows break, cool fresh air from outside is drawn in by the fire to fuel combustion. The larger windows allow more cool fresh air to enter the lower layer; thus reducing the average lower layer temperature.

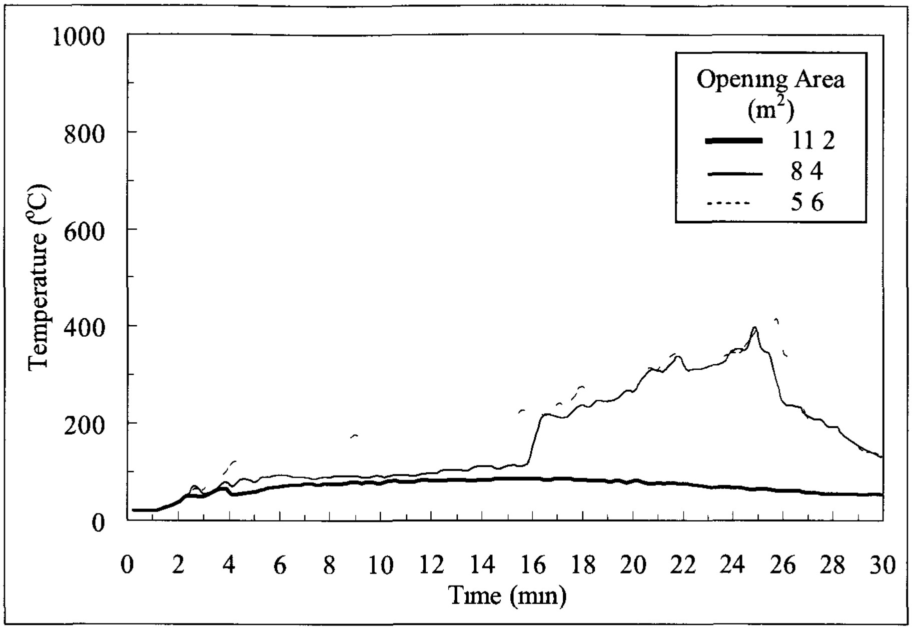


Figure 5-7: Lower layer temperatures for lıving room fires ın a 297-m² detached home

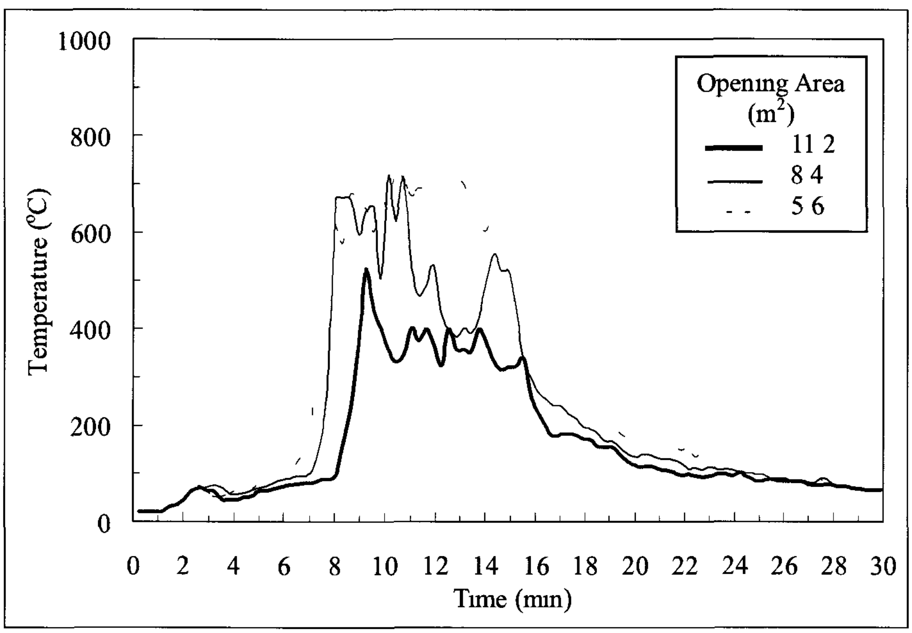


Figure 5-8: Lower layer temperatures for lıving room fires in a 260-m² detached home

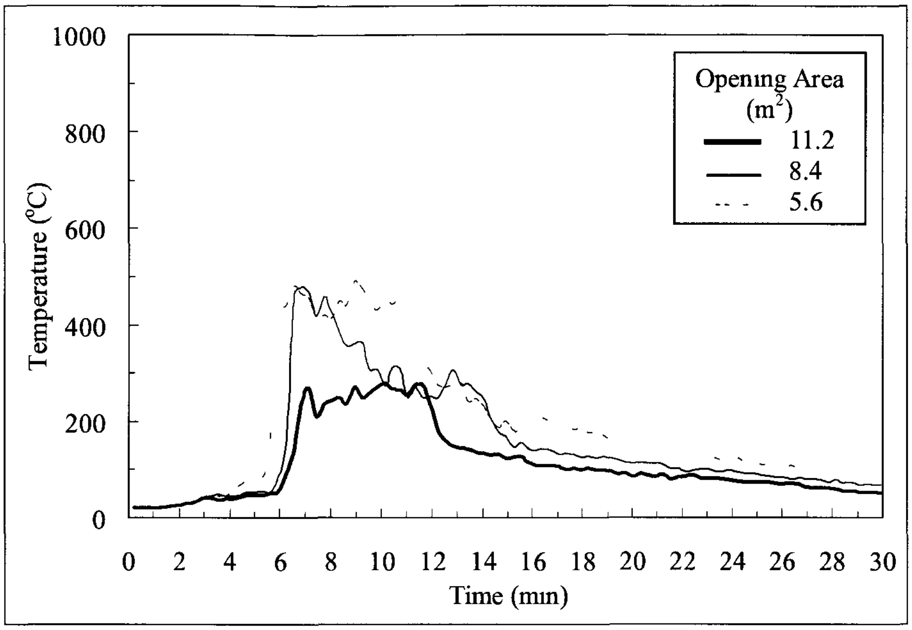


Figure 5-9: Lower layer temperatures for living room fires in a 223-m^2 detached home

5.1.1.3 Flashover

Flashover occurs once upper layer temperatures reach between 500-600°C. These temperatures were clearly surpassed in the living room fires as discussed in Section 5.1.1.2 , except for the 297-m^2 home. The results for both upper layer temperature and heat flux criteria for the time to reach flashover in the detached house are summarized in Table 5-4. Comparing results obtained from FDS, it is clear that determining flashover using 600°C gives similar results to when heat flux criteria of 20 kW/m^2 are used, especially for the smallest house. Heat flux was measured 1 m from the floor at the same two locations as the upper layer temperatures.

Table 5-4: Times of flashover in the room of fire origin

	Time to flashover (s)					
Total Floor Area (m^2)	**11.2 (m^2)**		**8.4 (m^2)**		**5.6 (m^2)**	
	Heat Flux	**upper layer**	**Heat Flux**	**upper layer**	**Heat Flux**	**upper layer**
297	-	-	955	1292	595	-
260	534	461	423	322	397	317
223	374	360	356	347	327	322

To further confirm the time at which flashover occurred, temperature slice profiles of the room were examined to assess the time to flashover; these results are listed in Table 5-5. Figure 5-10 demonstrates how this technique was applied to the 223-m^2 house. Clearly at 320 s, the 600°C isotherm stretches across the room, thus igniting the combustible items (Figure 5-10). If you compare Table 5-4 and Table 5-5 it is evident that the slice profile technique provides similar values to averaging the heat fluxes at two locations.

Table 5-5: Times of flashover in the room of fire origin using temperature slices

	Time to flashover (s)		
Total Floor Area (m^2)	**11.2 m^2**	**8.4 m^2**	**5.6 m^2**
297	-	950	594
260	475	420	370
223	345	340	320

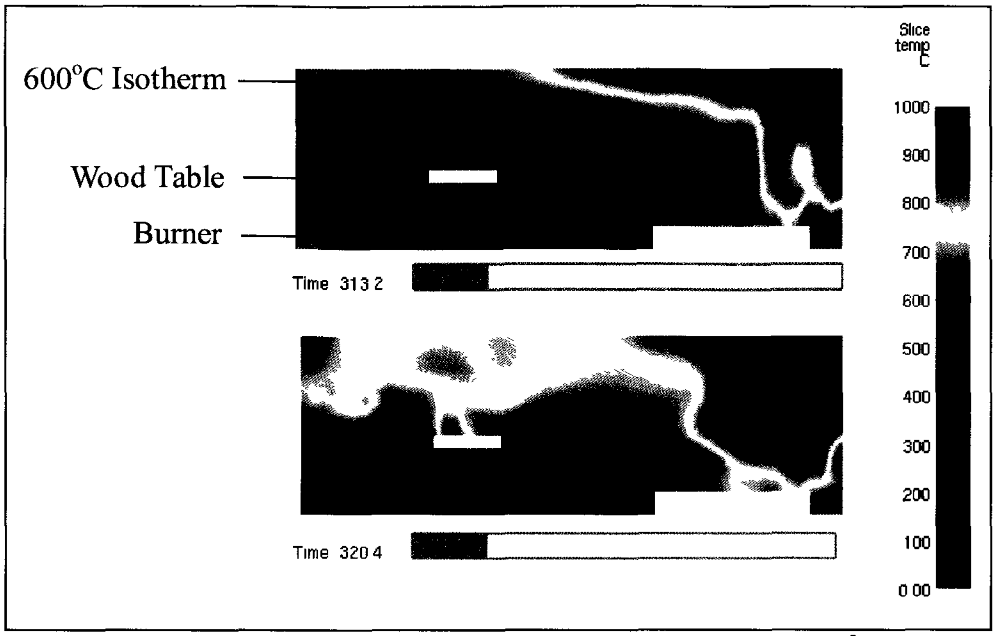


Figure 5-10: Temperature profiles for a living room fire in a 223-m^2 house with 5.6-m^2openings

Since flashover is closely linked to upper layer temperatures, the same trend is seen between the two with respect to increasing opening area and delaying growth. Larger openings allow more cool fresh air to enter the room and more hot smoke to leave the room resulting in lower temperatures in the upper layer, which can prolong the time to flashover. More openings allow hot smoke to leave the upper layer, it means less heat is being radiated by the smoke to room contents; therefore prolonging the time to flashover. This indicates that flashover trends are more closely associated with upper layer temperatures, despite larger window openings providing higher HRRs.

5.1.1.4 Device Activation

Ensuring occupants are notified of a fire by an alarm can provide valuable time needed for escape by alerting occupants of danger, which should occur prior to a fire reaching flashover. One aspect of this research is to determine how both ventilation and floor size impact the activation of fire safety devices. In all cases device activation began with the smoke alarm which activated at 27 s, followed by the heat detector which activated at 106 s, and finally sprinklers at 117 s, Table 5-6. There is no impact on the activation times of these devices when the amount of opening area is altered since the devices are triggered early in the fire before any windows have broken; the first window broke at 120 s (2 min).

Table 5-6: Device activation times for a detached home living room fire

Total Floor Area (m^2)	Activation Time (s)		
	Smoke	Heat	Sprinkler
297	27	108	119
260	27	106	117
223	27	104	112

5.1.1.5 Tenability and Smoke Movement

Smoke detectors are designed to trigger long before harmful situations are produced. Unfortunately not every house is equipped with working smoke detectors and as a result occupants may face untenable conditions (stemming from a lack of O_2, an excess of CO_2 and CO, or a combination of the three) when trying to evacuate. When assessing O_2, CO_2, CO, and FED in the living room simulations, decreasing the opening area resulted in an accumulation of harmful gases at critical heights, thereby decreasing the time to reach dangerous levels, as illustrated in Table 5-7. Toxicity is closely linked to smoke accumulation and larger windows allow more smoke to escape and cool fresh breathable air to enter the room, reducing toxicity levels and increasing the distance a person can see.

Table 5-7: Times tenability criteria are exceeded for living room fires in detached homes

Opening Area	Location	Time tenability criteria are exceeded (s)								
		A*			B*			C*		
	Floor area (m^2)	297	260	223	297	260	223	297	260	223
11.2 m^2	Toxicity	302	280	351	401	463	353	445	493	369
	Thermal	133	124	153	643	481	382	-	508	349
	Visibility	58	56	61	85	88	119	115	126	115
8.4 m^2	Toxicity	270	288	331	333	351	335	385	407	356
	Thermal	133	124	166	349	383	363	960	463	340
	Visibility	58	56	61	85	88	119	115	126	115
5.6 m^2	Toxicity	254	257	277	290	329	304	351	373	328
	Thermal	133	124	160	284	338	335	240	432	288
	Visibility	58	56	60	85	88	122	115	126	115

*A: inside the room of fire origin, B: at the base of the stairs, C: at the top of the stairs

In the room of fire origin, CO_2, CO, and FED concentrations reduced (while the concentration of O_2 increased) when more openings were added as shown in Figure 5-11, Figure 5-12, Figure 5-13, and Figure 5-14. These values are averaged over the same two locations where temperatures and heat fluxes were measured, and the complete series of tenability graphs can be found in Appendix G. This trend was continuous for Location 'B' and 'C' (at the bottom and top of the stairs respectively). Tenability criteria for gas concentrations were almost always reached first due to an excess of CO_2 at all locations; a depletion of O_2 was commonly the second criteria exceeded followed by CO. The only instance this was not true was in the smallest house at Location 'B,' where CO was the first criteria to exceed its limits by 30 s.

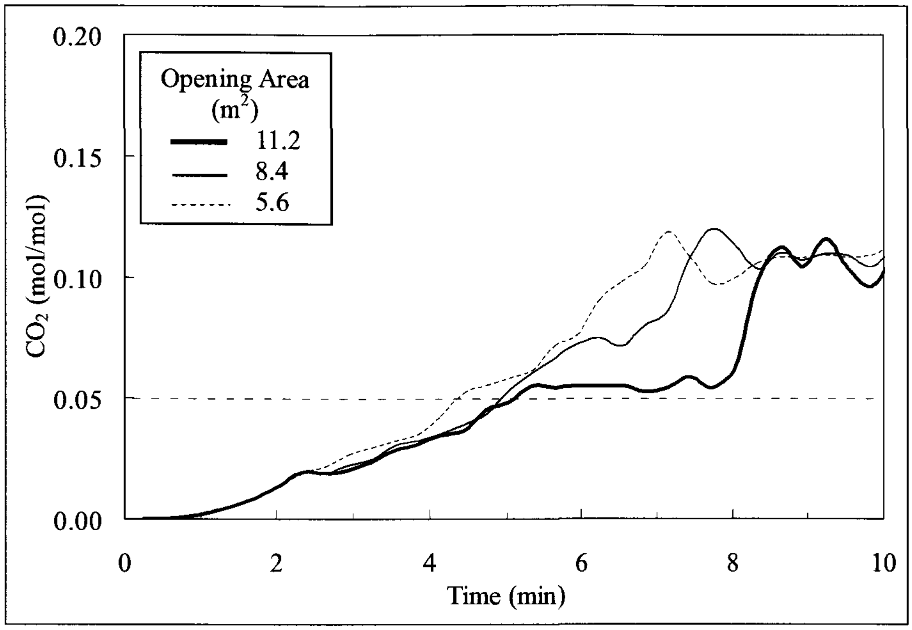


Figure 5-11: CO_2 concentration for a living room fire in a 260-m^2 detached home

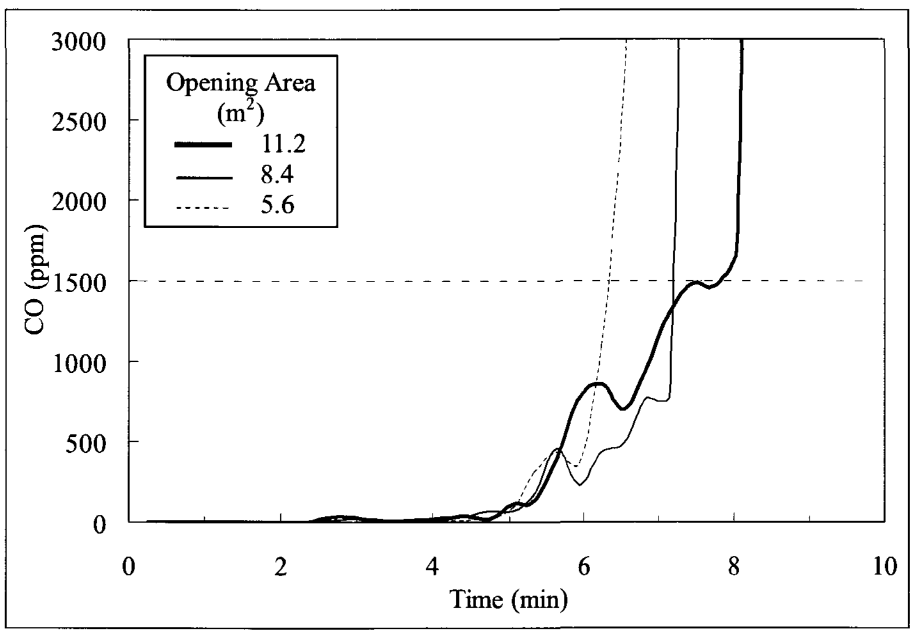


Figure 5-12: CO concentration for a living room fire in a 260-m^2 detached home

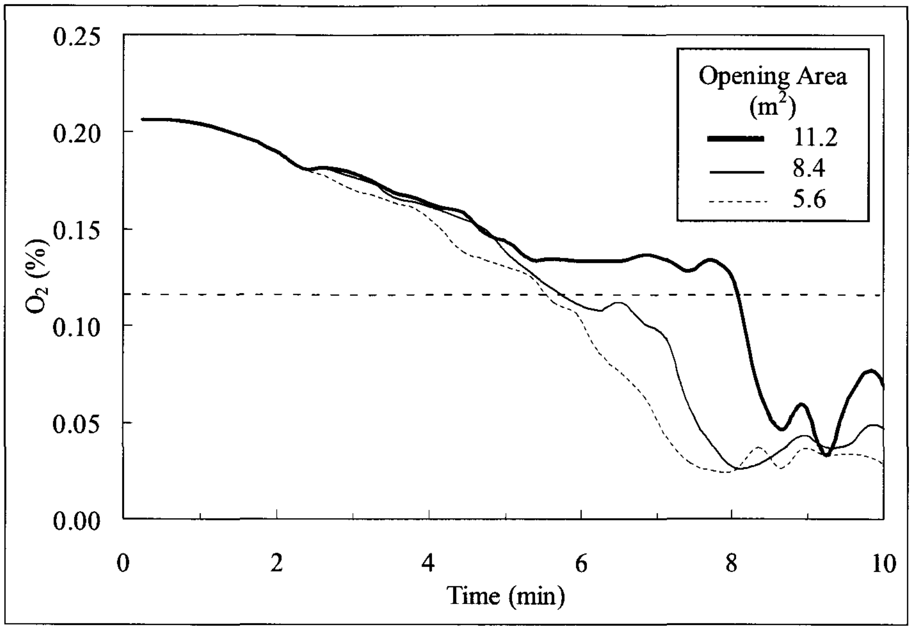


Figure 5-13: O_2 concentration for a living room fire in a 260-m^2 detached home

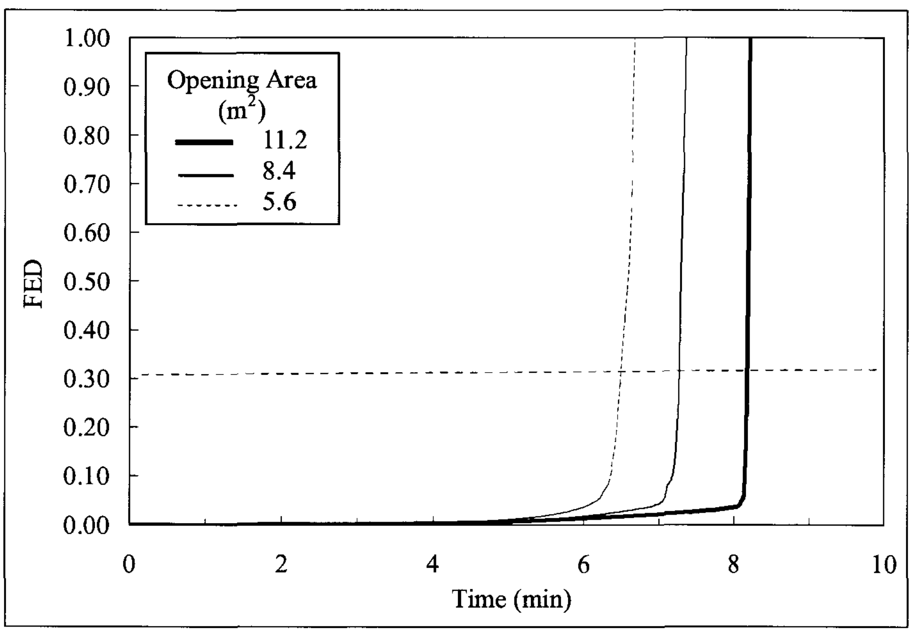


Figure 5-14: FED value for a living room fire in a 260-m^2 detached home

Thermal tenability was assessed using both lower layer temperatures and heat fluxes at 1.5 m from the floor (lower layer temperatures of 121°C or a radiative heat flux of 2.5 kW/m^2 were the criteria chosen to assess painful exposure). The heat flux criterion was generally reached first, except at Location ‘C’ (upstairs) where the lower layer reached harmful temperatures more quickly since there is no exposure to heat fluxes directly from the fire. At Location 'A' opening area had no affect on thermal criteria. At Location 'B' there was a significant drop in time to painful conditions when opening area was decreased, with the largest difference at 6 minutes in the 297-m^2 house. The same trend was apparent at Location 'C' but on a lesser scale; the largest difference was 1.3 minutes. The times to painful thermal exposure increased with increasing opening area. When cool fresh air from outside enters through the large windows, temperatures in the lower layer are reduced. Temperatures in the upper layer are also reduced due to mixing with the lower layer and heat venting.

Visibility was reduced below 2 m at Location 'A' around 60 s for all floor areas and opening areas, as illustrated in Figure 5-15. This time is consistent for all cases since no windows were broken and no other combustibles had caught on fire by this point in the simulation. Increasing the opening area had little effect on visibility at Location 'B', ranging from 85 to 120 s depending on the geometry of the house. The 223-m^2 house has the base of the stairs at the front of the house, whereas the other two geometries have the base of the stairs at the centre of the house, therefore the smoke has a longer distance to travel and took longer to meet the criteria. The time to reach this criterion at Location 'C' also displayed no variability, dropping to 2 m at approximately 120 s. The 260-m^2 house had a 10 s later time, likely related to geometry effects.

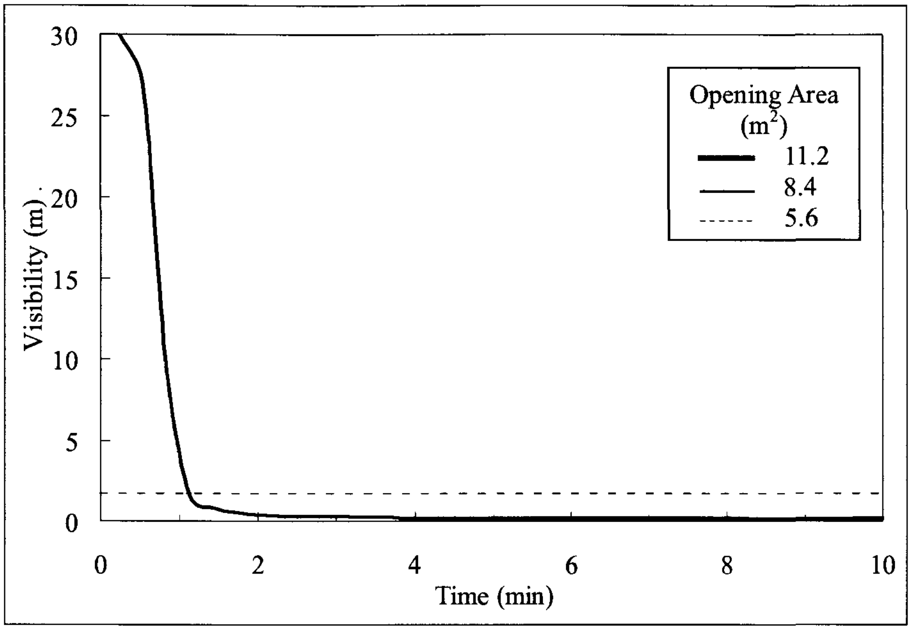
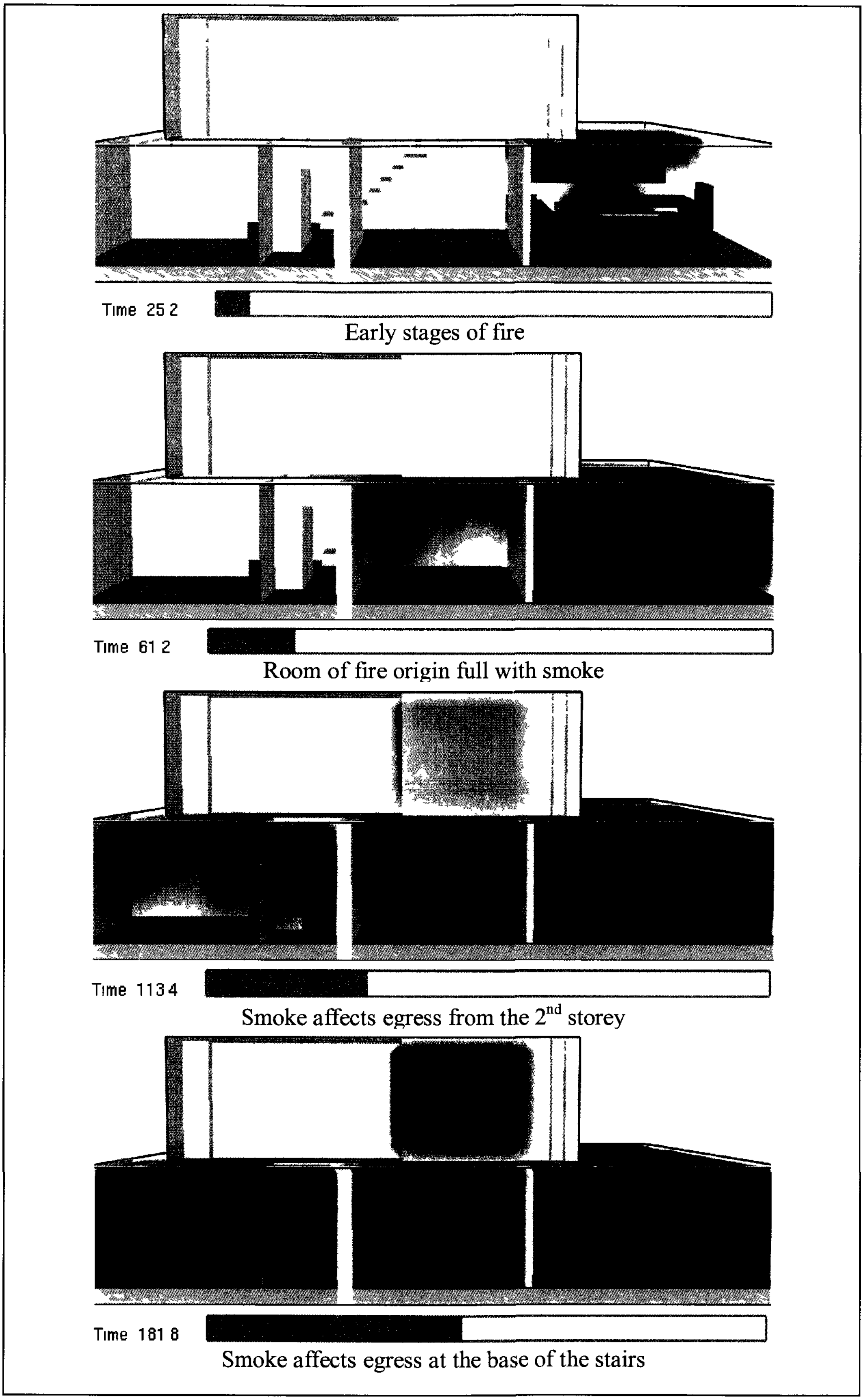


Figure 5-15: Visibility at Location 'A' for living room fires in a 297m² detached home

Location 'C,' at the top of the stairs, can be used to determine the feasibility of occupant egress from the second storey and how smoke moves throughout the home. Visibility was always the first tenability criterion exceeded (tenability is related to irritants causing harm to individuals, however in this study visibility is referred to as a tenability criteria when assessing the viability of occupant egress), this means that visibility dictates the available safe egress time (ASET). Figure 5-16 illustrates movement of smoke throughout the 223-m² house with 11.2 m² opening area, highlighting times which are indicated in Table 5-7. At 61 s the room of fire origin becomes filled with smoke. After 115 s smoke fills the upstairs, and by 180 s the entire house is completely filled with smoke.

In summary, larger openings resulted in a longer time before occupant evacuation was negatively impacted by either toxicity or thermal criteria; thus, implying that larger windows in the room of fire origin provided more time for occupants to escape safely. In terms of visibility, increasing opening area did not affect the ASET. Visibility criteria were always exceeded before any windows broke; therefore their size was not a factor.

A timeline of all major fire events for the 260-m^2 detached home with 11.2-m^2 openings is illustrated in Figure 5-17. The timeline shows the sequence in which all major fire events occur, and clearly demonstrates that device activation occurs early in the fire before an occupant would become incapacitated.



Early stages of fire

Room of fire origin full with smoke

Smoke affects egress from the 2nd storey

Smoke affects egress at the base of the stairs

Figure 5-16: Smoke movement of a living room fire in a 223-m^2 home with 11.2-m^2 openings

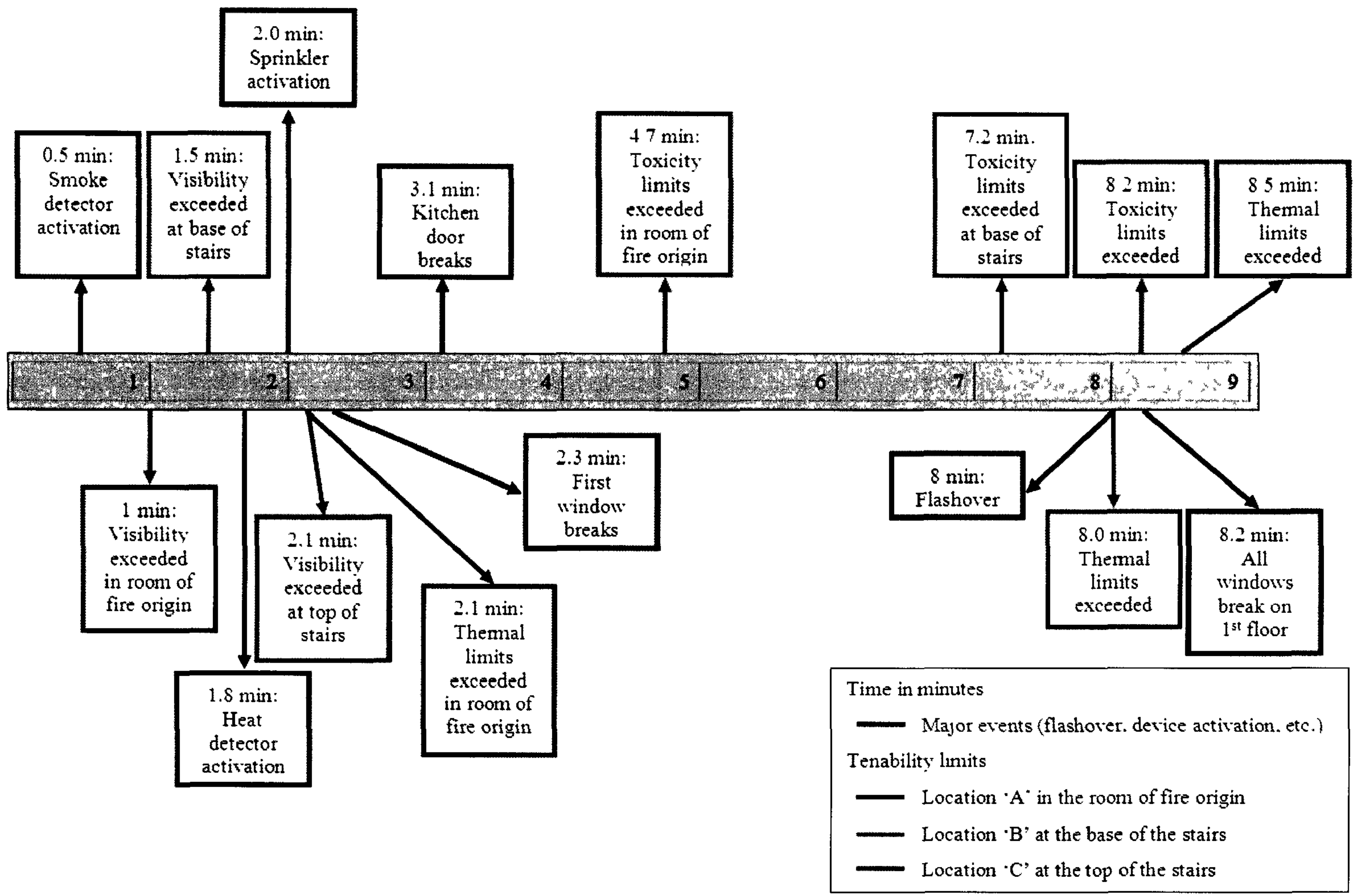


Figure 5-17: Timeline of major events for a 260-m^2 detached home with 11.2-m^2 openings

5.1.2 Townhomes

Townhomes are different from single-family detached homes in that they generally have a smaller total floor area (the sizes studied were 186, 167, and 149 m^2) and have similar dwelling units attached on either side, sharing exterior walls. Having units on either side of the home means that windows can only be located at the front and the back of the building (unless dealing with an end unit). This, paired with narrow unit dimensions, greatly limits the amount of total opening area in townhomes compared to detached houses. Opening areas investigated for living rooms were 6.5, 4.6, and 3.3 m^2.

The total area for the combined living room and dining room was significantly larger in the detached homes as opposed to the townhomes. This translates to a higher fuel load density in the townhomes with items located more closely together. As a consequence, the fire began to grow and spread more quickly to other items.

5.1.2.1 Heat Release Rate Histories

The heat release rates for all three townhomes are displayed in Figure 5-18, Figure 5-19, and Figure 5-20. From these plots, it is apparent that an increase in opening area results in higher HRRs for a fully-developed fire, since more oxygen is able to enter the room, promoting a stronger fire. This is consistent with the HRR trends observed for the detached homes.

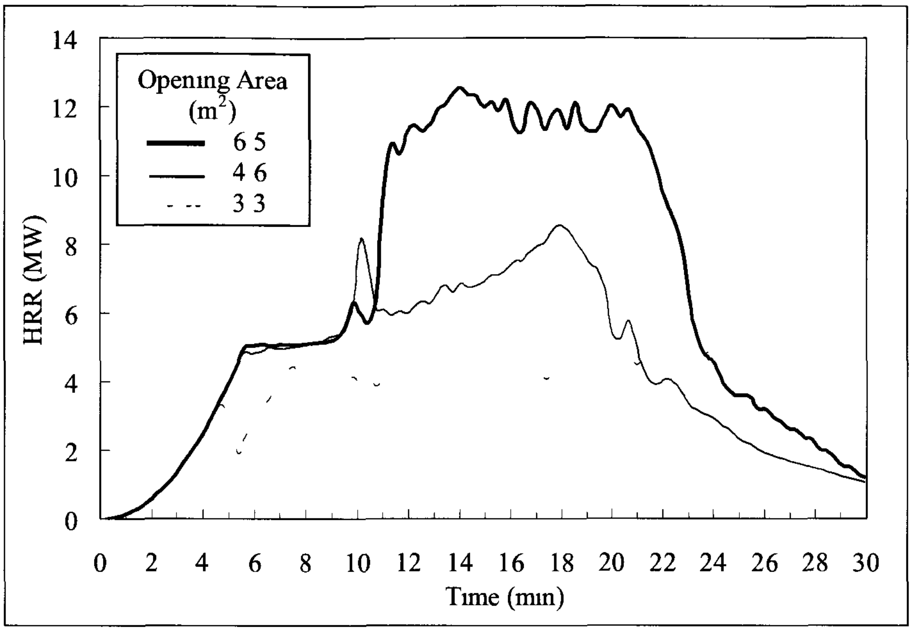


Figure 5-18: Heat release rates for living room fires in a 186-m^2 townhome

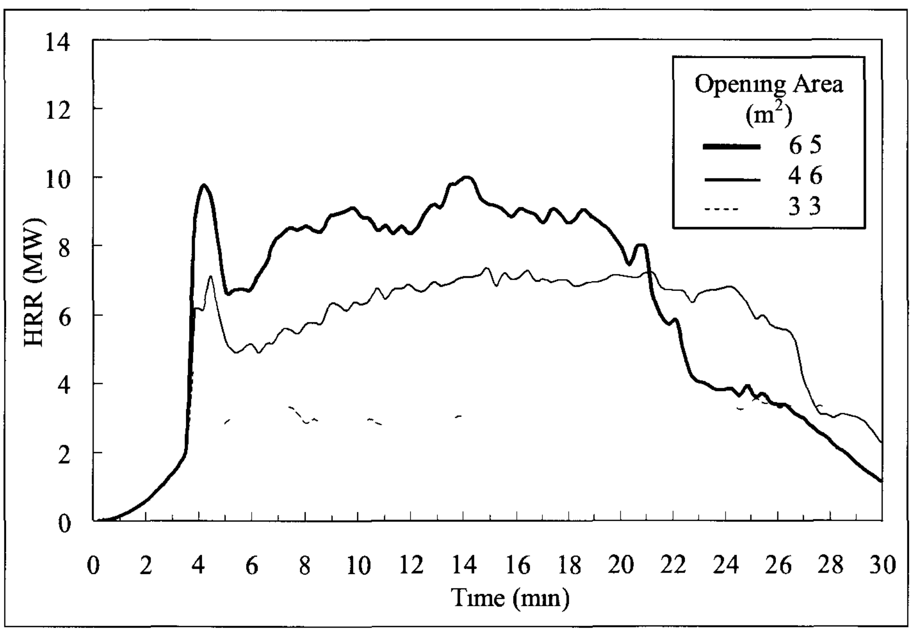


Figure 5-19: Heat release rates for living room fires in a 167-m^2 townhome

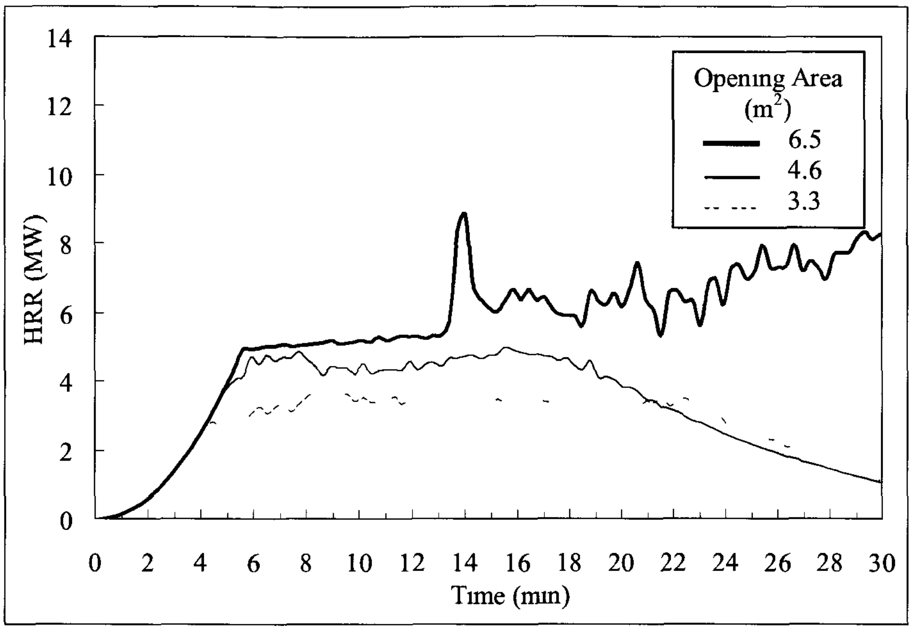


Figure 5-20: Heat release rates for living room fires in a 142-m^2 townhome

These heat release rates differ from those of the detached home fires in that the peaks are lower, and the effect of opening area has a more prominent impact (compare to Figure 5-1 to Figure 5-3). The time of the peak in the 167-m^2 house coincides with the glass kitchen doors breaking at approximately 3.8 minutes; in the townhomes the doors account for a minimum of 46% of the opening area in the living space. Times of window breakage are shown in Table 5-8. The doors broke earlier in the 186-m^2 simulations for 4.6 and 3.2-m^2 openings since the breakage temperature was set lower.

Table 5-8: Time of window breakage in townhomes

Opening Area	**6.5 m^2**		**4.6 m^2**		**3.3 m^2**	
Floor Area	**Window (min)**	**Door (min)**	**Window (min)**	**Door (min)**	**Window (min)**	**Door (min)**
186 m^2	2.2	4.3	2.2	3.5	2.2	3.5
167 m^2	2.0	3.6	2.2	3.6	2.2	3.6
149 m^2	2.2	3.5	2.2	3.4	2.2	3.5

The steady HRR level during the fully-developed fire can be an indication of a ventilation controlled fire, where the amount of oxygen is directly limiting how much heat a fire can generate. The limited ventilation results in the townhome fires exhibiting lower rates of heat over a longer period of time as compared to the detached home fires. The smaller opening areas produce fires with lower peak HRRs, but can sustain the fire for longer periods of time.

In the 186-m^2 home the two smaller opening areas did not promote fire growth; in both cases the HRR did not exceed 1 MW. Because of this small fire the glass kitchen door did not break (due to the geometry of this house the distance between the door and the burner is greater in this home than in the two other townhomes). To ensure that the fire continued to grow, the glass breakage temperature for the door thermocouple was reduced to 200°C for these two simulations.

The 3.3 m^2 opening area clearly limits the HRR to less than 4 MW for all of the townhomes. This value is less than the specified HRR of the burner, so fire growth is being restricted by its ventilation.

5.1.2.2 Temperatures

Upper layer temperatures began to increase more quickly in the townhomes than was observed in the detached homes. This is probably related to the smaller window and room sizes in the townhomes. In all three townhome floor areas that were examined there was little or no effect of opening area on the initial growth of the fire, up to 3.6 minutes (when doors break), as is seen in Figure 5-21, Figure 5-22, and Figure 5-23, which illustrate the upper layer temperatures for the townhomes.

Following the initial growth phase the temperatures reached a peak at a range of 650-900°C. When the patio door breaks, it allows hot smoke venting but also allows a lot of cool fresh air to enter the room.

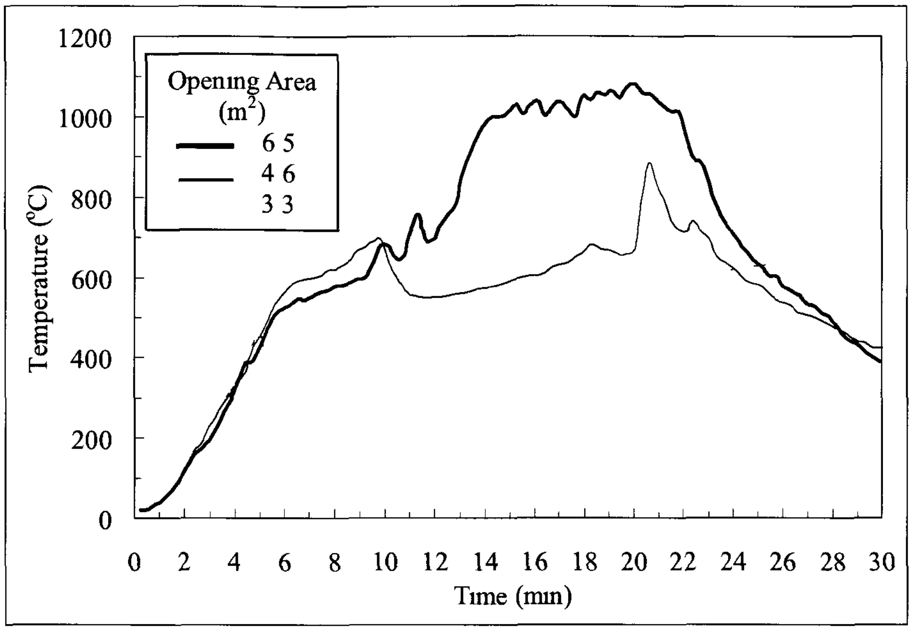


Figure 5-21. Upper layer temperatures for living room fires in a 186-m² townhome

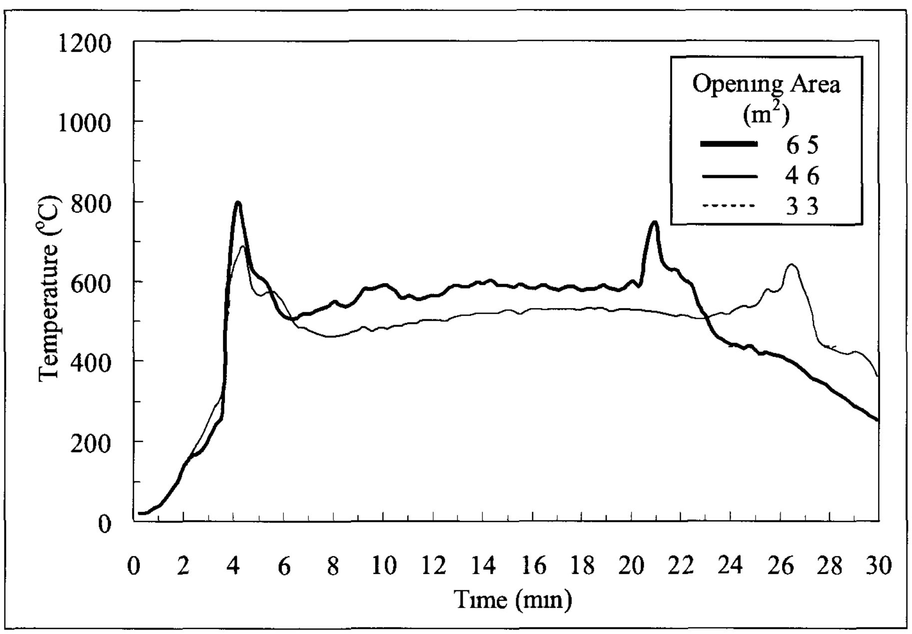


Figure 5-22· Upper layer temperatures for living room fires in a 167-m² townhome

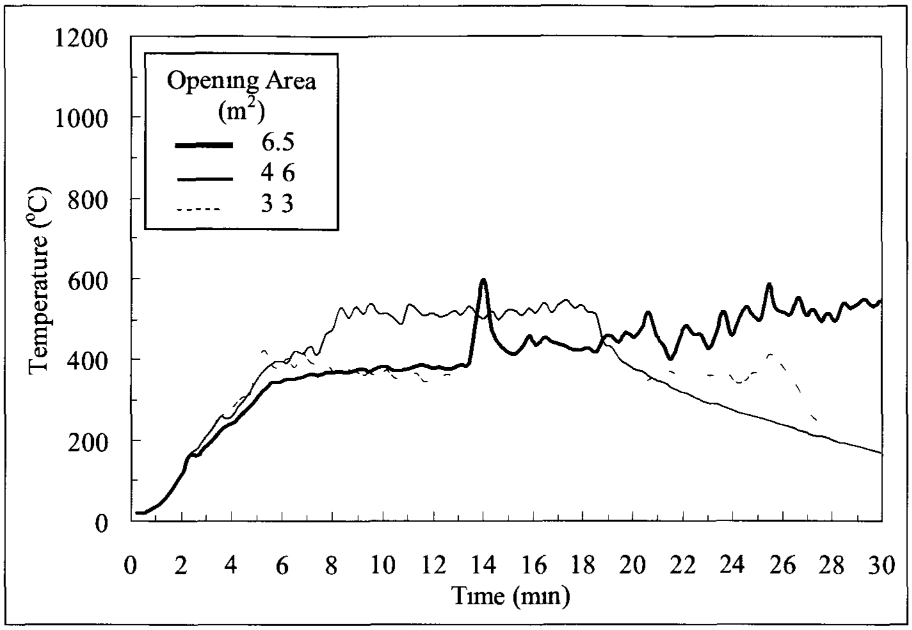


Figure 5-23: Upper layer temperatures for living room fires in a 149-m^2 townhome

The largest opening area results in the highest temperatures, while the smallest opening area results in the lowest. This is because the smaller windows limit the amount of oxygen entering and hot gas leaving the room. This is the opposite of what was observed in the detached homes.

The 3.3-m^2 opening area results in a heavily ventilation controlled fire, meaning that the fire does not continue to grow due to a lack of oxygen. The fire stays concentrated by the broken windows and doors since not enough oxygen is reaching the centre of the home where most of the furniture is located.

Lower layer temperatures followed the same trend as the upper layer temperatures, with larger openings resulting in larger fires (Figure 5-24, Figure 5-25, and Figure 5-26). Larger opening areas allow more fresh air to enter the room, reducing temperatures in the lower layer.

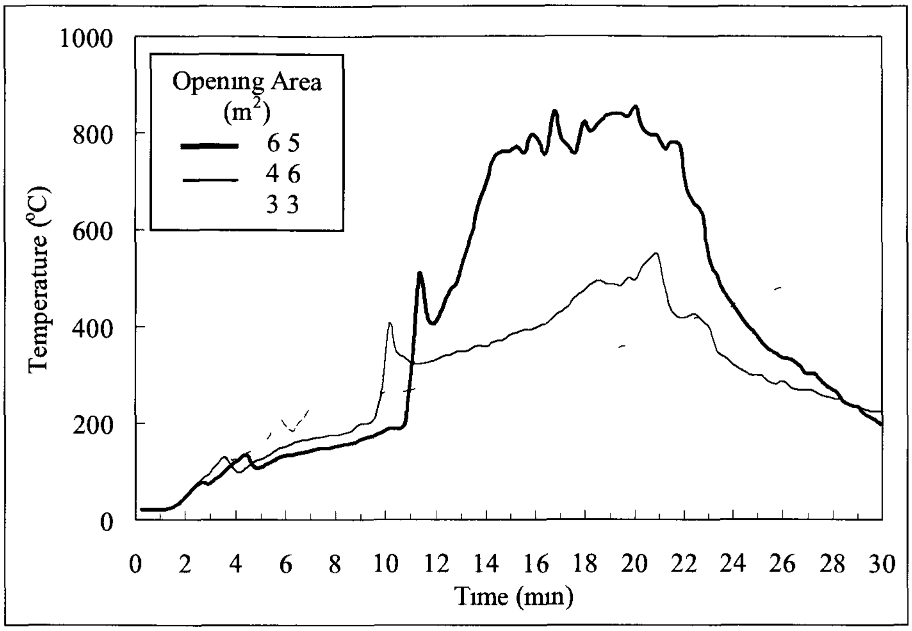


Figure 5-24: Lower layer temperatures for living room fires in a 186-m^2 townhome

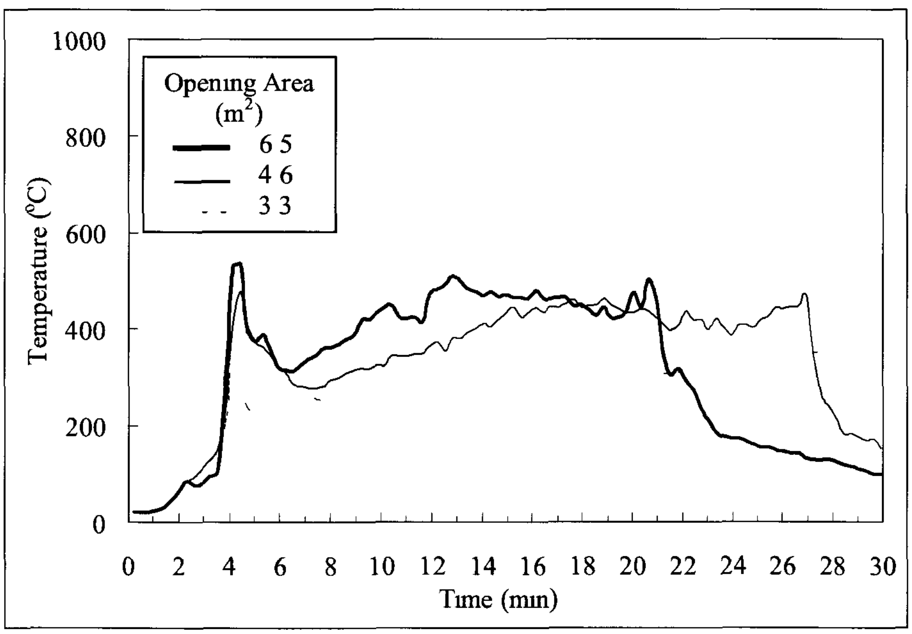


Figure 5-25: Lower layer temperatures for living room fires in a 167-m^2 townhome

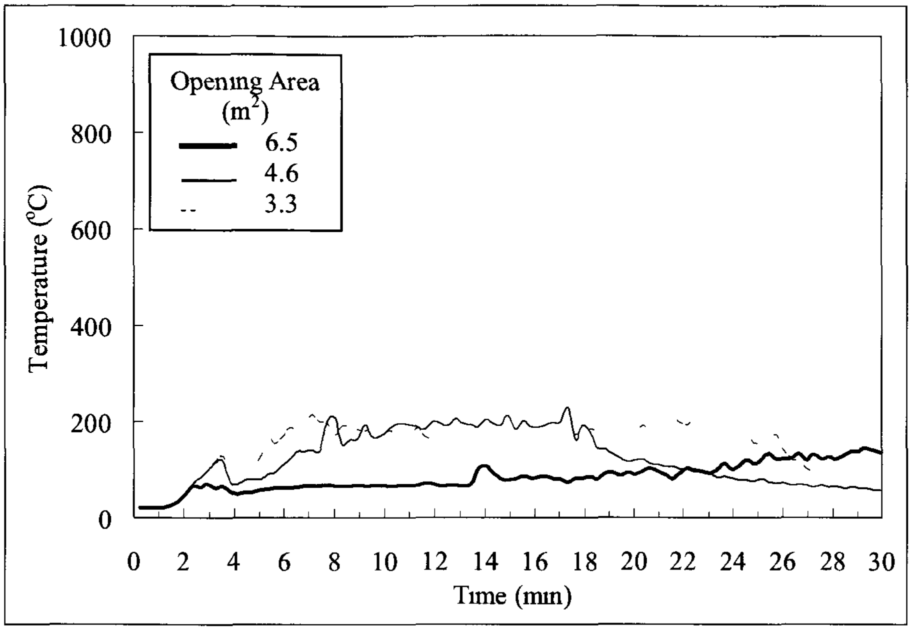


Figure 5-26: Lower layer temperatures for living room fires in a 149-m^2 townhome

5.1.2.3 Flashover

Since the room temperatures increase very quickly and are not impacted by the opening area during the growth stage, the time to flashover was consistent (within 15 seconds for both heat flux and upper layer temperatures) for each floor area regardless of ventilation conditions. The times to flashover are detailed below in Table 5-9.

Table 5-9: Times when flashover criteria were exceeded for townhome living room fires

	Time to flashover (s)					
Total Floor Area (m^2)	**6.5 (m^2)**		**4.6 (m^2)**		**3.3 (m^2)**	
	Heat Flux	**upper layer**	**Heat Flux**	**upper layer**	**Heat Flux**	**upper layer**
186	311	554	572	410	835	1360
167	223	230	228	248	-	-
149	833	824	-	-	-	-

5.1.2.4 Device Activation

Neither opening area nor total floor area impacted the time to alarm activation, since all were triggered before any windows broke (first began to break at 120 s). Smoke detectors in the living room were triggered at 27 s, heat detectors at approximately 104 s and sprinklers at 113 s. These times are very similar to those observed in the detached homes, Table 5-6. Any slight discrepancies are attributed more to geometry effects than anything else.

Table 5-10: Device activation times for living room fires in a townhome

Total Floor Area (m^2)	Activation Time (s)		
	Smoke	Heat	Sprinkler
186	27	104	113
167	27	103	113
149	29	104	106

5.1.2.5 Tenability and Smoke Movement

Tenability criteria were generally reached more quickly in the townhomes than in the single-family detached homes. This was partially due to smaller rooms sizes, which promote faster fire growth and allow the hot upper layer to descend more rapidly, therefore impacting occupants more quickly. The townhomes' smaller opening areas also limited the amount of smoke venting, keeping smoke inside the home and increasing the concentrations of toxic gases.

From Table 5-11 it can be seen that the time to dangerous concentrations followed the same pattern as the time to painful thermal conditions, where no difference was observed between the effects of the 3.3 and 4.6-m^2 opening areas. In comparison, the 6.5-m^2 opening area provided more time before injury occurred. For Location 'A' the largest opening area (compared to the smallest) allowed about 10 extra seconds before untenable conditions were reached; whereas, Location 'B' provided 30 s. Values at Location 'C' were similar for all opening areas. In all cases, the critical gas concentration is CO_2, followed by O_2 and CO.

Diminished visibility conditions were not affected by opening area, as was the case in the detached homes.

Table 5-11: Times at which tenability criteria for living room fires in a townhome

		Time tenability criteria were exceeded (s)								
Opening Area	**Location**	**A***			**B***			**C***		
	Floor area (m^2)	**186**	**167**	**149**	**186**	**167**	**149**	**186**	**167**	**149**
6.5 m^2	**Toxicity**	236	217	295	236	216	261	292	223	288
	Thermal	137	144	165	189	191	182	288	223	171
	Visibility	54	51	61	68	67	70	97	103	83
4.6 m^2	**Toxicity**	211	198	209	216	211	200	286	225	252
	Thermal	140	137	158	173	162	169	275	225	173
	Visibility	54	50	61	68	67	70	97	103	83
3.3 m^2	**Toxicity**	210	198	209	223	211	200	265	227	239
	Thermal	140	137	158	173	162	169	290	227	173
	Visibility	54	51	61	68	67	70	97	103	83

*A: inside the room of fire origin, B: in the hallway, C: at the top of the stairs

5.2 Bedroom Fires

5.2.1 Detached Homes

5.2.1.1 Heat Release Rate Histories

Heat release rates for bedroom fires in single-family detached homes are shown in Figure 5-27, Figure 5-28, and Figure 5-29. Each figure represents a different total floor area: 297, 260, and 223 m^2.

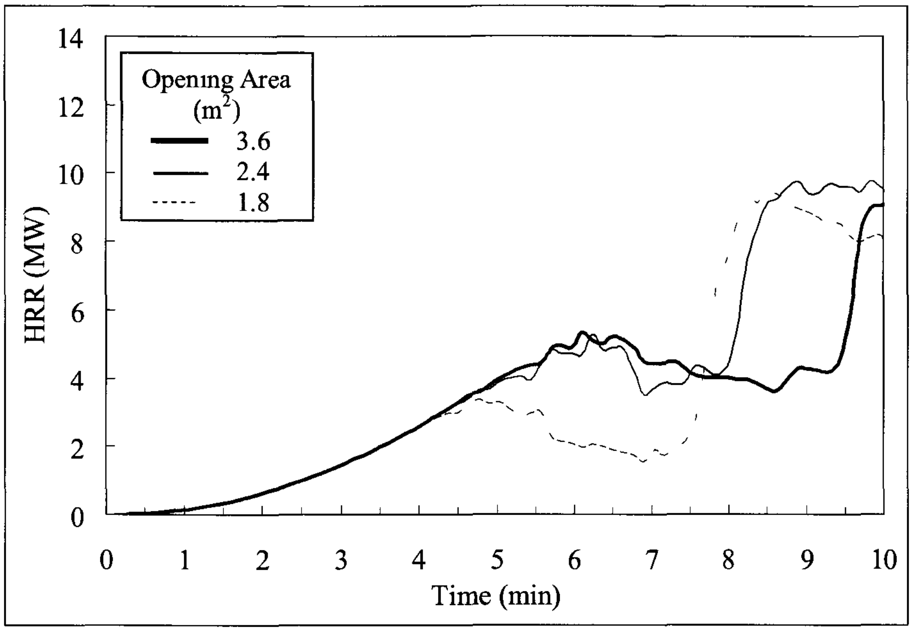


Figure 5-27: Heat release rates for a bedroom fire in a 297-m^2 detached home

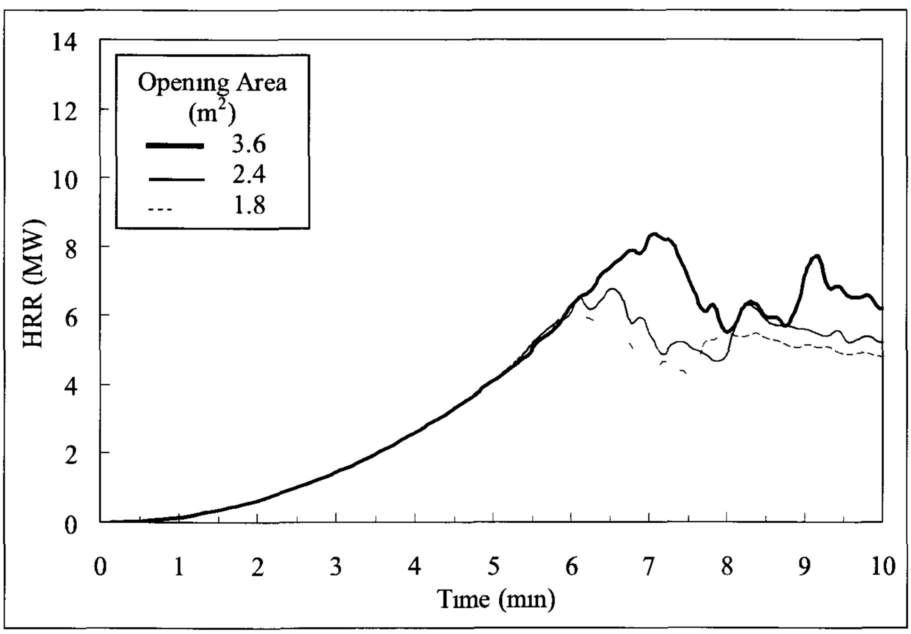


Figure 5-28: Heat release rates for a bedroom fire in a 260-m^2 detached home

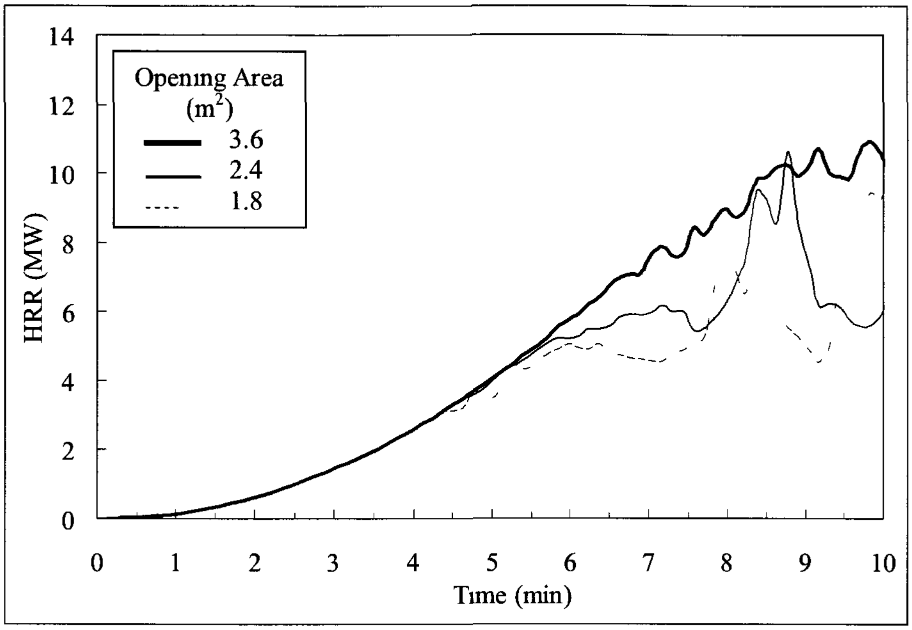


Figure 5-29: Heat release rates for a bedroom fire in a 223-m^2 detached home

In all three graphs, the HRR curve follows the t-squared growth initially. The first window breaks in the master bedroom around 2 minutes in all detached house scenarios; the precise times of window breakage are listed in Table 5-12. Despite the windows breaking, the curves continue to grow to a peak; higher peaks are associated with larger opening areas as was observed in all other simulations.

Table 5-12: First window breakage for a bedroom fire in a detached home

	Window breakage (s)		
	Opening Area		
Total Floor Area	**3.6 m^2**	**2.4 m^2**	**1.8 m^2**
297 m^2	110	110	115
260 m^2	116	116	116
223 m^2	108	109	109

Table 5-13: Window breakage outside room of fire origin for a bedroom fire in a detached home

	Window breakage (s)		
	Opening Area		
Total Floor Area	**3.6 m^2**	**2.4 m^2**	**1.8 m^2**
297 m^2	512	419	413
260 m^2	460	450	434
223 m^2	308	280	272

The first peak HRR coincides with O_2 levels dropping to 5% in the bedroom. After this peak there is a slight decline when the fire moves towards the openings. This decline in HRR is followed by a second growth which begins once windows outside the master bedroom break, such as a loft or a hall window. Table 5-13 shows that larger openings result in longer time to window breakage outside the room of fire origin. The 223-m^2 HRRs don't follow the same behaviour as the 297 and 260-m^2 homes since windows break much earlier in the smaller house. Once the windows have broken the HRR is able to continue to rise.

In the master bedroom, opening size has no effect on the first windows breaking. Early window breakage has no impact on HRR, but it does have an effect on the upper and lower layer temperatures, discussed later in Section 5.2.1.2 . Breakage of windows in other rooms is affected by opening area in the room of fire origin, where a smaller opening area causes other windows to break sooner.

The geometry of each house is different, the master bedroom is not necessarily in the same location and windows are placed in different locations. Therefore the 2nd window breaking outside the master bedroom cannot be directly compared between different houses.

The jump in HRR at 9 minutes for the 3.6-m^2 openings in the 297-m^2 house is attributed to windows in the other bedrooms breaking at 8.5 minutes. This is illustrated in Figure 5-30, where at 330 s (5.5 minutes) flames can be observed extending outside of the bedroom (flashover). At 560 s (9 minutes) it can be seen that windows have broken throughout the top floor and the rooms are entirely engulfed in flames.

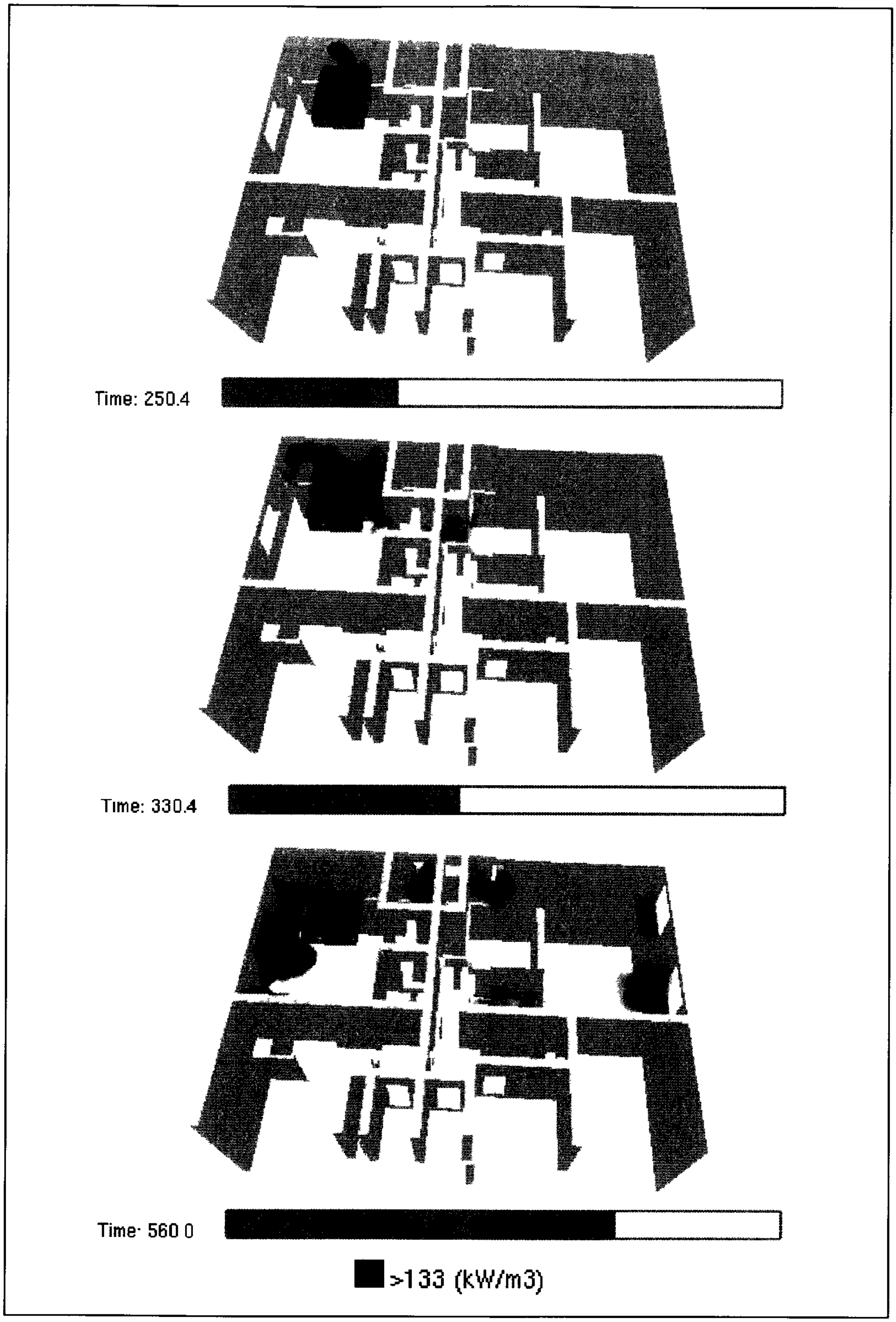


Figure 5-30: Fire movement for a bedroom fire in a 297-m^2 detached home with 3.6-m^{2}openings

5.2.1.2 Temperatures

The upper layer temperatures for a bedroom fire in each of the three detached family homes are displayed in Figure 5-31, Figure 5-32, and Figure 5-33. Larger openings in the room result in higher peak temperatures, which are linked to higher HRRs.

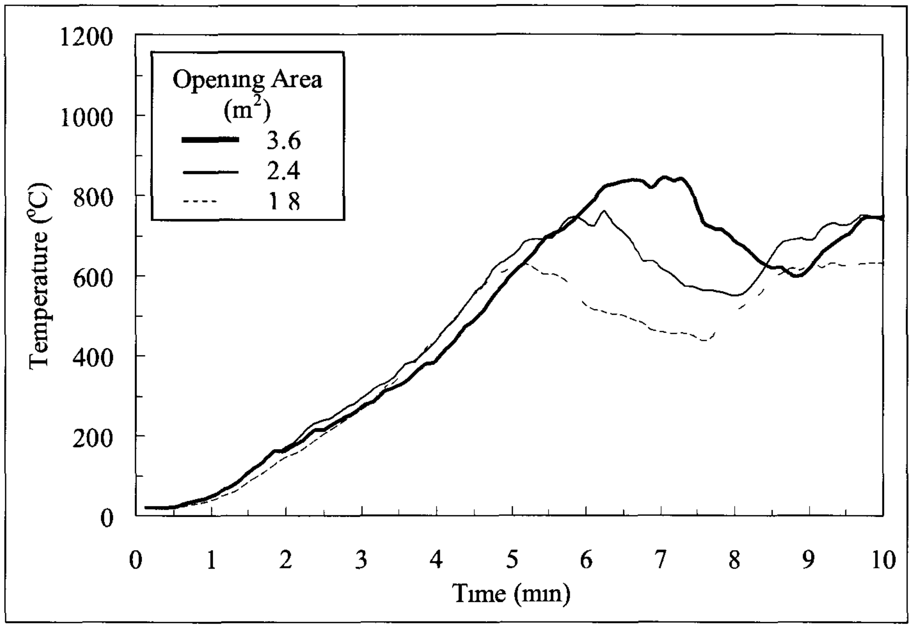


Figure 5-31: Upper layer temperatures for a bedroom fire in a 297-m^2 detached home

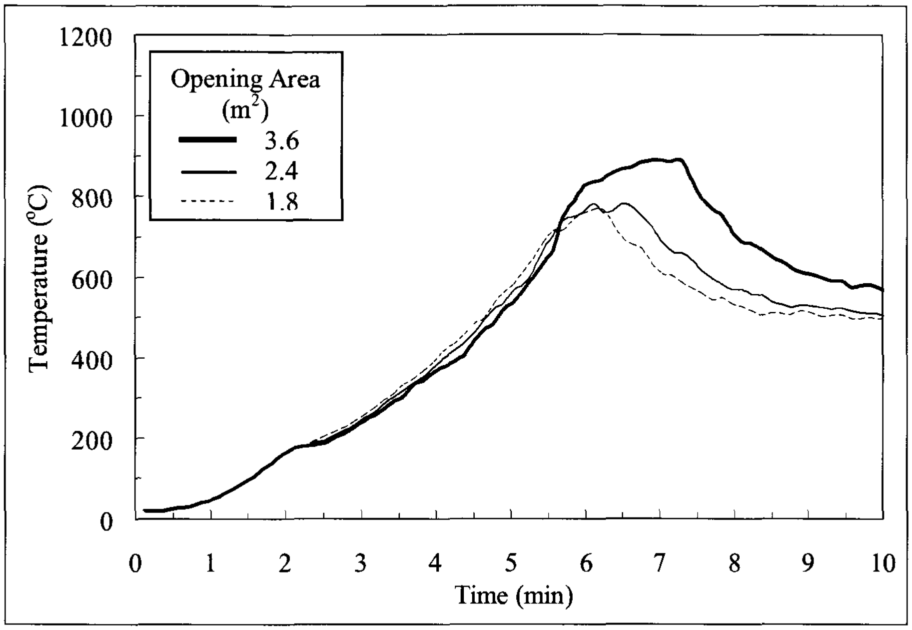


Figure 5-32: Upper layer temperatures for a bedroom fire in a 260-m^2 detached home

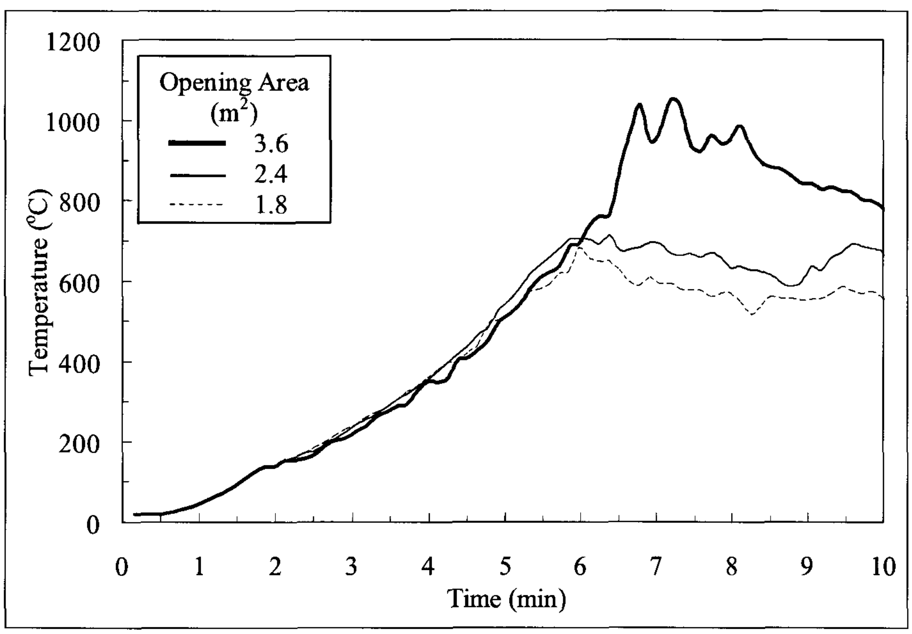


Figure 5-33: Upper layer temperatures for a bedroom fire in a 223-m^2 detached home

The lower layer temperatures gradually increased to a peak varying between 400-800°C at about 7 minutes into the fire, with the highest temperatures occurring in the smallest house. Larger openings are associated with higher temperatures, since more openings promote a stronger fire and hotter upper layer which radiates to the lower layer.

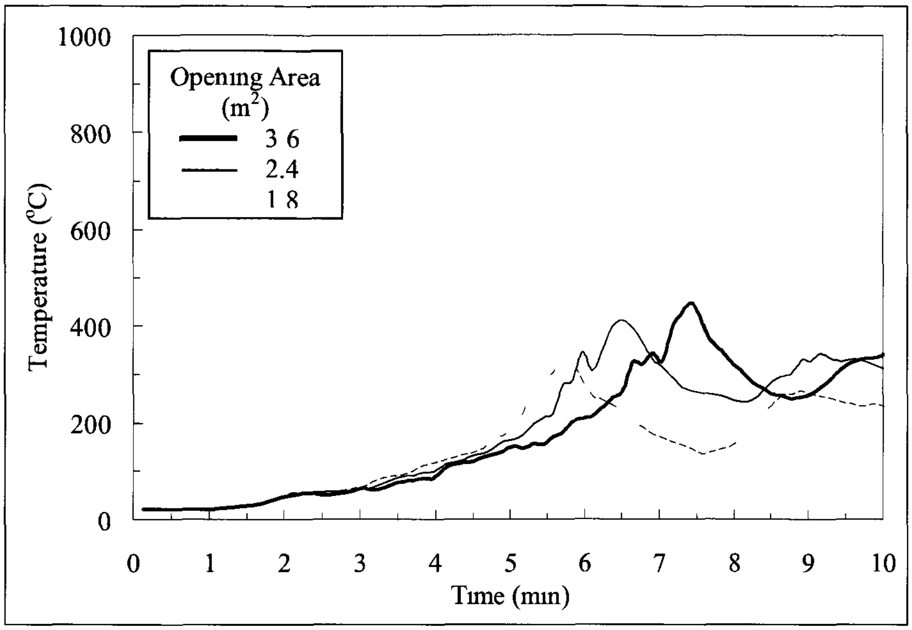


Figure 5-34: Lower layer temperatures for a bedroom fire in a 297-m² detached home

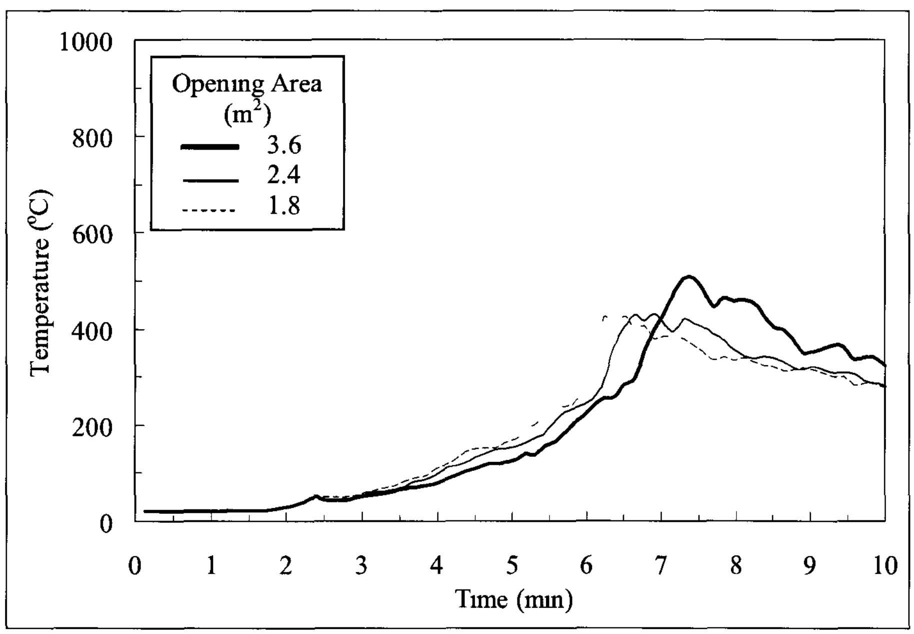


Figure 5-35: Lower layer temperatures for a bedroom fire in a 260-m² detached home

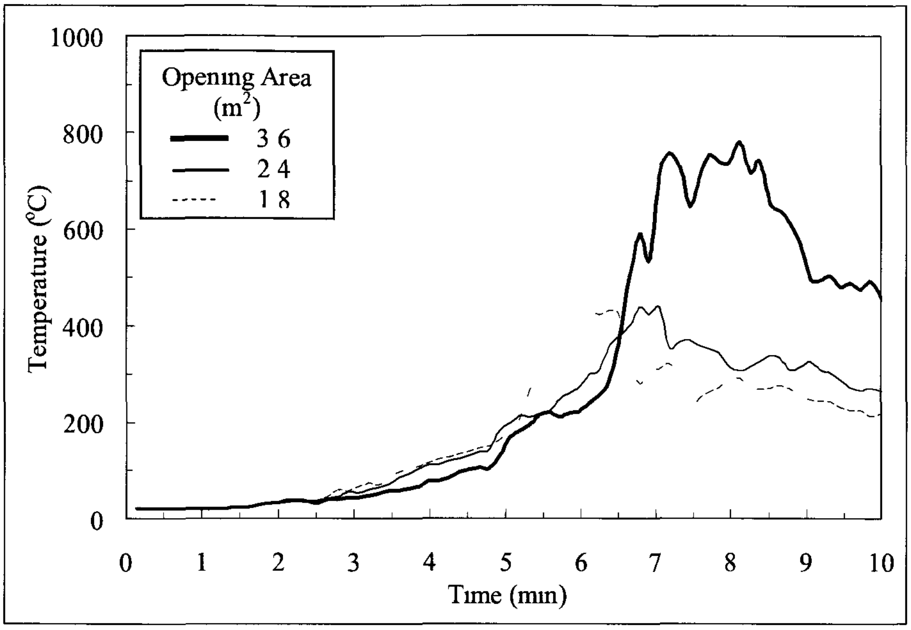


Figure 5-36: Lower layer temperatures for a bedroom fire in a 223-m^2 detached home

5.2.1.3 Flashover

Table 5-14 summarizes the time to flashover found using the slice profile and upper layer techniques. Using the slice profile method the time to flashover was found to decrease with reduced opening area. Figure 5-37 shows the upper layer descending once flashover occurs at 331 s. However, using the upper layer temperatures this trend is less prominent, flashover was determined to occur around 300 s in all simulations using this method.

Table 5-14: Times to flashover for a bedroom fire in a detached home

	Time to flashover (s)					
	Slice Profile			**Upper Layer**		
	Opening Area (m^2)					
Floor Area (m^2)	**3.6**	**2.4**	**1.8**	**3.6**	**2.4**	**1.8**
297	345	331	285	302	286	286
260	320	310	300	311	311	310
223	315	295	285	291	284	325

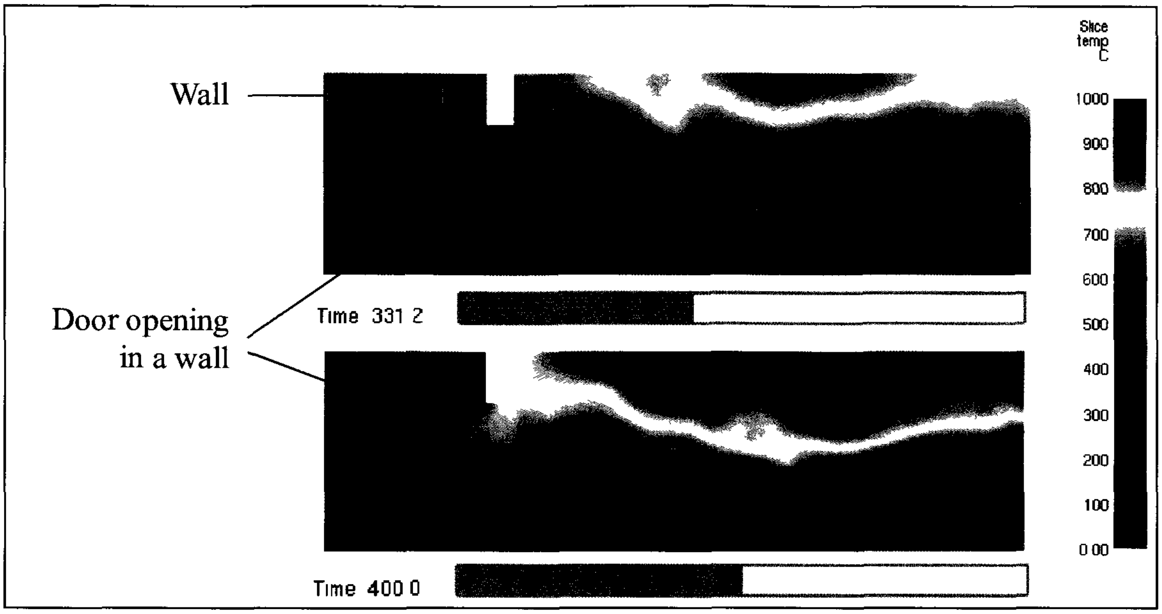


Figure 5-37: Temperature profile at flashover for a 297-m^{2}house with 2.4-m^2 openings

5.2.1.4 Device Activation

All detection devices were unaffected by varying opening area; activation times are listed in Table 5-15. The activation of a smoke and heat detector at Location 'A' was also provided for comparison, where detectors inside the room activated earlier.

Table 5-15: Device activation times for a bedroom fire in a detached home

Total Floor Area (m^2)	Activation Time (s)				
	Typical Location			Location 'A'	
	Smoke	Heat	Sprinkler	Smoke	Heat
297	54	159	95	26	111
260	49	126	104	29	114
223	42	130	104	26	117

5.2.1.5 Tenability and Smoke Movement

Table 5-16 summarizes the times at which tenability criteria in terms of toxicity, thermal conditions, and visibility were met. The time to reach dangerous toxicity levels decreases when opening area is decreased in the three houses for all locations examined.

The time at which temperatures and/or heat fluxes reached dangerous levels for occupants at Location 'A' were similar despite varying openings. At other locations there was a more prominent time lag, up to 1.7 minutes. Thermal criteria were not reached at Location 'C' in the 297-m^2 house, since there are very large windows in the common area. Once these windows break large amounts of smoke are vented, resulting in lower temperatures and heat fluxes in the second bedroom.

The time to reach visibility conditions was not affected by opening area, at any location.

Table 5-16: Times when tenability criteria were exceeded for a bedroom fire in detached homes

		Time tenability criteria were exceeded (s)								
Opening Area	**Location**	**A***			**B***			**C***		
	Floor area (m^2)	**297**	**260**	**223**	**297**	**260**	**223**	**297**	**260**	**223**
3.6 m^2	**Toxicity**	222	333	237	345	397	253	442	389	298
	Thermal	145	174	162	421	377	225	-	438	406
	Visibility	55	54	49	116	87	55	199	114	109
2.4 m^2	**Toxicity**	202	257	230	317	324	230	416	358	275
	Thermal	140	171	159	365	350	213	-	414	379
	Visibility	55	54	49	117	87	55	193	114	109
1.8 m^2	**Toxicity**	190	243	219	302	328	218	425	338	262
	Thermal	140	166	158	356	337	211	-	408	354
	Visibility	55	54	48	113	87	55	195	114	109

*A: inside the room of fire origin, B: in the hallway at the top of the stairs, C: in the 2nd bedroom

5.2.2 Townhomes

The same three townhomes as examined for living room fires were used in bedroom fire simulations with overall floor areas 186 m^2, 167 m^2, and 149 m^2. The three opening areas examined were 2.4 m^2, 1.8 m^2, and 1.2 m^2. Three window panes are typical of a townhome master bedroom, which is similar to 1.8 m^2.

5.2.2.1 Heat Release Rate Histories

The HRRs in the townhomes are about half as high as those with the same opening area in detached homes, Figure 5-38, Figure 5-39, and Figure 5-40. However, when considering the house as a whole, the townhome has far fewer window openings (Table 4-3 and Table 4-4).

The HRRs grow until the fire is limited by the amount of oxygen in the room. In the 186-m^2 house, oxygen levels drop below 6% at 5 minutes, which coincides with the decrease in HRR from the initial peak. At this point, both the upper layer temperatures, Figure 5-41, and the thickness of the upper layer decreases until about 7.5 minutes. The HRR begins to rise again around 7 minutes, which coincides with a drop in oxygen levels on the first floor; so as the fire receives more oxygen it is able to grow. At about 8 minutes another window breaks on the second floor, thereby sustaining the HRR at the current level.

The fire in the 167-m^2 home stays concentrated at the windows so most of the combustion is occurring outside the room, which explains the lower HRRs. This behaviour is not typical of a bedroom fire, where the fire would spread due to a high concentration of combustible items in the room. But it seems to suggest that FDS has difficulty to model room fires that have limited ventilation. However, the same is not observed in the 149-m^2 house. The patio door actually breaks in the simulation before windows on the second floor, which did not happen in the other two models.

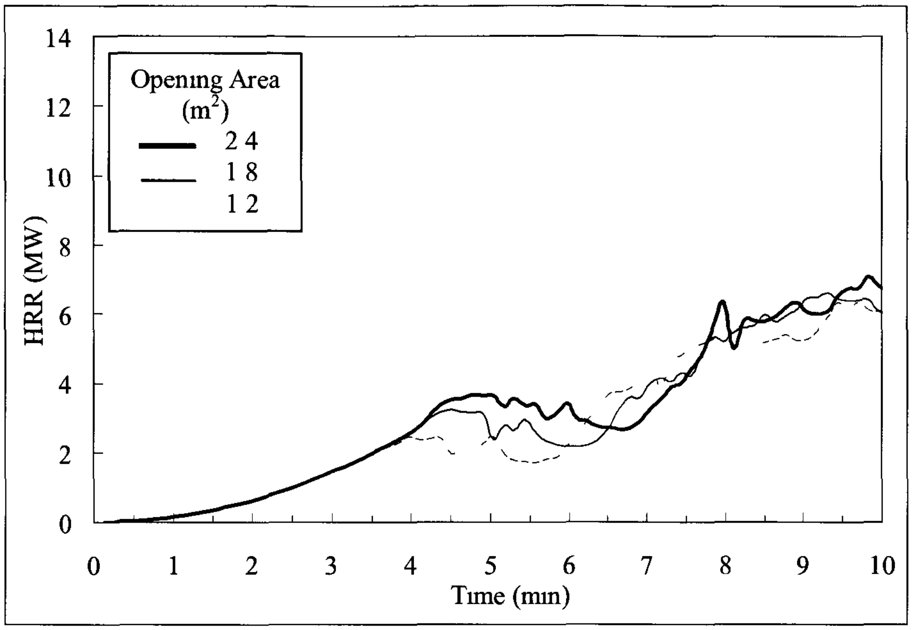


Figure 5-38: Heat release rates for a bedroom fire in a 186-m^2 townhome

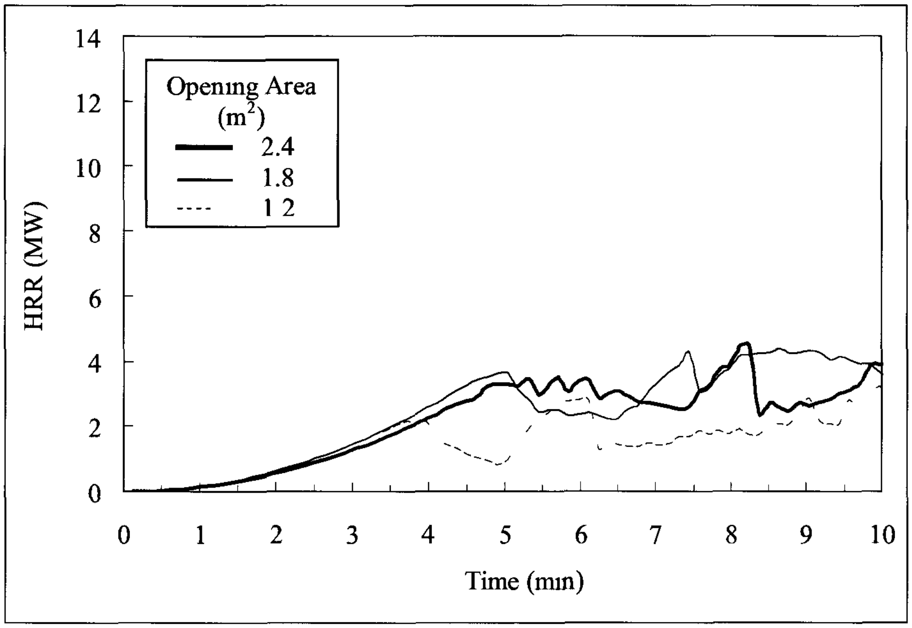


Figure 5-39: Heat release rates for a bedroom fire in a 167-m^2 townhome

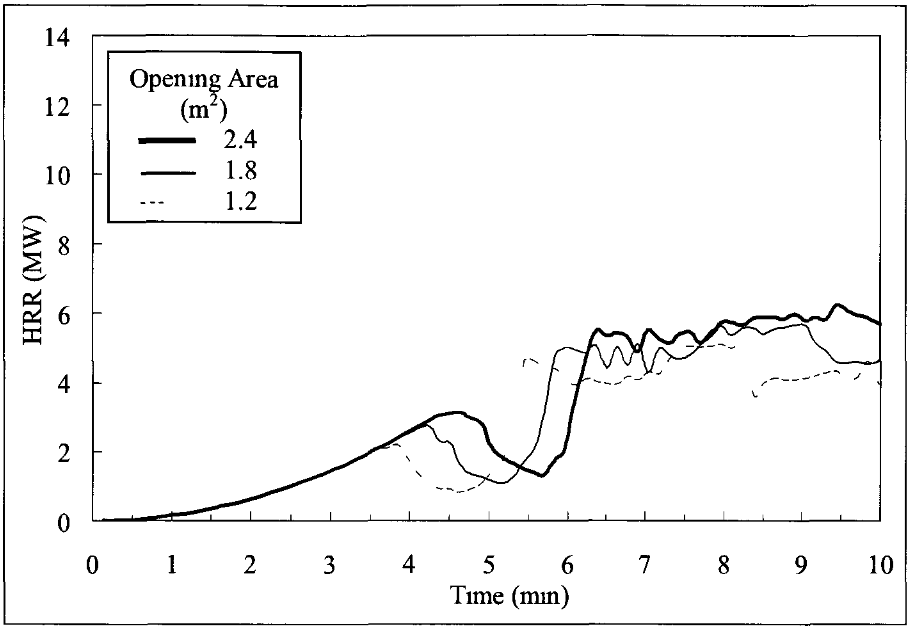


Figure 5-40: Heat release rates for a bedroom fire in a 149-m^2 townhome

The master bedroom windows break within the first 2 minutes for the three townhomes in all ventilation cases, Table 5-17. The first window to break outside the room of fire origin breaks earlier when the opening area is smaller in the master bedroom, Table 5-18. Windows outside the master bedroom break when the HRR begins to grow again after a brief decline. For example, this occurs at 6 minutes for the 2.4-m^2 opening area. In these trials, changing from the 1.2 to 2.4-m^2 opening area causes the second window to break 30 s later. The burner is slightly closer to the windows than in the other two homes because the geometry of the room was much smaller, which explains why the first windows broke earlier.

Table 5-17: First window breakage for bedroom fires in a townhome

	Window breakage (s)		
	Opening Area (m^2)		
Total Floor Area	**2.4**	**1.8**	**1.2**
186 m^2	107	106	107
167 m^2	117	108	113
149 m^2	85	85	85

Table 5-18: Time of window breakage outside room of fire origin for bedroom fires in a townhome

	Window breakage (s)		
	Opening Area (m^2)		
Total Floor Area	**2.4**	**1.8**	**1.2**
186 m^2	459	446	410
167 m^2	492	449	696
149 m^2	360	337	313

5.2.2.2 Temperature Profiles

As it can be seen from the following upper layer temperatures for a townhome bedroom fire in Figure 5-41, Figure 5-42, and Figure 5-43, the fires never seem to reach flashover. The largest house comes closest with peak temperatures lying between 500-600°C. The larger opening areas produce higher upper layer temperatures.

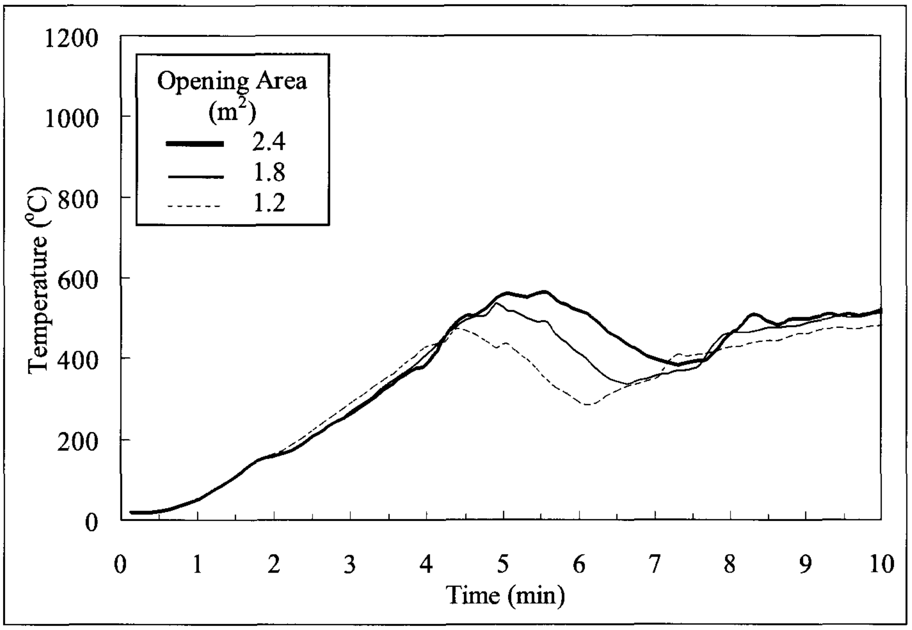


Figure 5-41: Upper layer temperatures for a bedroom fire in a 186-m^2 townhome

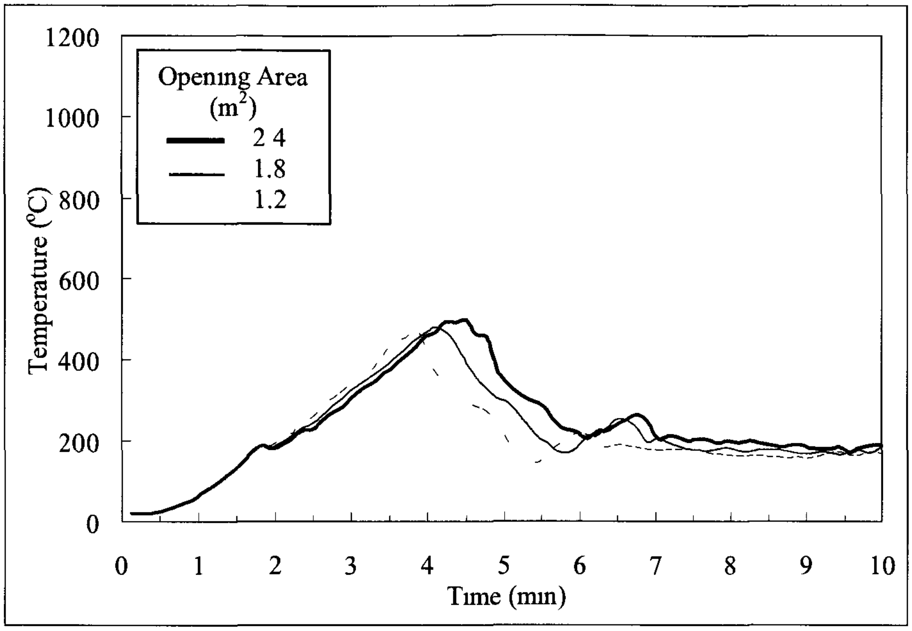


Figure 5-42: Upper layer temperatures for a bedroom fire in a 167-m^2 townhome

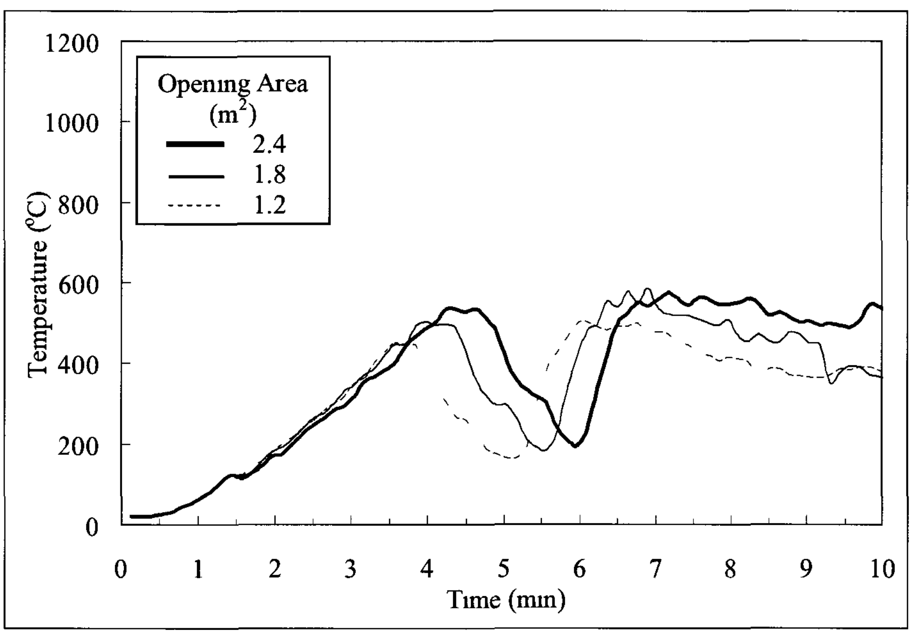


Figure 5-43: Upper layer temperatures for a bedroom fire in a 149-m^2 townhome

The lower layer temperatures for the townhomes seem to not be greatly affected by opening area, Figure 5-44, Figure 5-45, and Figure 5-46. The only differences are associated with other windows breaking at different times; other windows break earlier when less opening area is present.

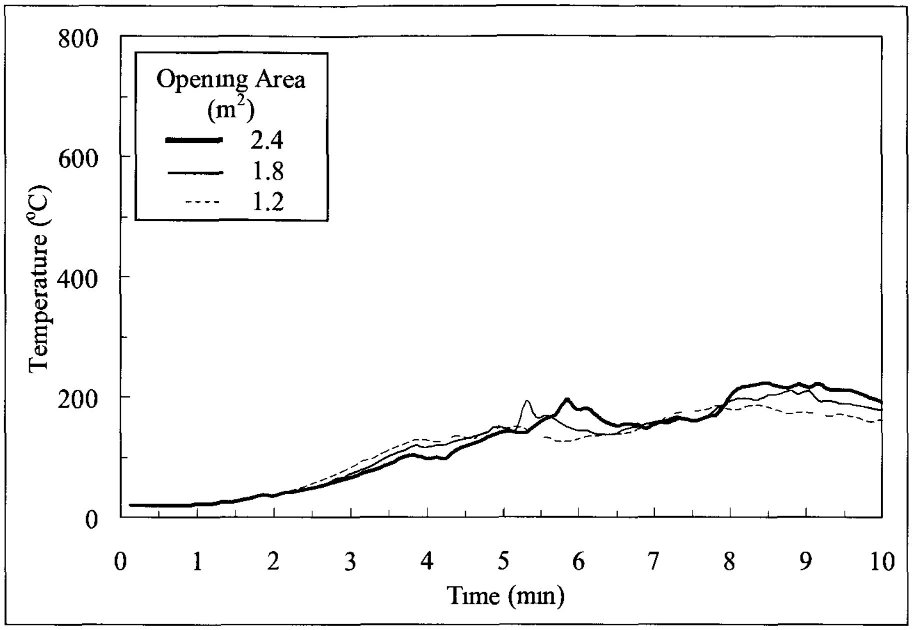


Figure 5-44: Lower layer temperatures for a bedroom fire in a 186-m^2 townhome

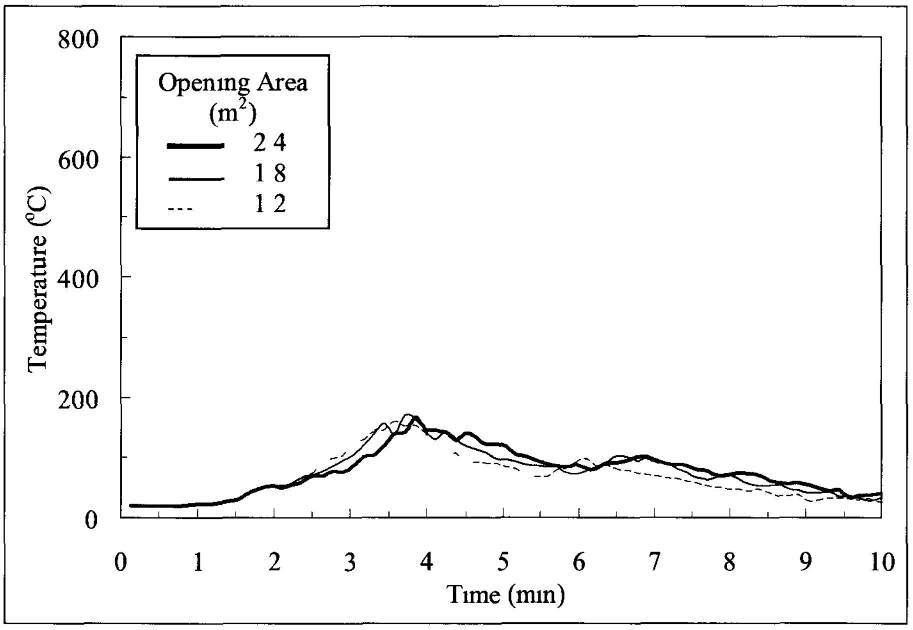


Figure 5-45: Lower layer temperatures for a bedroom fire in a 167-m^2 townhome

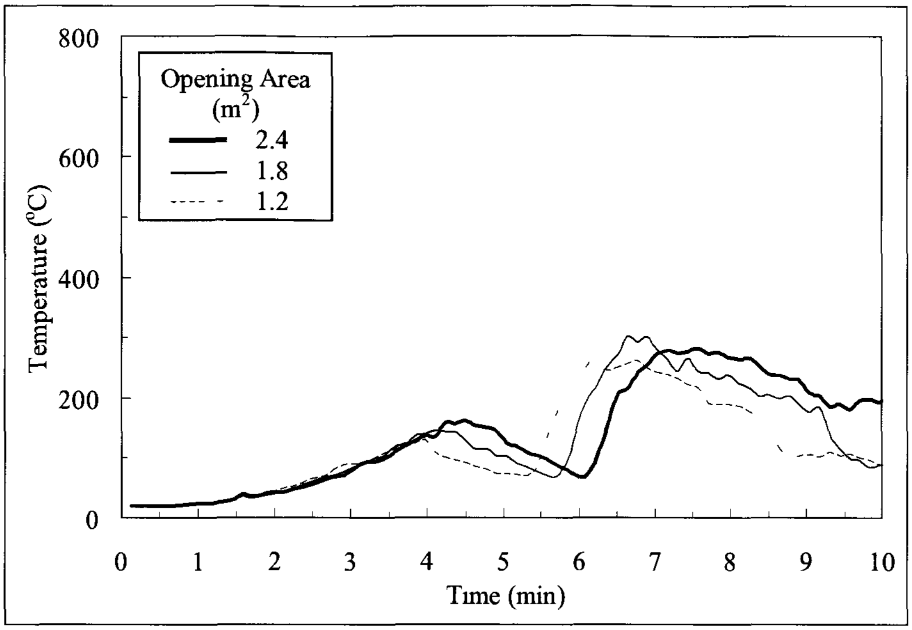


Figure 5-46: Lower layer temperatures for a bedroom fire in a 149-m^2 townhome

5.2.2.3 Flashover

Flashover was not reached in any of the townhome bedroom models. Around 4.5 minutes into the fire, upper layer temperatures reach just under 600°C, but shortly after temperatures begin to drop due to a lack of oxygen in the room. Using the temperature slice profile, the 600°C isotherm descended to 0.3 m from the ceiling, but then temperatures quickly dropped as the fire moved outside the room. The time of the first peak is listed in Table 5-19.

Table 5-19: Time to flashover potential for townhome bedroom fires

	Time to flashover (s)		
Total Floor Area (m^2)	**2.4 m^2**	**1.8 m^2**	**1.2 m^2**
186	300	285	-
167	257	285	244
149	268	235	225

5.2.2.4 Device Activation

Opening area did not have any effect on the activation of the smoke and heat detectors and the sprinklers in typical locations, Table 5-20. The time of smoke and heat detector activation at Location 'A' is also listed for comparison; the detectors inside the room activated earlier.

Table 5-20: Device activation times for townhome bedroom fires

Total Floor Area (m^2)	Activation Time (s)				
	Typical Locations			Location 'A'	
	Smoke	Heat	Sprinkler	Smoke	Heat
186	38	109	100	28	94
167	42	110	98	28	94
149	45	116	99	27	95

5.2.2.5 Tenability and Smoke Movement

Opening area had a small or no effect on the time to reach untenable gas concentrations at all locations, where a reduction in the opening area reduced the time to dangerous conditions. Thermal criteria followed a similar pattern, except for the 149-m^2 house at Location 'A' and Location 'B' and the 186-m^2 house at Location 'C'. Visibility was constant for each opening area for each location throughout the house.

Table 5-21: Times when tenability criteria were exceeded for townhome bedroom fires

Opening Area		Time tenability criteria were exceeded (s)								
	Location	A*			B*			C*		
	Floor area (m^2)	186	167	149	186	167	149	186	167	149
2.4 m^2	**Toxicity**	206	230	214	216	243	238	259	263	261
	Thermal	171	219	114	198	301	278	302	479	391
	Visibility	40	44	45	50	66	67	88	86	89
1.8 m^2	**Toxicity**	198	198	198	206	220	228	246	237	242
	Thermal	142	119	104	173	239	266	296	428	276
	Visibility	40	44	45	50	60	67	88	81	89
1.2 m^2	**Toxicity**	190	190	182	182	212	208	223	227	233
	Thermal	132	124	118	167	234	288	358	361	265
	Visibility	40	44	45	50	57	67	88	81	90

*A: inside the room of fire origin, B: in the hallway at the top of the stairs, C: in the 2nd bedroom

5.3 Summary

Varying opening area in the room of fire origin produced similar effects for both living room and bedroom fires in detached homes and townhomes.

5.3.1 Heat Release

For all scenarios examined, increasing opening area resulted in higher HRRs. Each peak took progressively longer to reach when more opening area was added. Peaks were higher in detached homes than townhomes for both living room and bedroom fires.

5.3.2 Temperatures

Opening area did not significantly impact the maximum temperatures reached in the detached home living room fires, which were at about 1000°C. This might imply that the fires were in fact fuel surface controlled. In this case the larger openings created slightly lower temperatures. This is related to larger vents allowing larger amounts of hot gases to be vented from the room and producing lower temperatures [50]. However, larger openings resulted in higher upper layer temperatures for all other simulations, indicating ventilation controlled fires. The difference may be due to the fact that there was significantly more opening area in the detached home living room cases. For the rest of the simulations, the larger windows promoted a stronger fire, i.e. HRR, which resulted in higher temperatures in the upper layer. This is related to Equation 3-2 and Equation 3-9 where larger openings result in higher HRR and maximum temperatures.

5.3.3 Window Breakage

Window breakage has a clear impact on HRR and upper layer temperatures; when more oxygen is allowed into the room a fire can grow stronger. The first window breakage in living rooms is not greatly affected by opening area. Some of the windows broke later when fewer openings were present. This was because larger overall windows meant that there was likely a window closer to the fire than if there were fewer windows. For the bedroom fires, window breakage occurred slightly earlier in the townhomes, this is related to the burner being closer to the windows due to smaller room size.

5.3.4 Flashover

For living room fires, flashover occurred earlier when fewer openings were present and earlier in the townhomes than the detached homes. For the bedroom fires, flashover seemed to consistently occur near 300 s for all of the detached homes regardless of opening area. This suggests that the time to flashover is more dependent on opening area when the size of the room is larger.

5.3.5 Device Activation

Device activation was unaffected by varying opening area for living rooms and bedrooms since all devices activated before any of the windows broke.

5.3.6 Tenability

The time to reach dangerous gas concentrations and heat fluxes (and/or lower layer temperatures) decreases when opening area is decreased in all houses at all locations examined for both living room and bedroom fires. Simply put, larger openings provide occupants with more time to evacuate safely when looking at each criterion individually; when larger openings are present more cool fresh air enters the room and smoke is vented therefore reducing gas concentrations, decreasing temperatures in the lower layer, and increasing visibility. However, in these scenarios the visibility criteria were always reached before windows broke, so they were not affected by opening area. Visibility is the critical factor in determining the ASET since it was the first tenability criterion met. Because visibility was unaffected by opening area this means that occupant evacuation is not affected by opening area either.

5.3.7 Implications for life safety

Generally larger opening area resulted in a more dangerous fire, with higher HRRs and higher temperatures; however, smaller openings retain heat and smoke inside the room causing critical events to be reached sooner. So in terms of life safety having smaller windows poses a more direct threat to occupant safety.

Larger opening area in the room of fire origin can provide occupants with more time to evacuate safely when examining each criterion individually. However, reduced visibility can cause disorientation and prevent an occupant from safely evacuating. Since this criterion is reached throughout the homes before any windows break, opening area does not affect evacuation.

6 <u>Results and Discussion: Effects of varying floor area</u>

6.1 Living Room Fires

6.1.1 Detached Homes

The second variable examined in this research is how changes in floor area affect the growth of a fire and time to major events. Total floor area of a house is tied to fuel load and distance between furniture items, therefore impacting the possible size a fire can reach and how quickly it spreads.

6.1.1.1 Heat Release Rate Histories

Figure 6-1, Figure 6-2, and Figure 6-3 show the heat release rates for living room fires in the three detached homes (297, 260, and 223 m^2) when the opening area was kept constant.

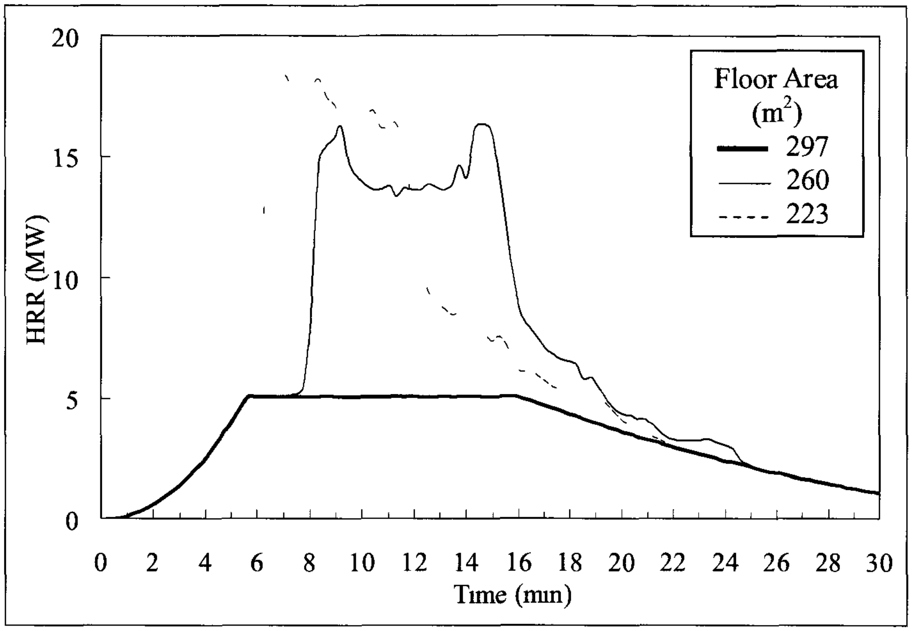


Figure 6-1: Heat release rates for detached home living room fires, 11.2-m^2 openings

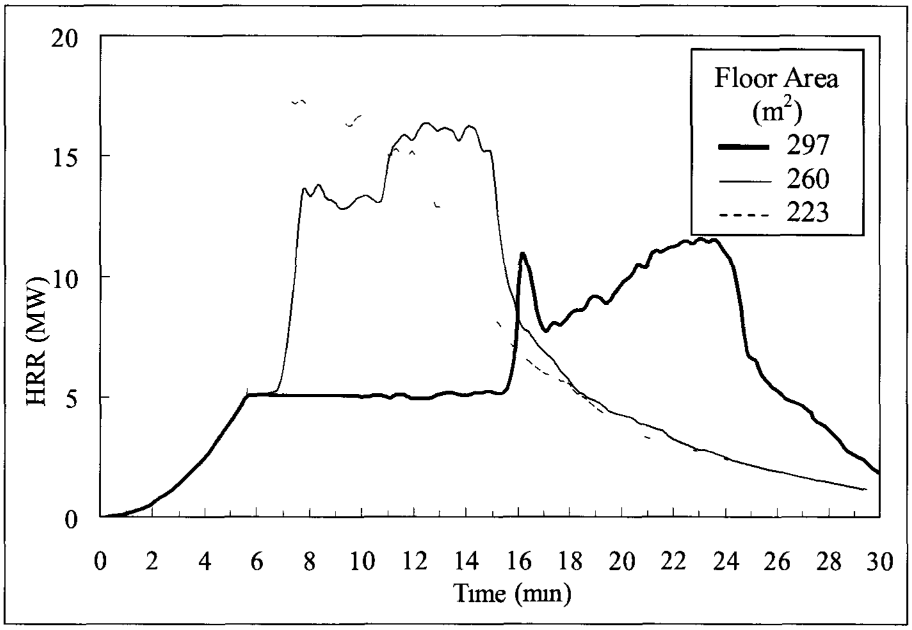


Figure 6-2: Heat release rates for detached home living room fires, 8.4-m^2 openings

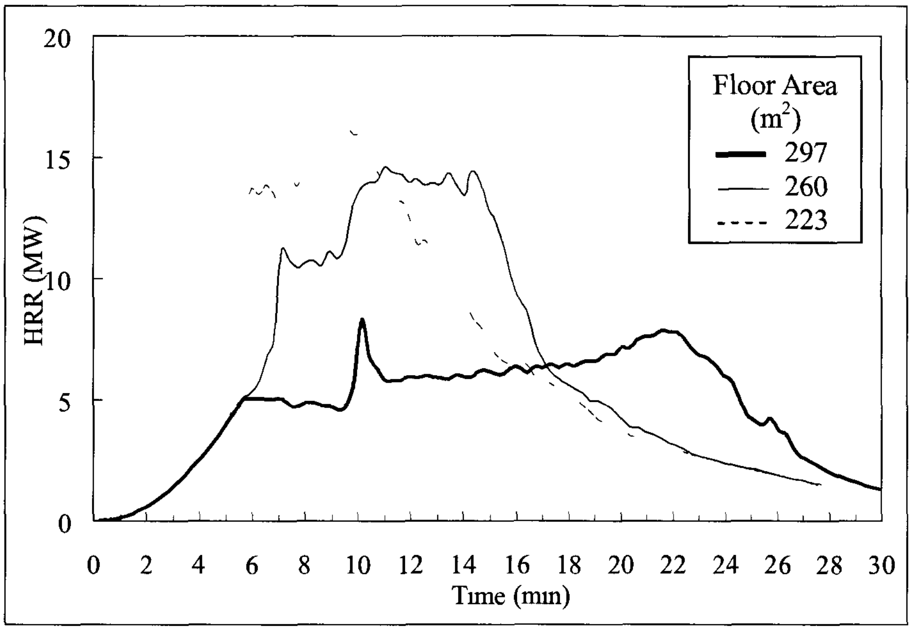


Figure 6-3: Heat release rates for detached home living room fires, 5.6-m^2 openings

An increased floor area results in longer times to reach the peak HRR and overall lower peak HRRs. Since the larger houses have a lower fuel load density, furniture is more spread out which means it can take longer for the fire to spread from one item to the next. The fire did not spread to any secondary items in the 297-m^2 home with 11.2-m^2 of openings. The 297-m^2 house has a slightly different geometry compared to the other two houses, where the living area is shaped like an 'L' with the kitchen along the side of the house, around a corner. This creates a wall between the primary living room fire and some of the combustibles located in the kitchen. This could also possibly explain the lack of fire spread.

Having a lower fuel load density translates to items being further from the primary ignition source (the burner in this case), therefore slowing the spread of fire. The HRR peaks are lower because heat is released more gradually and burns for a longer time. For the 223 and 260-m^2 homes similar values were observed for total heat released, within 500 kW of each other, where nearly all combustible material burned in both cases.

Just over 75% of materials burned in the 297-m^2 house in the case illustrated in Figure 6-3.

6.1.1.2 Temperature Profiles

Increasing the total floor area resulted in a delay in the time to reach peak upper layer temperatures in the room of fire origin. This trend is demonstrated in Figure 6-4, Figure 6-5, and Figure 6-6. The larger houses have larger living room areas and therefore a larger volume of smoke will be required to fill the entire space, meaning that the upper layer will descend more slowly.

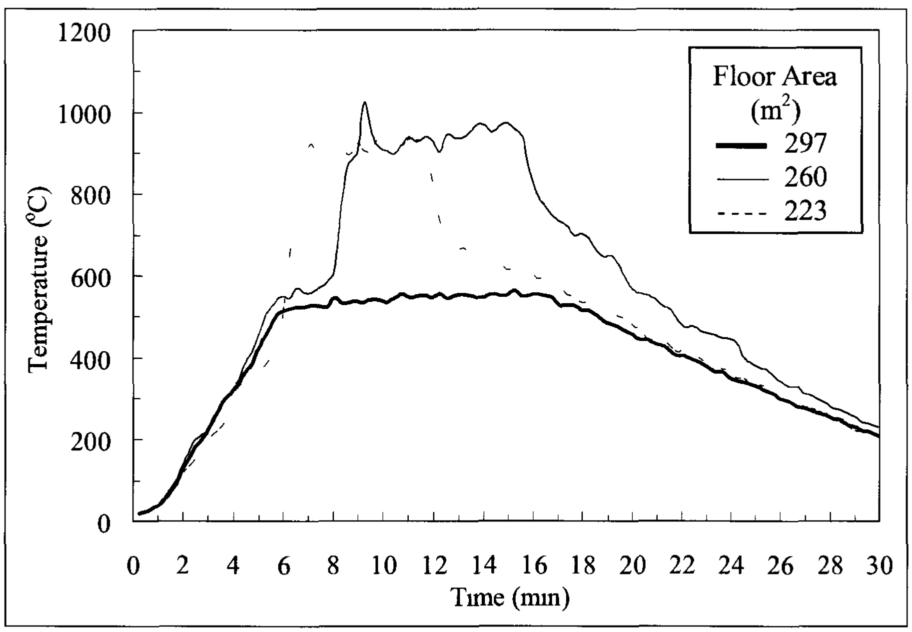


Figure 6-4: Upper layer temperatures for detached home living room fires, 11.2-m^2 openings

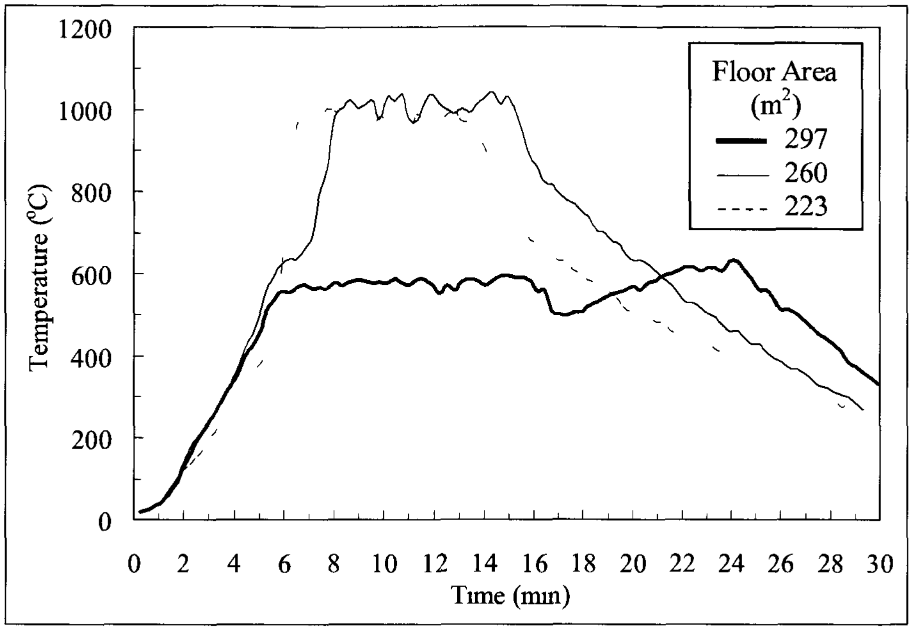


Figure 6-5: Upper layer temperatures for detached home living room fires, 8.4-m^2 openings

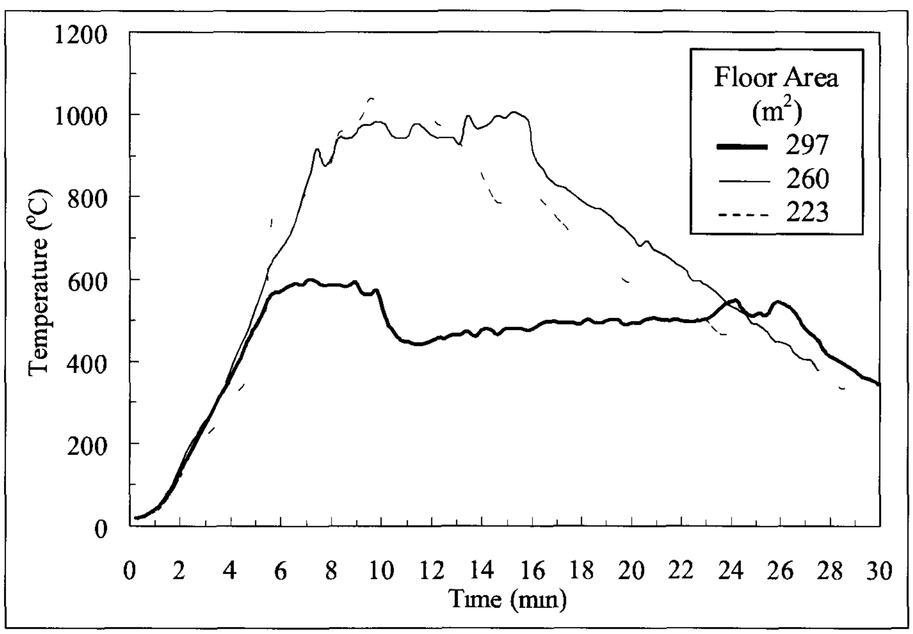


Figure 6-6: Upper layer temperatures for detached home living room fires, 5.6-m^2 openings

When examining lower layer temperatures, the larger houses had a delay in the time to reach peak temperatures.

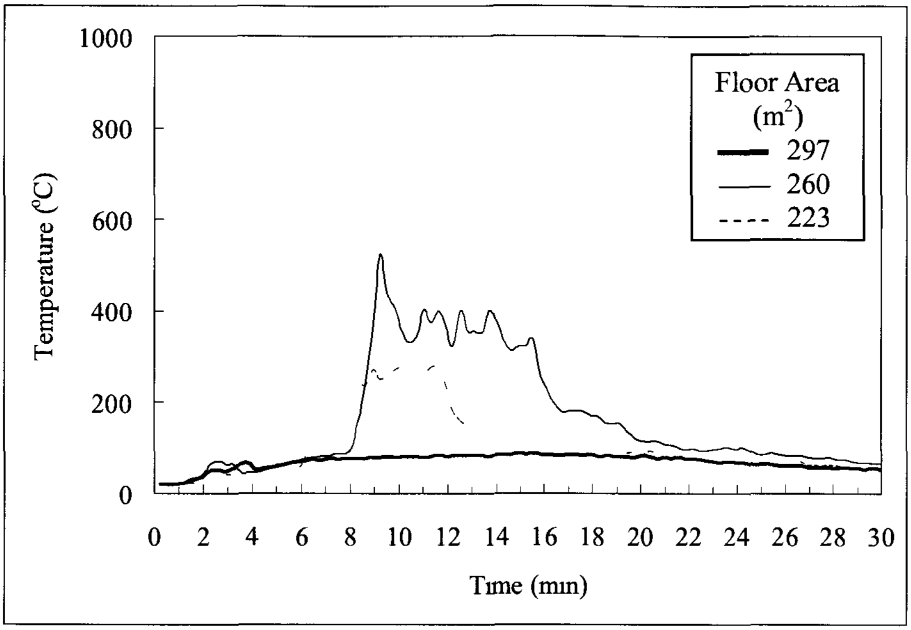


Figure 6-7: Lower layer temperatures for detached home living room fires, 11.2-m² openings

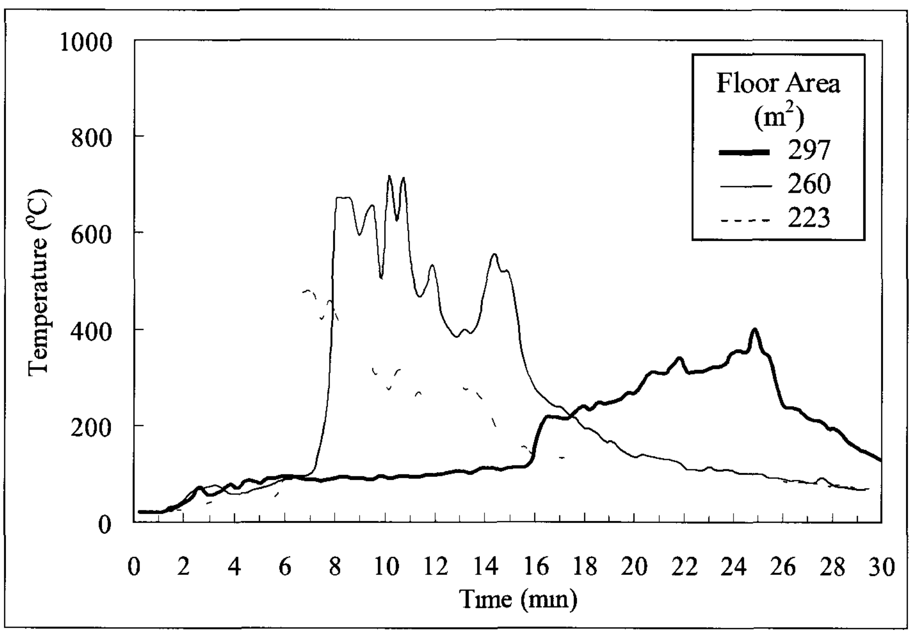


Figure 6-8: Lower layer temperatures for detached home living room fires, 8.4-m² openings

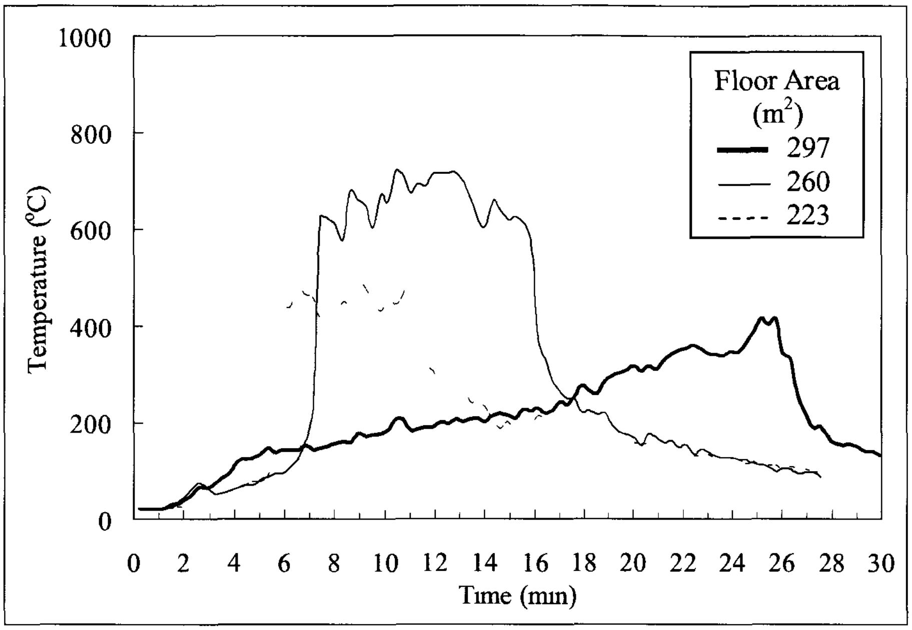


Figure 6-9: Lower layer temperatures for detached home living room fires, 5.6-m^2 openings

6.1.1.3 Flashover

Referring back to both Table 5-4 and Table 5-5 an increase in total floor area resulted in a longer time to flashover. Looking at 5.6-m^2 openings with the 223-m^2 house being the base case, flashover occurs 1 minute later in the 260-m^2 case and 4.6 minutes later in the 297-m^2 case. The time difference to flashover between the largest and smallest window openings increased significantly as the floor area increased. Larger windows paired with larger floors areas result in the longest time to flashover.

6.1.1.4 Device Activation

As discussed previously, little or no difference (less than 10 seconds) was observed in the time to activation of smoke detectors, heat detectors, and sprinklers for all cases, Table 5-6.

6.1.1.5 Tenability and Smoke Movement

Full data on the times to reach tenability criteria are presented in Table 5-7. For toxicity, no trend is seen between the three floor areas for the largest window opening condition. Having a large amount of window openings introduces significant turbulence and mixing of effluent gases, resulting in highly varied times to reach tenability. However, for 8.4 and 5.6-m^2 openings there is an increase in the time to detrimental conditions with increased floor area. The smaller rooms have a smaller volume of air, therefore less gas species are required to achieve unsafe concentrations. The values for Location 'B' and Location 'C' are difficult to compare since the distance between the burner and each location varied with the house geometry.

There was no trend in the times to reach painful temperatures or heat fluxes or reduced visibility. For all floor areas, the visibility criterion were exceeded essentially at 60 s in the room of fire origin and was always the first tenability threat encountered by occupants for all locations.

The lack of trends for tenability criteria are likely related to the changes in house geometry. Specifically, Location 'B' is at the bottom of the staircase and each layout had the base of the stairs in a different location. The 223-m^2 house had the base of the stairs near the front door and the other two houses had the staircase beginning near the middle of the house. Also some houses were more 'open concept' than others (i.e. the 260 and 223-m^2 houses) allowing smoke to spread out, resulting in longer times to reduced visibility. Another factor to consider is the size of the opening to upstairs (the 223-m^2 house had an 11-m^2 opening to upstairs, which was almost double the size of the two other homes), which allows more smoke to rise to the second level resulting in faster smoke accumulation upstairs and longer times on the main level.

6.1.2 Townhomes

6.1.2.1 Heat Release Rate Histories

Unlike the detached homes, the townhomes did not display the same delay to peak HRR with increasing floor area, shown in Figure 6-10, Figure 6-11, and Figure 6-12. There is in fact, no correlation between the time to peak and floor area. The only real emerging trend is the link between larger floor area and higher HRR values (as well as total heat released), which is the opposite of that observed for the detached homes. Even though the living room floor area is higher in the detached homes, the total surface area (A_T) in the townhome living rooms was higher due to their more complex geometry. The ratio of A_T to room area actually increased for smaller floor areas (where as this ratio decreased in the detached home), and a higher ratio demonstrated lower HRRs. Having a high A_T meant that walls shielded some parts of the room from the fire, which resulted in lower HRRs.

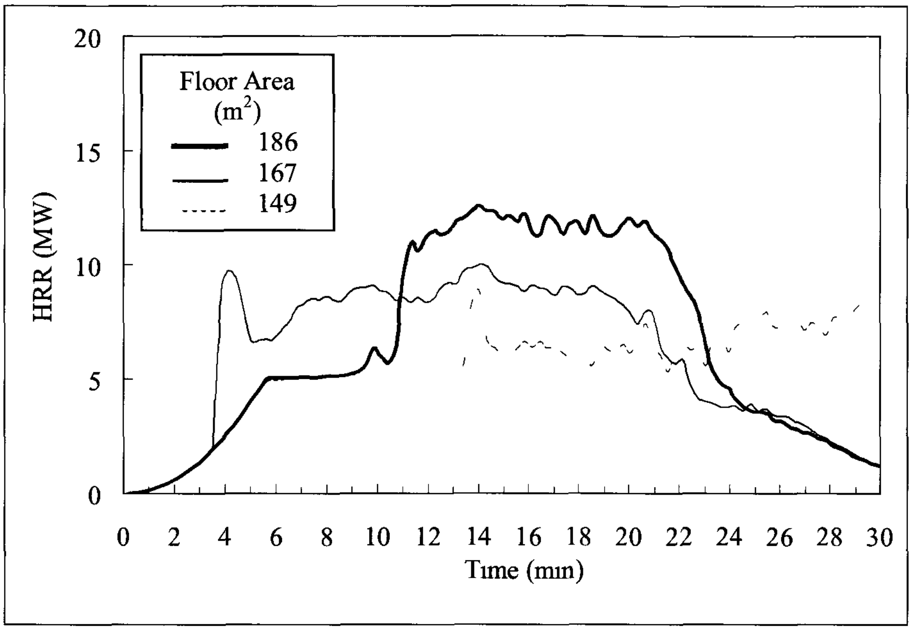


Figure 6-10: Heat release rates for townhome living room fires, 6.5-m^2 openings

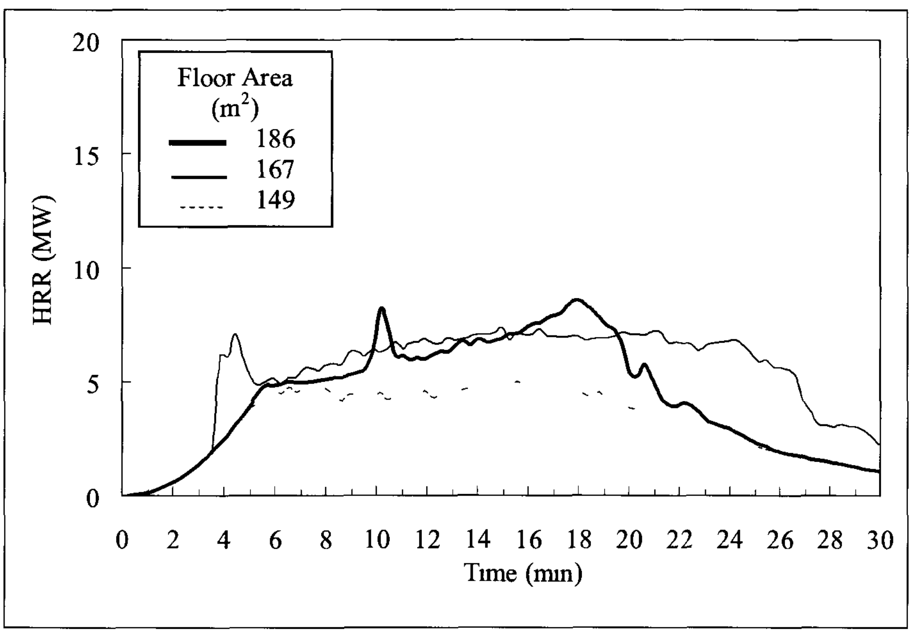


Figure 6-11: Heat release rates for townhome living room fires, 4.6-m^2 openings

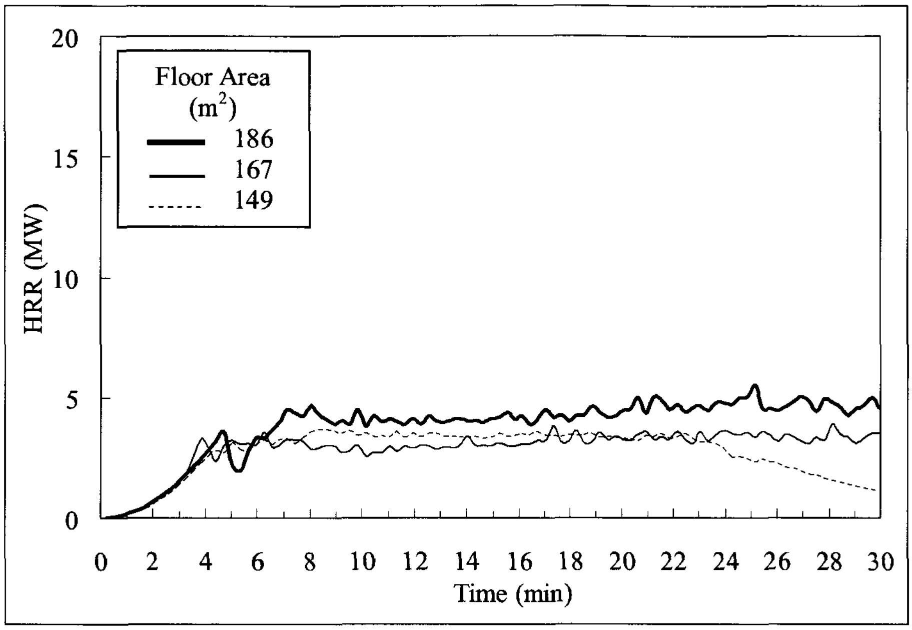


Figure 6-12: Heat release rates for townhome living room fires, 3.3-m^2 openings

3.3 m^2 of openings significantly limited burning to around 4 MW for all of the floor areas, which is less than the prescribed HRR for the burner. This illustrates that this size of opening creates a highly ventilation controlled fire. The small openings significantly limited the amount of oxygen available and therefore dictated the maximum size of the fire.

6.1.2.2 Temperatures

A larger house floor area generally resulted in higher upper layer temperatures in the room of fire origin during the steady burning phase, as seen in Figure 6-13, Figure 6-14, and Figure 6-15, which is consistent with the trends observed for the HRRs. The 3.3-m^2 opening did not result in flashover temperatures, since the small openings significantly limited the amount of oxygen available.

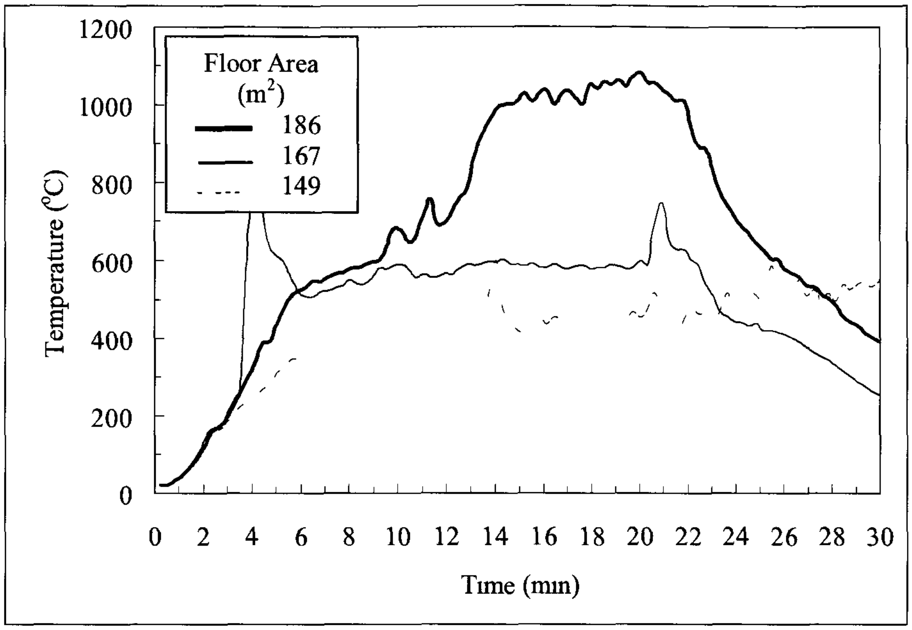


Figure 6-13: Upper layer temperatures for townhome living room fires, 6.5-m^2 openings

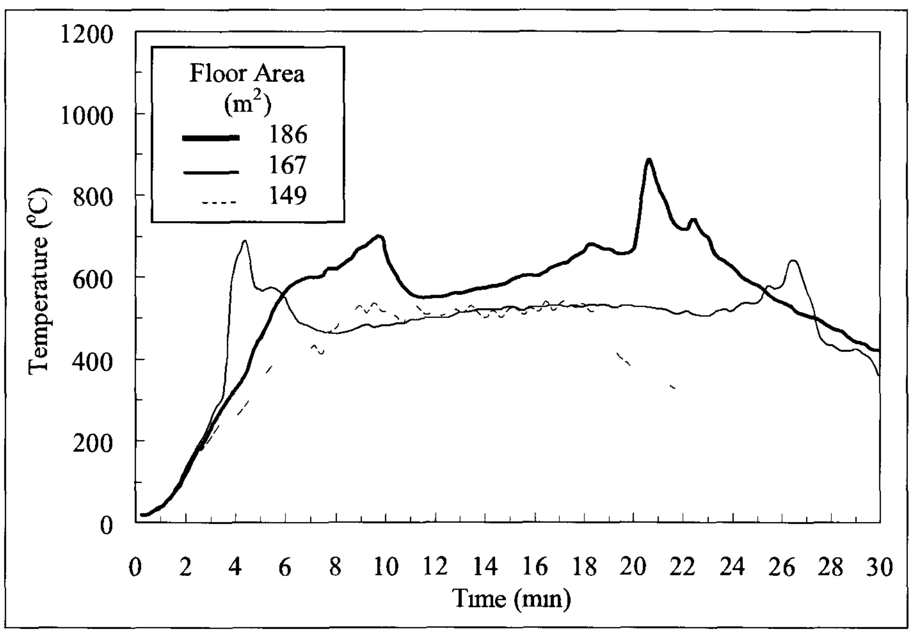


Figure 6-14: Upper layer temperatures for townhome living room fires, 4.6-m^2 openings

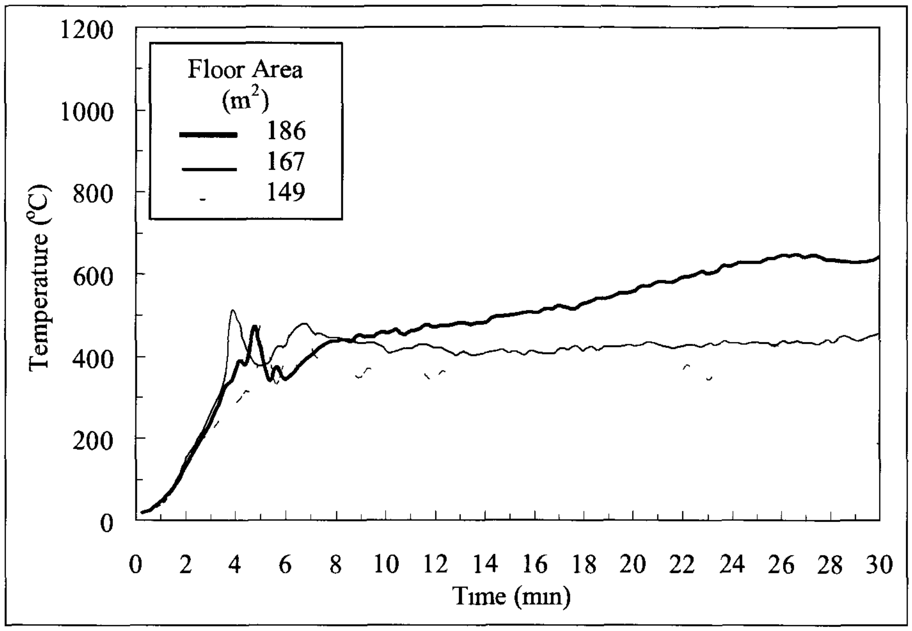


Figure 6-15: Upper layer temperatures for townhome living room fires, 3.3-m^2 openings

The lower layer temperatures reached higher peaks in the houses with the larger floor areas, seen in Figure 6-16, Figure 6-17, and Figure 6-18, which coincides with observed upper layer temperatures.

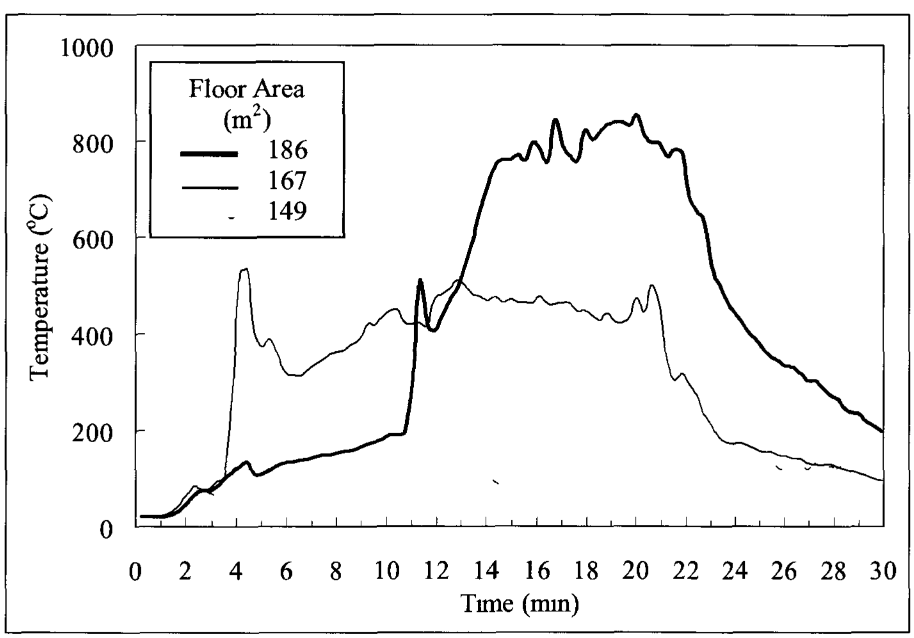


Figure 6-16: Lower layer temperatures for townhome living room fires, 6.5-m^2 openings

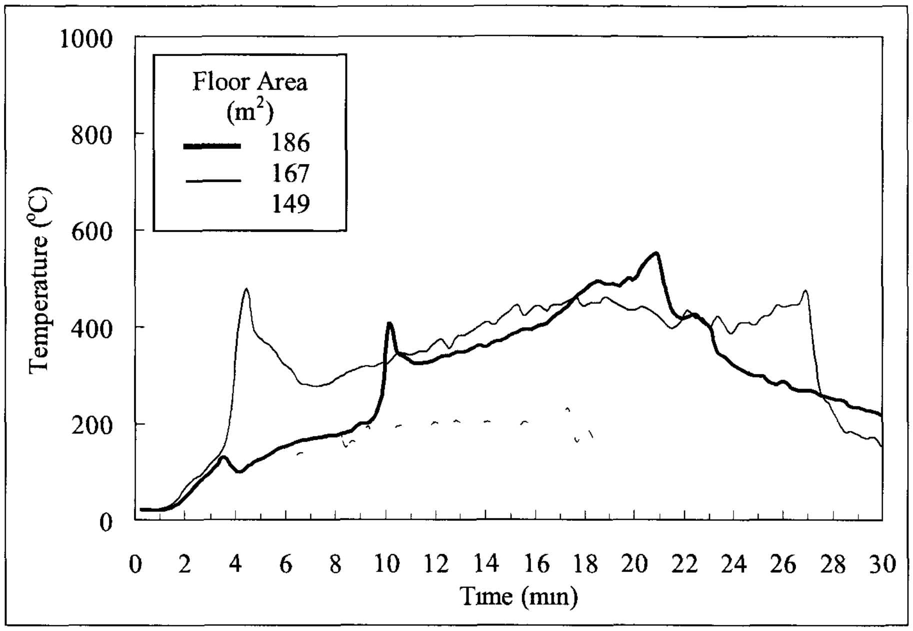


Figure 6-17: Lower layer temperatures for townhome living room fires, 4.6-m^2 openings

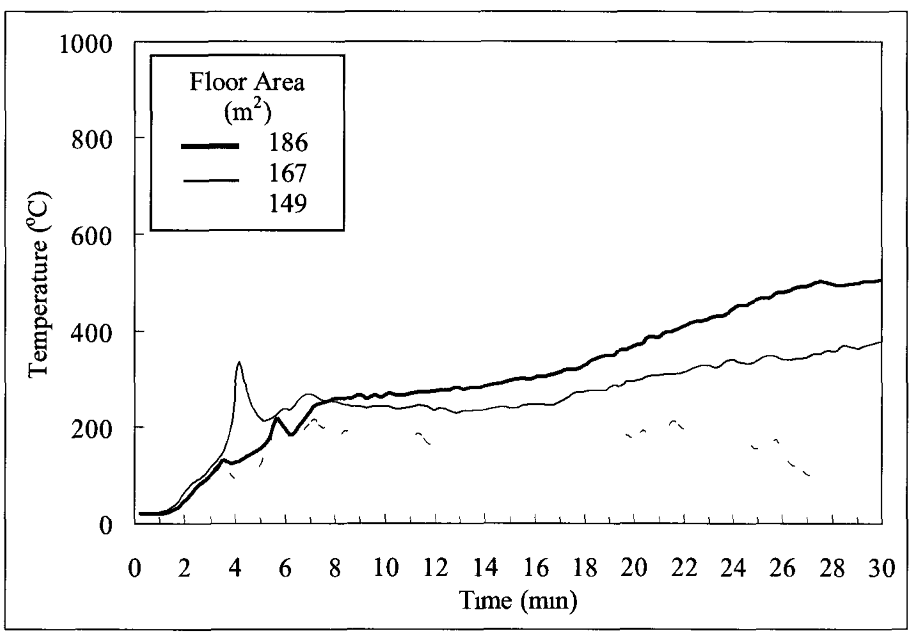


Figure 6-18: Lower layer temperatures for townhome living room fires, 3.3-m^2 openings

The sharp decline in temperatures around 22 minutes in the 167 and 186-m^2 homes in Figure 6-16 is associated with the decay of the fire since all of the furniture in the room has burned completely at this point and cool air is entering through the windows.

6.1.2.3 Flashover

The time to flashover is listed in Table 5-9. Flashover did not seem to occur when 3.3-m^2 openings were present. Flashover occurred in the 167-m^2 home earlier than the 186-m^2 home, but the 149-m^2 home had flashover occurring much later. This implies that floor area doesn't necessarily have an affect on the time to flashover.

6.1.2.4 Device Activation

Varying the floor area did not have any affect on the time to device activation in townhomes, Table 5-10.

6.1.2.5 Tenability and Smoke Movement

Very little change was observed in the times to untenable conditions when the total floor area was varied, Table 5-11. Times in which toxicity posed a threat were relatively similar for each opening area regardless of floor area, within 1 minute. This is likely due to the fact that the amount of window openings in the townhomes was so small that ventilation greatly limited the growth of the fire. This implies that in townhomes the total amount of window openings cause much greater differences in fire characteristics and time to major events than varying the total floor area. No trends were observed in terms of thermal criteria.

The time for visibility to drop below 2 m at Location 'A' was consistent for all houses around 60 s. The times at Location 'B' and Location 'C' were consistent within 20 s.

6.2 Bedroom Fires

6.2.1 Detached Homes

6.2.1.1 Heat Release Rate Histories

Again it can be seen that after the initial growth phase following the t-squared curve, each of the HRRs deviates from the path. For the same ventilation conditions, the larger houses resulted in fires with lower HRRs for the largest opening, 3.6 m^2, Figure 6-19. The HRR increased whenever more windows broke (Table 5-13).

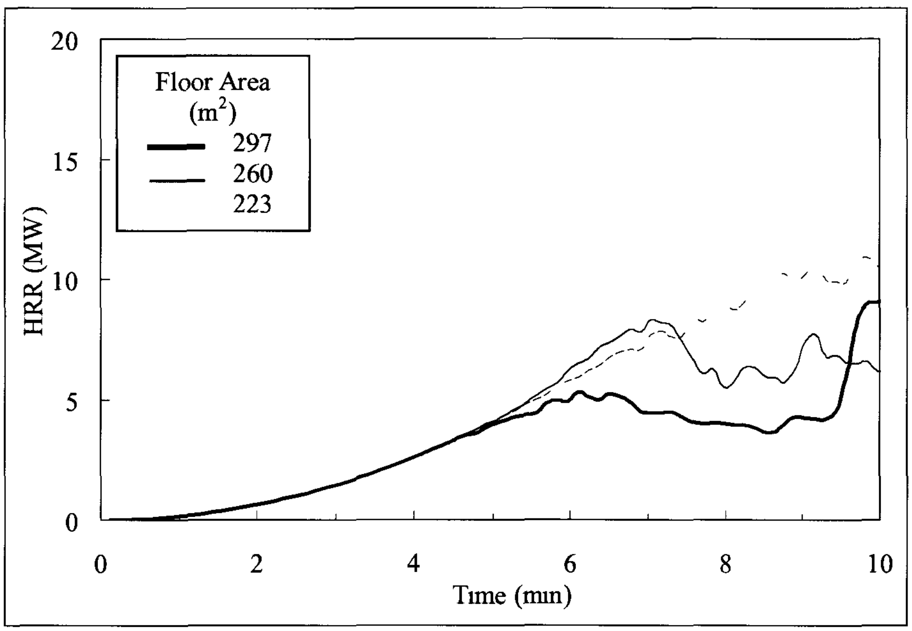


Figure 6-19: Heat release rates for detached home bedroom fires, 3.6-m^2 openings

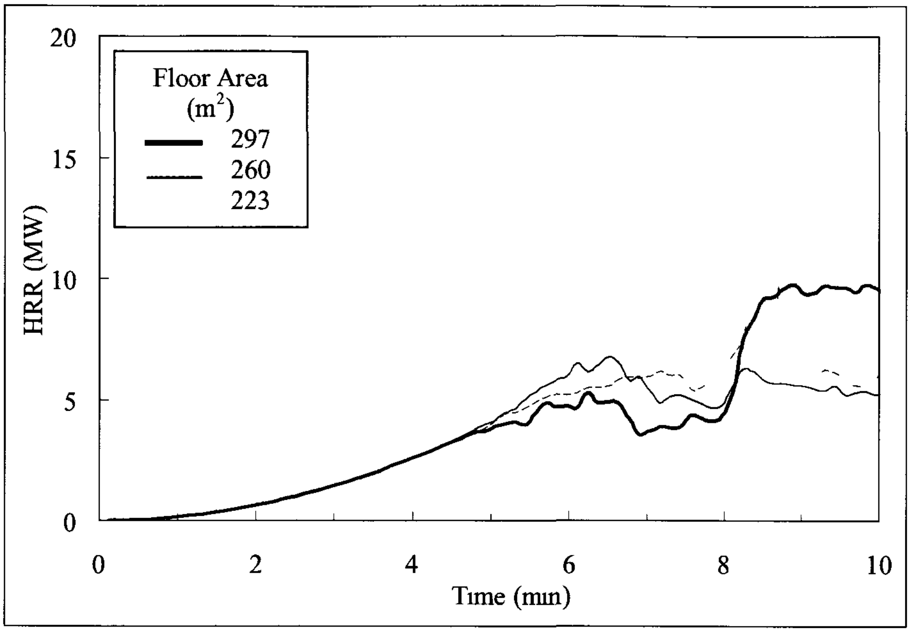


Figure 6-20: Heat release rates for detached home bedroom fires, 2.4-m^2 openings

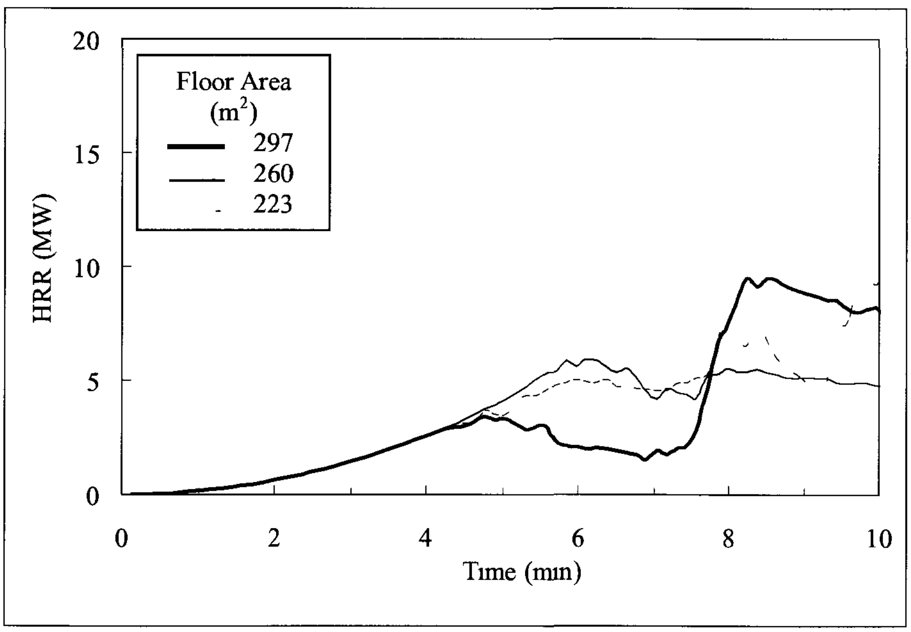


Figure 6-21: Heat release rates for detached home bedroom fires, 1.8-m^2 openings

6.2.1.2 Temperatures

Initially during the growth stage, the larger houses demonstrate higher upper layer temperatures by about 100°C: Figure 6-22, Figure 6-23, and Figure 6-24. But as the fire progressed, all of the upper layer temperatures reached similar levels for each of the opening areas. The 3.6-m^2 opening reached approximately 900°C, the 2.4-m^2 about 750°C, and the 1.8-m^2 about 700°C.

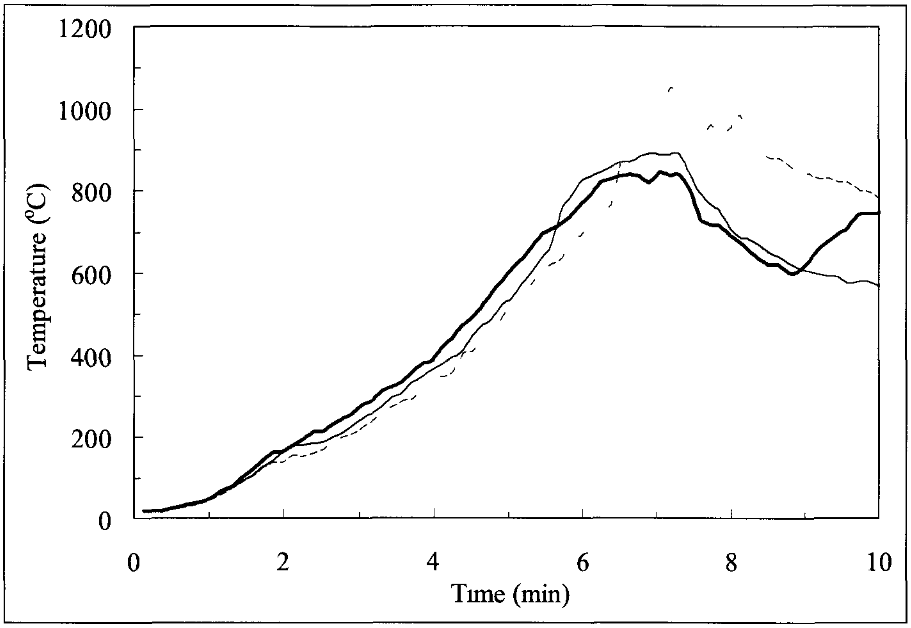


Figure 6-22: Upper layer temperatures for detached home bedroom fires, 3.6-m^2 openings

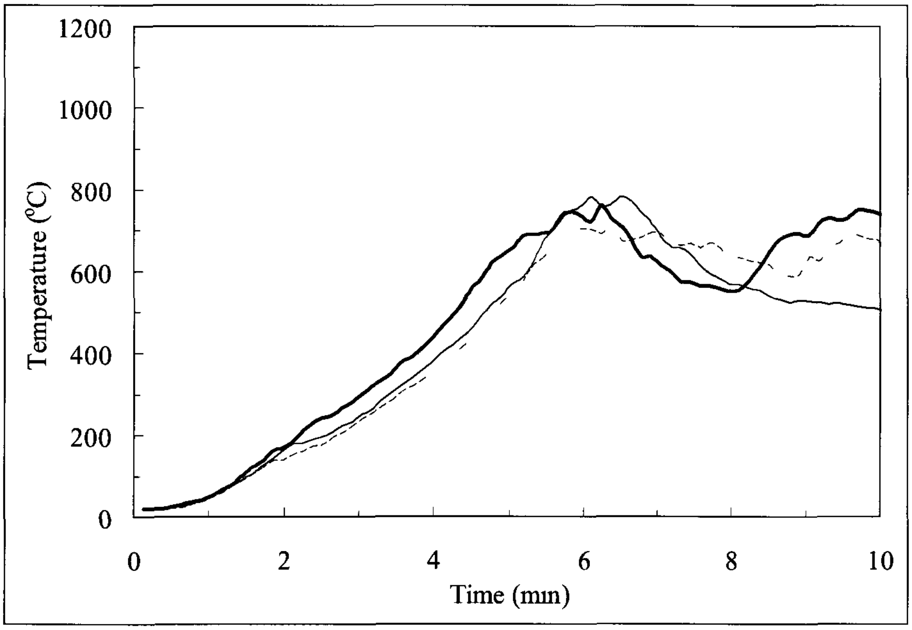


Figure 6-23: Upper layer temperatures for detached home bedroom fires, 2.4-m^2 openings

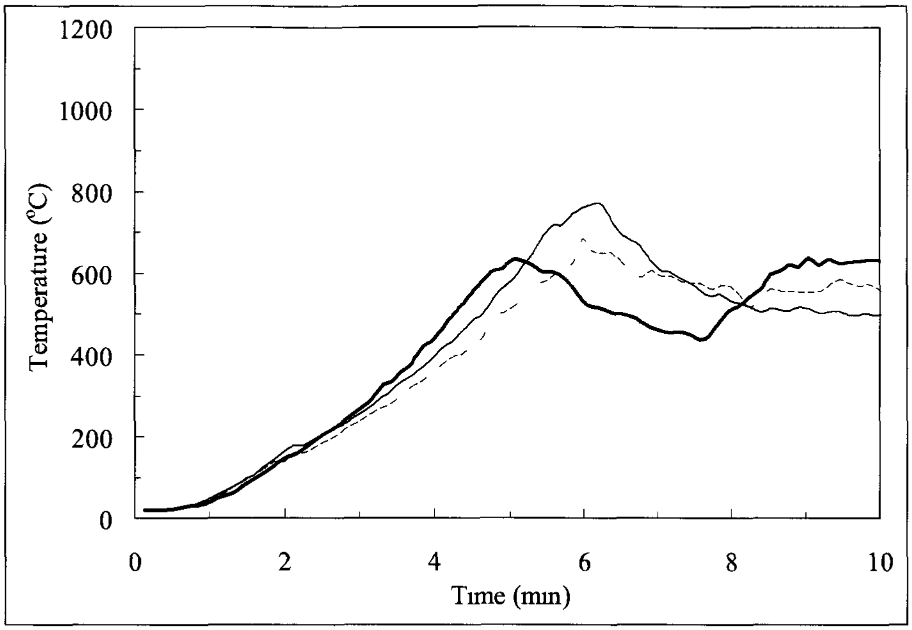


Figure 6-24: Upper layer temperatures for detached home bedroom fires, 1.8-m^2 openings

The only apparent connection between varying total floor area and lower layer temperatures is that the smaller floor areas permitted higher peak temperatures in the lower layer, Figure 6-25, Figure 6-26, and Figure 6-27. Around 10 minutes into the fire, the temperatures seem to be consistent at 300°C for the two smaller opening areas.

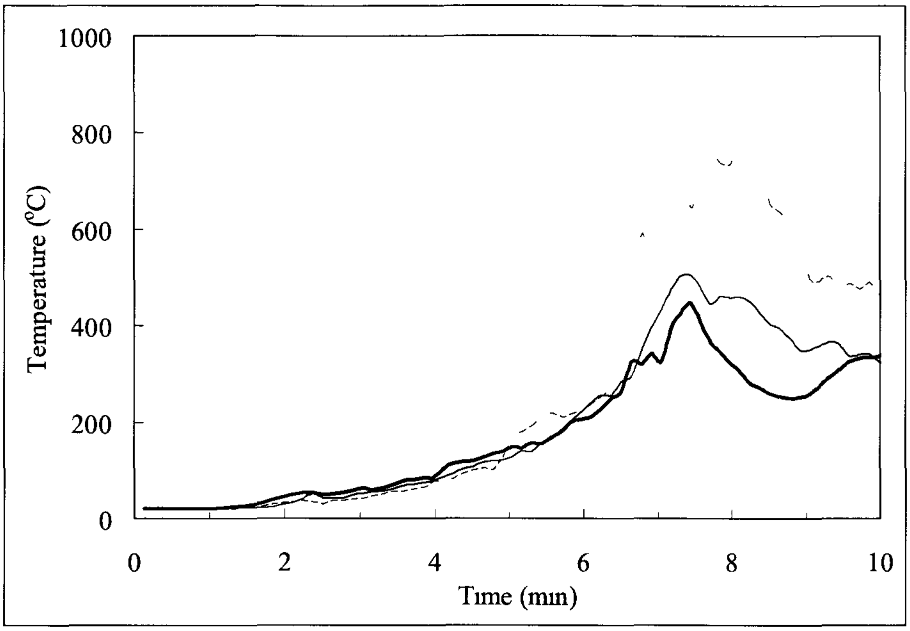


Figure 6-25: Lower layer temperatures for detached home bedroom fires, 3.6-m^2 openings

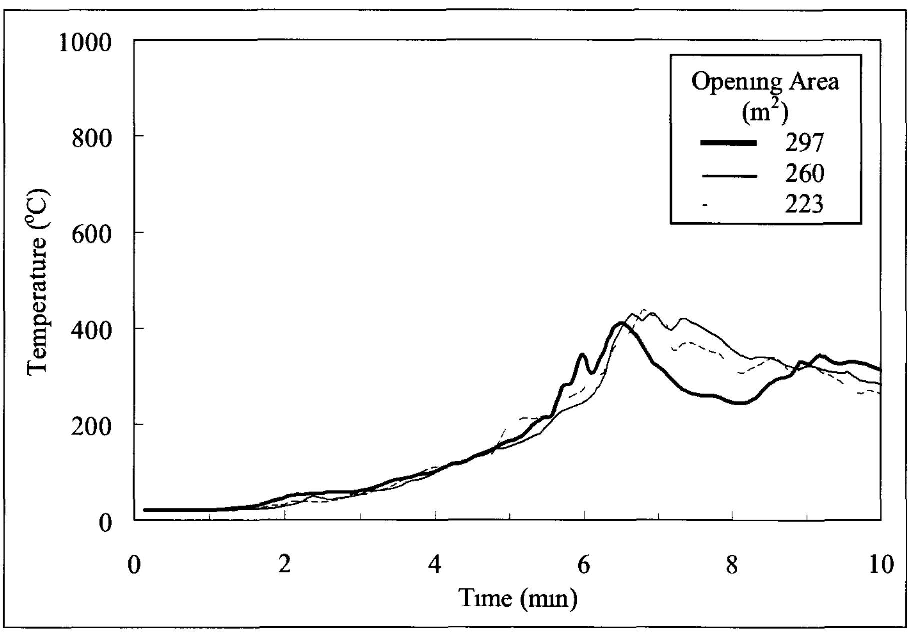


Figure 6-26: Lower layer temperatures for detached home bedroom fires, 2.4-m^2 openings

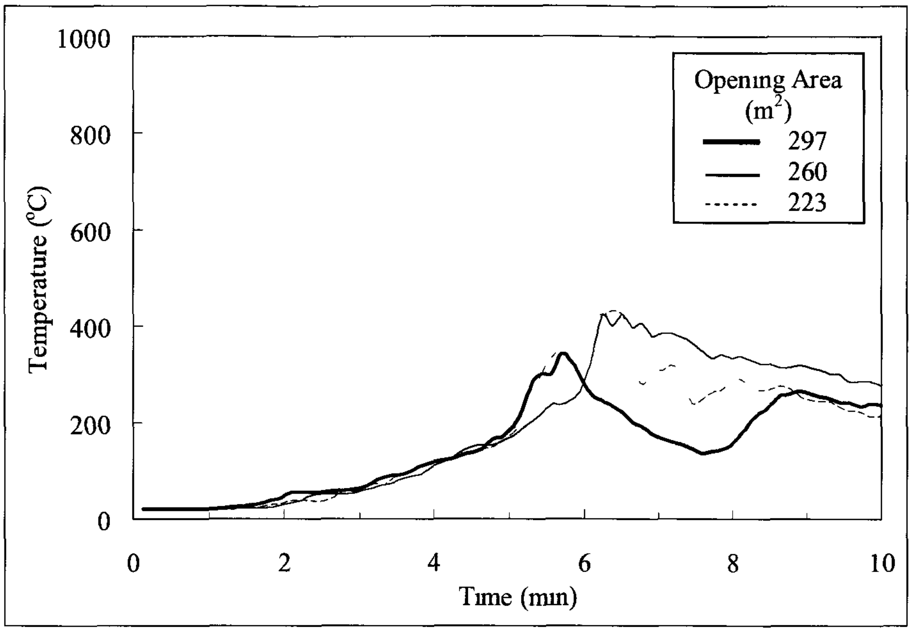


Figure 6-27: Lower layer temperatures for detached home bedroom fires, 1.8-m^2 openings

6.2.1.3 Flashover

Flashover occurred consistently around 300 s for all of the homes, see Table 5-14. For the opening area sizes considered, total floor area does not seem to be an important factor in determining flashover for large fires in small enclosures.

6.2.1.4 Device Activation

From Table 5-15, it can be seen that the larger floor area had a slight delay for smoke alarm activation. This is more related to house geometry since a smoke detector in the centre of the hallway is further from the initial location of the fire in the larger houses.

No trend was observed for heat detectors or sprinklers. Sprinkler placement is closely tied to geometry, specifically wall (obstruction) locations, which may affect sprinkler activation times.

6.2.1.5 Tenability and Smoke Movement

The time taken to reach tenability criteria (toxicity, thermal conditions) was not affected by floor area since there is no apparent trend, (Table 5-16), except at Location 'C' where an increase in floor area allowed more time for egress. The time to visibility criteria, however, was longer in the larger houses for Locations 'A', 'B', and 'C'. There was only a 6 s difference in the time to diminished visibility conditions in the room of fire origin, but there was a full minute difference at the top of the stairs. This is an important location since it is the only means of egress from the 2nd floor.

6.2.2 Townhomes

6.2.2.1 Heat Release Rate Histories

The largest house reaches a slightly higher value at the first peak around 4 minutes, Figure 6-28, Figure 6-29, and Figure 6-30. The 167 and 149-m^2 houses display very little difference in the time to reach the first peak and its corresponding value. Once this peak is reached, the oxygen levels in the room are significantly reduced so the fire begins to burn near the window.

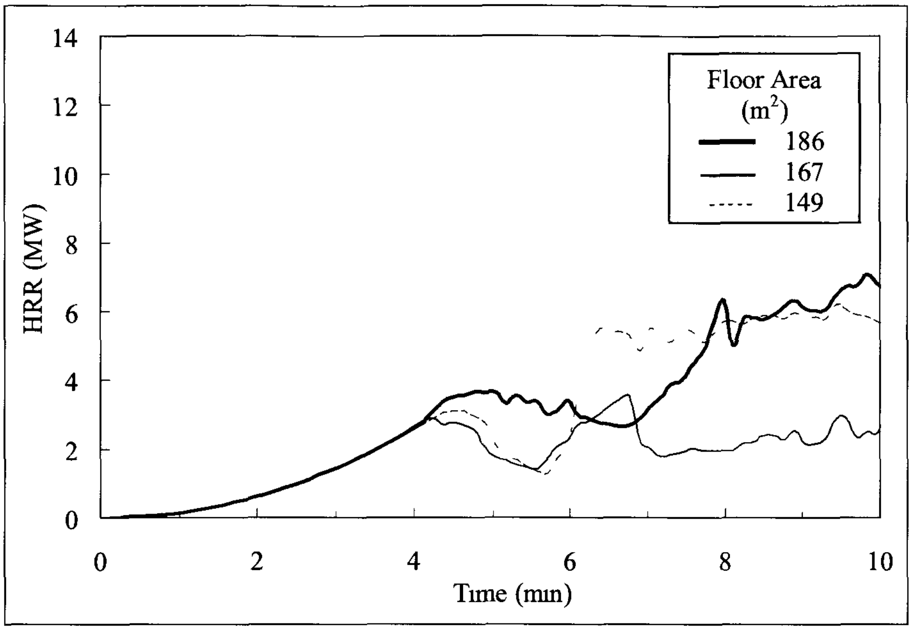


Figure 6-28: Heat release rates for townhome bedroom fires, 2.4-m^2 openings

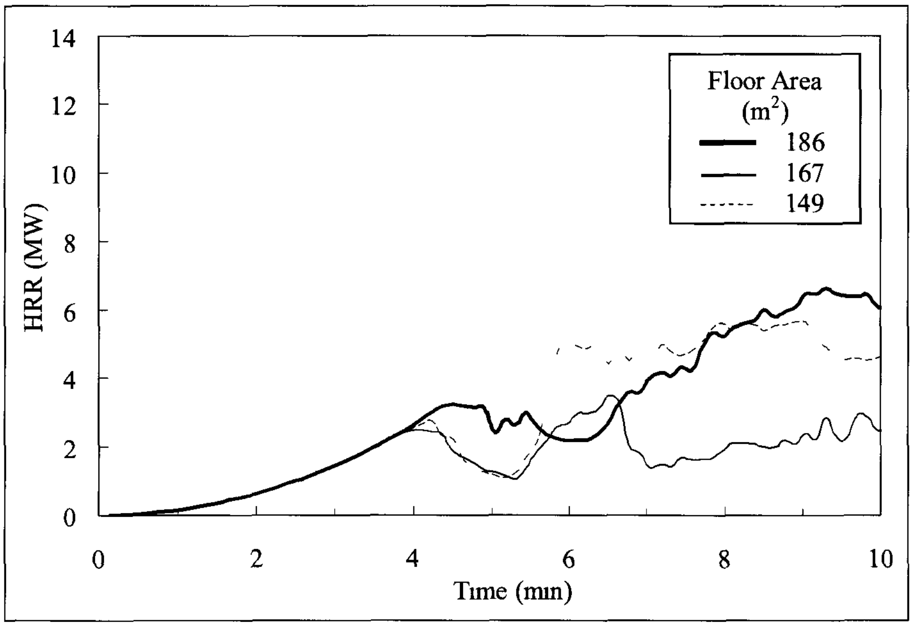


Figure 6-29: Heat release rates for townhome bedroom fires, 1.8-m^2 openings

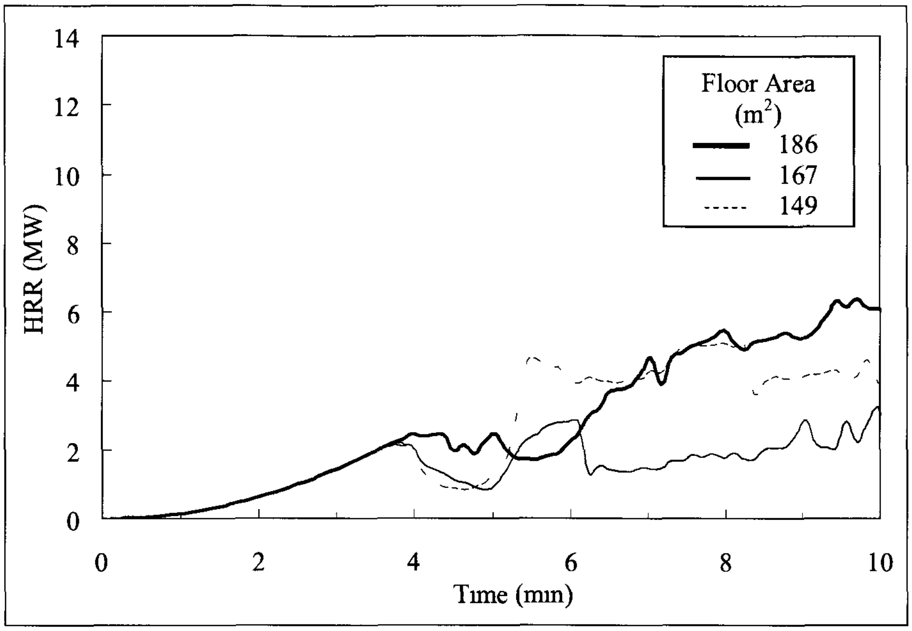


Figure 6-30: Heat release rates for townhome bedroom fires, 1.2-m^2 openings

6.2.2.2 Temperature Profiles

None of the upper layer temperatures reach flashover (600°C) since the opening areas are so small, Figure 6-31, Figure 6-32, and Figure 6-33. Temperatures in the smaller houses seem to rise slightly more quickly.

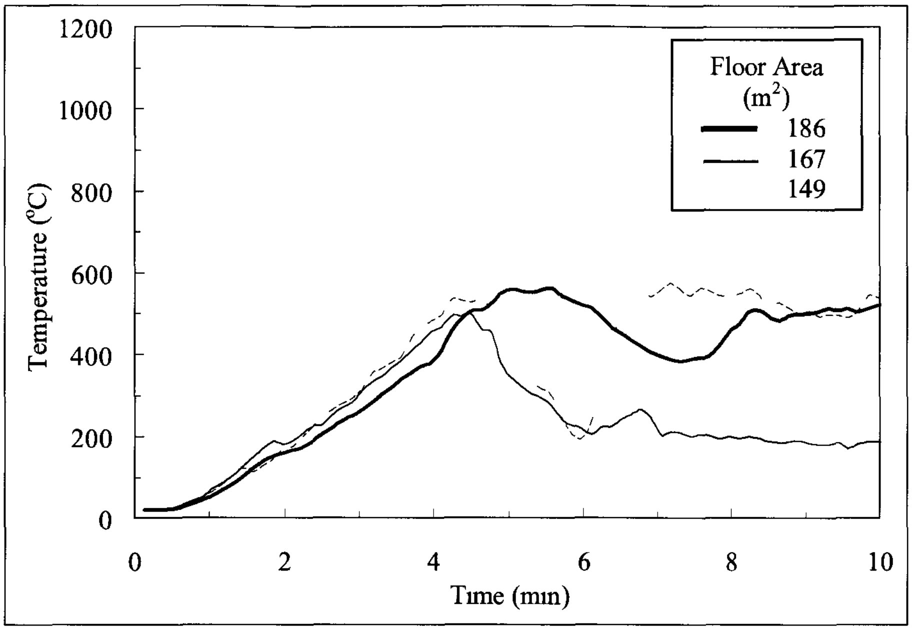


Figure 6-31: Upper layer temperatures for townhome bedroom fires, 2.4-m^2 openings

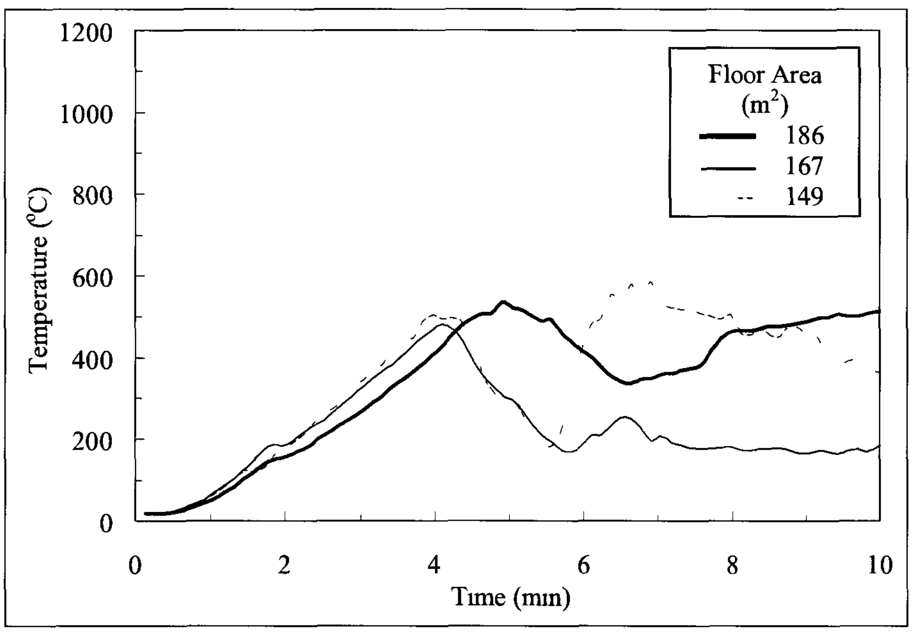


Figure 6-32: Upper layer temperatures for townhome bedroom fires, 1.8-m^2 openings

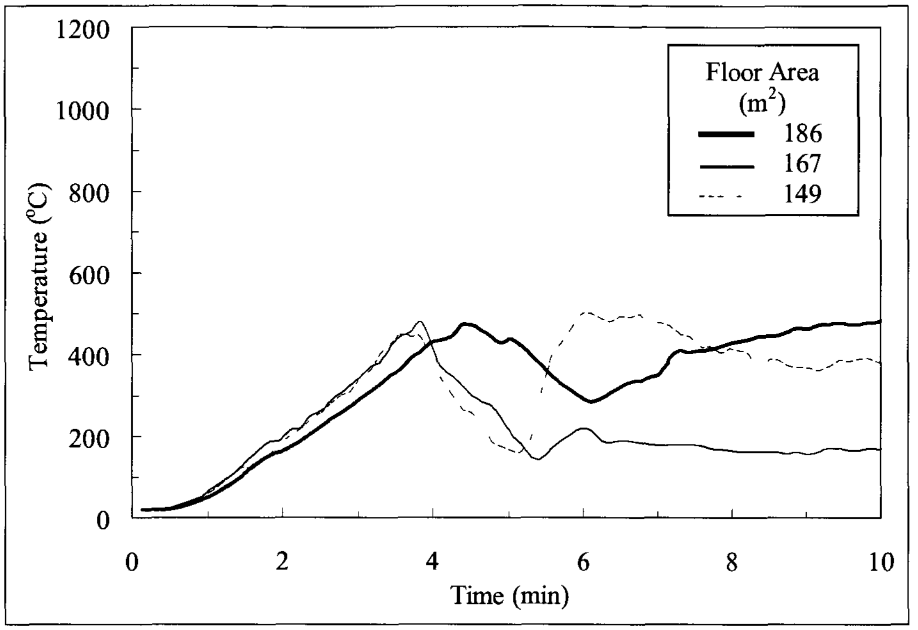


Figure 6-33: Upper layer temperatures for townhome bedroom fires, 1.2-m^2 openings

Lower layer temperatures stay relatively low in these townhome bedroom simulations, Figure 6-34, Figure 6-35, and Figure 6-36. The lower layer temperatures for the 2.4-m^2 openings were maintained roughly at 200°C, 1.8 m^2 at 150°C, and for the 1.2 m^2 at 100°C.

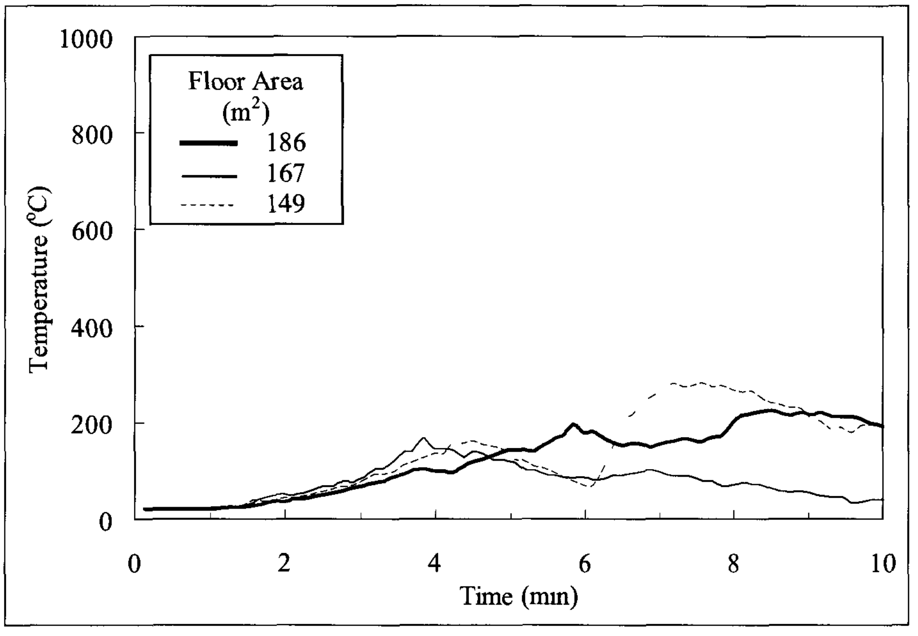


Figure 6-34: Lower layer temperatures for townhome bedroom fires, 2.4-m^2 openings

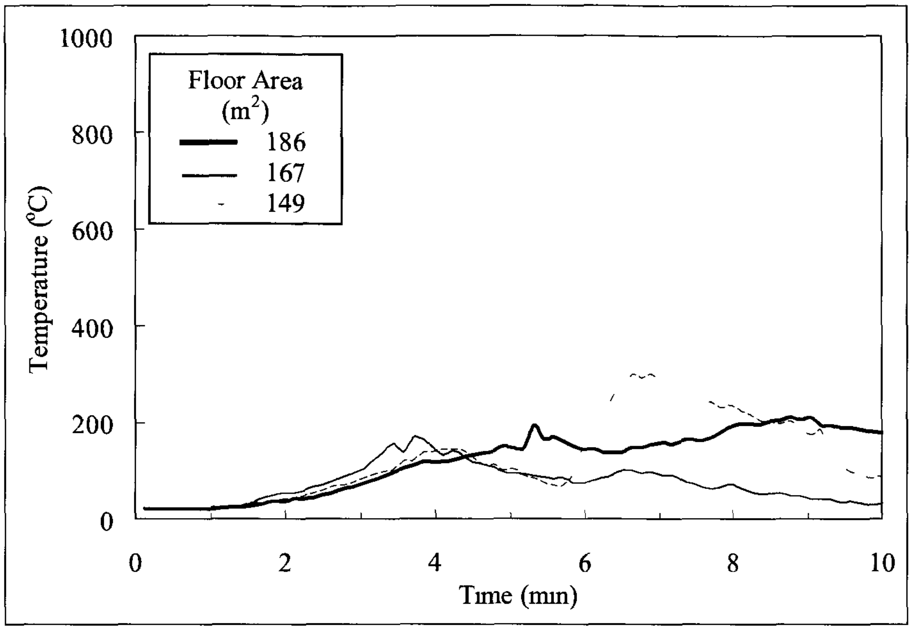


Figure 6-35: Lower layer temperatures for townhome bedroom fires, 1.8-m^2 openings

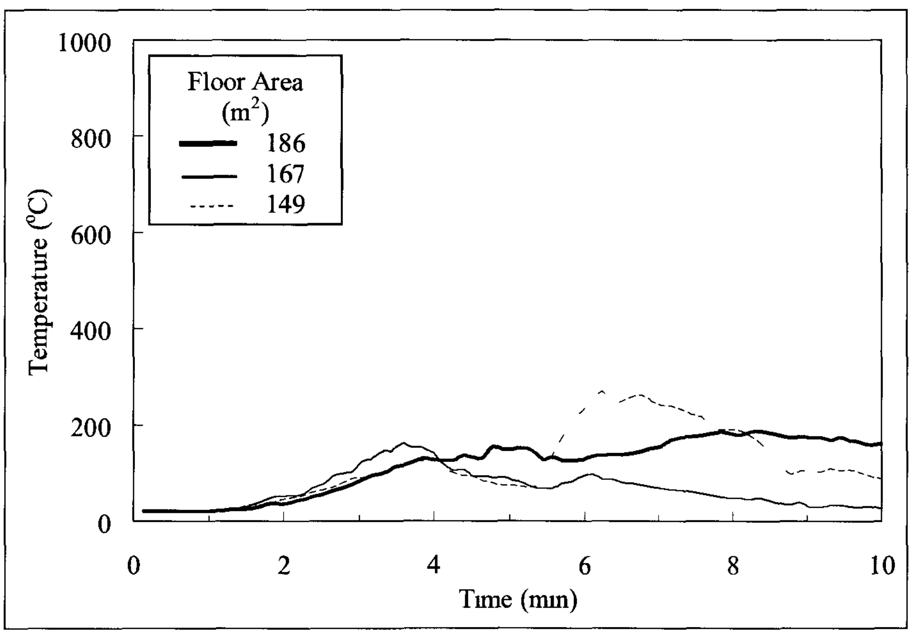


Figure 6-36: Lower layer temperatures for townhome bedroom fires, 1.2-m^2 openings

6.2.2.3 Flashover

No trends were seen in the time to flashover in relation to the floor areas considered, Table 5-19.

6.2.2.4 Device Activation

All devices were activated at essentially the same time, Table 5-20. The distance to these devices was not constant for all houses since their placement depended on geometry and room size, therefore it is difficult to compare these values. What is important is that they were all activated within a short period of time from each other.

6.2.2.5 Tenability and Smoke Movement

The times to reach toxicity criteria generally decreased when the floor area was decreased, but these times were very similar at Location 'A' for all houses and opening areas, around 190 s, Table 5-21. Thermal criteria were reached around 135 s for Location 'A', but no trend was seen for Locations 'B' and 'C'. Visibility was poor after 45 s at Location 'A' and was therefore unaffected by floor area.

6.3 Summary

6.3.1 Heat Release

In the detached home fires larger floor areas lead to lower peak HRRs, for both living room and bedroom fires. In these living room fires this was related to a delay in fire to spread since the distance between the burner and combustible items was greater; in the largest house the fire did not spread to in all of the simulations. Also, windows outside the room of fire origin broke earlier in houses with smaller floor areas, allowing HRRs to reach higher levels.

The townhome fires have lower peak HRRs than the detached homes, mainly because the window sizes are smaller in the townhomes. The townhome fires had reverse effects with respect to HRR. The HRR increased with floor area. This was attributed to the ratio of A_T to room area increasing for smaller floor areas and a higher ratio resulted in lower peak HRRs. Having a high A_T meant that walls shielded some parts of the room from the fire, which resulted in lower HRRs

6.3.2 Temperatures

In detached home fires where flashover occurred, upper layer temperatures ultimately reached the same maximum value at around 1000°C in living room fires and 800°C in bedroom fires. Similar temperatures would be expected when opening area is kept constant, since maximum temperatures are a function of A_V, and H_V (Equation 3-9). The only other factor affecting the maximum temperatures is A_t, which doesn't produce a significant difference in results when floor area is varied.

In comparison, townhome fires reached the peak upper layer temperatures more quickly since the walls and ceilings of the smaller rooms provide more radiative heat feedback to the fire. Townhome bedroom fires reached peaks just below 600°C; therefore the rooms did not experience flashover. The fire concentrated burning near the window, and appeared to continue burning outside the room of fire origin for a portion of time which reduced the HRR and prevented flashover from occurring.

6.3.3 Window Breakage

Windows in the living room fires broke slightly earlier for smaller total floor area houses. First window breakage was consistent at around 2.3 minutes for both types of homes. The doors broke later in the townhomes due to the geometry effects.

In the bedrooms, windows broke earlier for smaller floor areas, therefore they broke earlier in the townhomes. They all roughly broke at around 1.7 minutes.

6.3.4 Flashover

For the detached home living room fires, flashover occurred earlier in smaller houses. This is consistent with findings in the CBUF, where higher average mass loss rates were observed in smaller rooms, as would be expected from the larger amounts of heat being radiated from the walls and hot upper layer, implying that smaller rooms reach flashover conditions more quickly [59].

The time to flashover in townhome living room fires varied for each of the opening areas. The complex geometries of the rooms (with higher surface areas than the detached home) likely was a predominant factor in the time to flashover.

The detached home bedroom fires consistently reached flashover at 300 s. The small rooms and small openings provided no room for variability. Flashover did not occur in the townhome bedroom fires. A large portion of the fire appeared to burn near the windows and outside the room. This lowered the HRR and prevented the room from reaching flashover.

6.3.5 Device Activation

All device activation times in the townhome living room fires decreased with floor area, but the differences were re only a few seconds and would most likely not have a huge impact on the life safety. Smoke detector activation was consistently close to 27 s. Smoke alarms activated later, at around 45 s for bedroom fires, since the detectors were located outside the room of fire origin. Heat detectors in living room fires activated at around 105 s. For the bedroom fires, heat detectors activated earlier in townhomes by about 30 s. Sprinklers activated in the living room fires at around 113 s, and 99 s in the bedroom fires.

6.3.6 Tenability

For all cases examined there was no apparent trend between toxicity and floor area at Location 'A', except that criteria were reached earlier in the townhomes. House geometry is a likely cause of the variations. Visibility criteria were reached consistently at around 60 s in the living room, and at around 50 s in the bedrooms.

Comparing tenability criteria at Location 'B' and 'C' is difficult since they are closely linked to the house geometry. But generally toxicity, thermal, and visibility criteria were reached earlier in the townhomes for living room and bedroom fires.

6.3.7 Implications for life safety

The safest house for occupants seemed to be those with the largest floor area for detached homes. A larger house hinders the spread of the fire, providing extra time for occupants to evacuate; therefore townhomes pose a greater risk to life safety.

Bedroom fires have smaller openings than living room fires and therefore reached lower peak HRRs. But the small room area posed a greater risk to life safety, where tenability criteria were exceeded earlier. Bedroom fires can be especially dangerous since they are likely to occur at night while occupants in the house are sleeping.

7 MODEL COMPARISON WITH THEORETICAL EQUATIONS

7.1 Living Room Fires

The expected peak HRRs, using Equation 3-2, for a fire with the window areas of 5.6 or 6.5 m^2 are shown in Table 7-1. This equation was intended to apply to a simple room where air enters through a single window, which is not the case in this project. The geometry of the living rooms, although generally rectangular overall, contains walls and obstructions that would introduce complexity to the model. Also the windows are not necessarily located on a single wall, which would likely create more turbulence in the hot upper layer interface. Another factor that influences the results is that these rooms are not enclosed by a door; the space is open to the remainder of the house. Therefore as more windows break, more opening area will be introduced into the system which would potentially result in a higher HRR, which was observed in the majority of the simulations.

Table 7-1: Theoretical values for living room fires with 5.6-m^2openings for detached and 6.5-m^2openings for townhomes

Total Floor Area (m^2)	Theoretical Max HRR (MW)	FDS Max HRR (MW)	Theoretical Max Temp (°C)	FDS Max Temp (°C)
297	10.6	9.2	1200	755
260	10.6	15.7	1210	1047
223	10.6	17.1	1170	1127
186	12.2	12.4	1072	1221
167	12.2	11.7	1145	923
149	12.2	14.3	1165	717

Equation 3-9 was used to determine the theoretical maximum temperatures that would be observed in the upper layer. A simplified rectangular geometry was used. The FDS values were taken as the highest measured upper layer temperature. Since the maximum temperature equation has two Ω terms, it is difficult to make a generalization about the affect of increasing this value or it's component terms (A_V and A_t). For these reasons it is difficult to predict whether the values in the model should be higher or lower than the theoretical values in this case. There are complex interactions occurring between the fire and the opening area, total surface area, and geometry of the house. When comparing the theoretical values to the FDS predicted values, several are very similar or higher than the FDS values.

The maximum upper layer temperatures are important for assessing when flashover has occurred, but ultimately flashover is a function of HRR. Therefore Equation 3-3, Equation 3-4, and Equation 3-5 are used to determine the HRR that should cause flashover in a room of similar dimension. The results are listed in Table 7-2 for detached homes with 5.6 m^2 of opening area and townhomes with 6.5 m^2 and are compared to the values found using FDS. The max HRR from FDS is taken once all of the windows have broken in the room of fire origin but before windows break in the rest of the house. All of the equations used are again linked to total opening area. Babrauskas's equation is the simplest and basically states that as more opening area is present, a higher HRR will be required to cause flashover. Generally windows breaking outside the room of fire origin were a result of high flashover temperatures, but there is a hallway connecting this room to the rest of the house which acts as an opening area since there is a supply of air in the rest of the house. For this reason, higher values would be expected in the model, which was the case for the detached homes.

The MQH and Thomas criterion are both directly proportional to A_V and A_t. So again, the rough value used in calculating the equations is likely underestimated and would therefore generate lower values than would be expected from the model. Flashover in the 167-m^2 house is lower in the FDS prediction than all of the theoretical models.

Table 7-2: Theoretical values for living room flashover with 5.6-m^{2}openings for detached and 6.5-m^{2}openings for townhomes

Total Floor Area (m^2)	Babrauskas (MW)	MQH (MW)	Thomas (MW)	FDS (MW)
297	5.3	4.1	4.0	5.1
260	5.3	3.9	3.9	5.3
223	5.3	3.1	3.4	5.0
186	6.1	4.5	4.3	5.3
167	6.1	4.0	3.9	2.1
149	6.1	3.8	3.8	5.3

Flashover occurred much later in the FDS living room that in the Kemano tests. The living rooms in the Kemano test, however, were much smaller in area.

The smoke detector activation times in the Dalmarnock fire test (Section 3.10.1) are almost identical to those found in these FDS simulations (Table 5-6). The activation criteria were less intense and the floor area was much smaller in the Dalmarnock tests, but the ceiling height was 0.3 m taller. So it is difficult to say which detector would have activated first, but it is apparent that the two were activated within a reasonable timeframe of the each other.

Sprinklers were activated in the Kemano sprinkler test at 59 s into the fire, but these were quick response sprinklers rated to 68.3°C. In the FDS model sprinklers rated to 74°C were activated at 117 s in the detached homes and at 110 s in the townhomes.

In the Kemano tests where the integrity of the structure was challenged, untenable conditions were always exceeded before the structure was involved in the fire. This was the same as what was seen in the FDS models, where tenability criteria were always exceeded in the first few minutes.

7.2 Bedroom Fires

All of the equations used above can also be applied to assess the validity of the bedroom fire results as well. The size of the door is incorporated into the calculation of A_V for these rooms because it is a well defined opening, unlike in the living room models.

FDS predicted higher HRR values than the theoretical maximum for the detached homes which would be expected, Table 7-3. But the values for the townhome fires were under predicted. In these simulations the fire began to burn in the centre of the room, but once windows broke the fire became concentrated at the windows. It is believed that the fire continued to burn outside the room, which explains why there is a decrease in HRRs and temperatures. This is not realistic of an actual bedroom fire; however this happens later in the fire and does not affect the time to major events that occur early in the fire (tenability criteria, device activation). Due to the manner in which the fire was modeled, the fire was not able to spread to other combustible items that would likely be found in a bedroom.

The maximum temperatures recorded in the upper layer were almost always higher than the theoretical values.

The HRRs recorded just before flashover were found to be within the range given by the three equations, Table 7-4. This indicates that FDS did an accurate job of assessing upper layer temperatures and heat fluxes. The FDS values were always higher than the MQH values and were mostly higher than the Thomas flashover criterion. The values were always lower than Babrauskas' estimates.

Table 7-3: Theoretical and measured values for bedroom fires with 2.4-m^2 openings

Total Floor Area (m^2)	Theoretical Max HRR (MW)	FDS Max HRR (MW)	Theoretical Max Upper Layer Temp (°C)	FDS Max Upper Layer Temp (°C)
297	7.2	12.7	893	984
260	9.4	14.6	933	914
223	9.5	12.1	986	748
186	9.5	7.7	1096	670
167	9.5	7.1	1073	711
149	10.3	6.8	1116	820

Table 7-4: Theoretical and measured values for bedroom flashover with 2.4-m^2 openings

Total Floor Area (m^2)	Babrauskas (MW)	MQH (MW)	Thomas (MW)	Actual (MW)
297	3.6	2.8	2.7	4.5
260	4.7	3.0	3.2	4.4
223	4.8	2.9	3.1	3.9
186	4.8	2.4	2.9	3.6
167	4.8	2.5	3.0	2.8
149	5.1	2.5	3.1	3.1

8 CONCLUSION

A fast t^2 fire occurring in a living room of two-storey single-family detached homes and townhomes was modeled using FDS, where three total floor areas were examined for each type of house. The sizes used for the detached homes were 297 m^2, 260 m^2, and 223 m^2; whereas, the sizes for the townhomes were 186 m^2, 167 m^2, and 149 m^2. Both living room and bedroom fire scenarios were examined. The goal was to study the affect of varying opening area in the room of fire origin and total floor area to assess the impact of fire growth and the time to major fire events (such as flashover, window breakage, and reaching tenability criteria).

The major findings of this study include no impact on the time to device activation or visibility impeding egress when opening area or floor area was altered. For both types of houses visibility was the first major event to impede egress, and CO_2 was the first untenable condition to exceed limits related to toxicity.

Results indicated that an increase in opening area resulted in higher peak HRRs. For fire scenario in the detached home living room, the time to peak was delayed as opening area increased. In addition, more opening area provided extra time for egress; which was not true for townhomes.

An increase in floor area also resulted in lower peak HRRs and upper layer temperatures, as well as, longer time to reach peaks and flashover in detached homes. In comparison, for townhomes the duration of high HRRs was longer for smaller floor areas, as well as, townhomes had more drastic drops in temperatures especially when windows broke.

In terms of life safety, a large house with larger opening areas will provide the longest time before flashover is reached and the longest times to untenable conditions. However, these criteria are associated with the least affordable type of housing, making them less likely to be built in urban areas. Smaller, more compact townhomes are the more likely option. Unlike the detached homes, the times to untenable conditions in townhomes were essentially unaffected by increasing the opening area.

9 RECOMMENDATIONS FOR FUTURE WORK

Determining the characteristics of a residential house fire can be very difficult due to the numerous variables involved. It is very difficult to generalize the contents of a house, since occupants have ultimate control over the items they choose to furnish it with and where they place their items; both contents and furniture placement play a significant role in shaping the growth of a fire. Residential fires are some of the most deadly and devastating fires in Canada, for this reason they warrant more research.

It would be ideal to conduct a series of large-scale house experiments to assess the validity of the predicted FDS results. However, due to expenses this is likely not feasible. Some smaller room fire tests (which are more feasible) could be performed using the specified room and window sizes and burner HRR to verify HRRs, time to flashover, and toxic concentrations.

The same research methodology could also be applied using other models to see how each predicts fire growth and how that compares to the FDS predictions. Each type of model has its own limitations which affect the results.

Further FDS modeling could be performed using detached homes and townhomes of different overall floor area size to broaden the database of information for designers. This would also help to further confirm trends that were observed.

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APPENDIX A

FED Calculations

Fractional Effective Dose (FED): An excerpt from FDS User's Guide [73]

The Fractional Effective Dose index (FED), developed by Purser [67] is a commonly used measure of human incapacitation due to the combustion gases. The present version of FDS uses only the concentrations of the gases CO, CO_2, and O_2 to calculate the FED value as

$$FED_{TOT} = FED_{CO} \times HV_{CO_2} + FED_{O_2}$$

The fraction of an incapacitating dose of CO is calculated as

$$FED_{CO} = 4.607 \times 10^{-7} (C_{CO})^{1.036} t$$

where t is time in seconds and CCO is the CO concentration (ppm). The fraction of an incapacitating dose of low O_2 hypoxia is calculated as

$$FED_{O_2} = \frac{t}{60 \exp\left[8.13 - 0.54\left(20.9 - C_{O_2}\right)\right]}$$

where C_{O2} is the O_2 concentration (volume per cent). The hyperventilation factor induced by carbon dioxide is calculated as

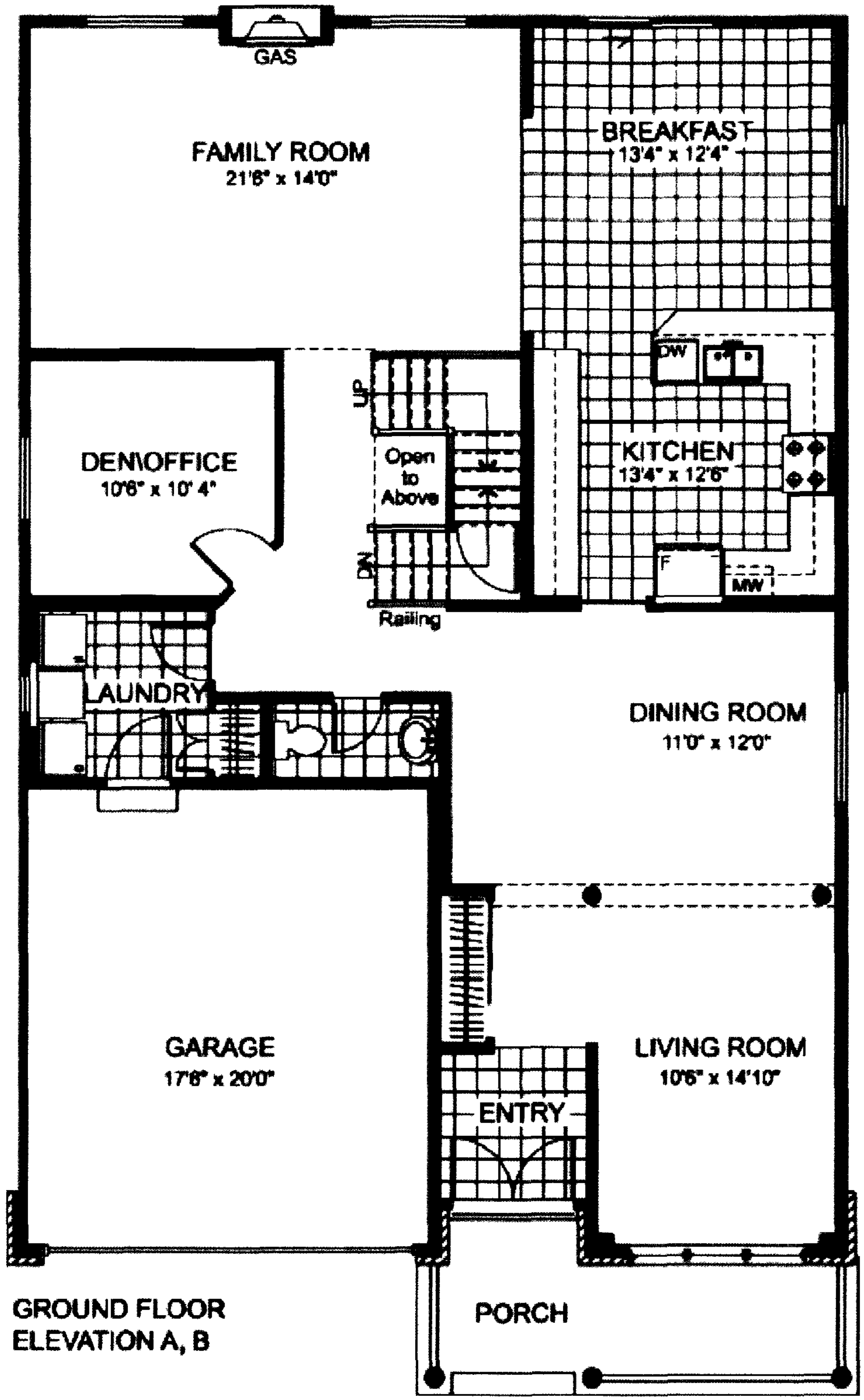
$$HV_{CO_2} = \frac{\exp\left[0.1930 C_{CO_2} + 2.0004\right]}{7.1}$$

where C_{CO2} is the C_{O2} concentration (percent).

APPENDIX B

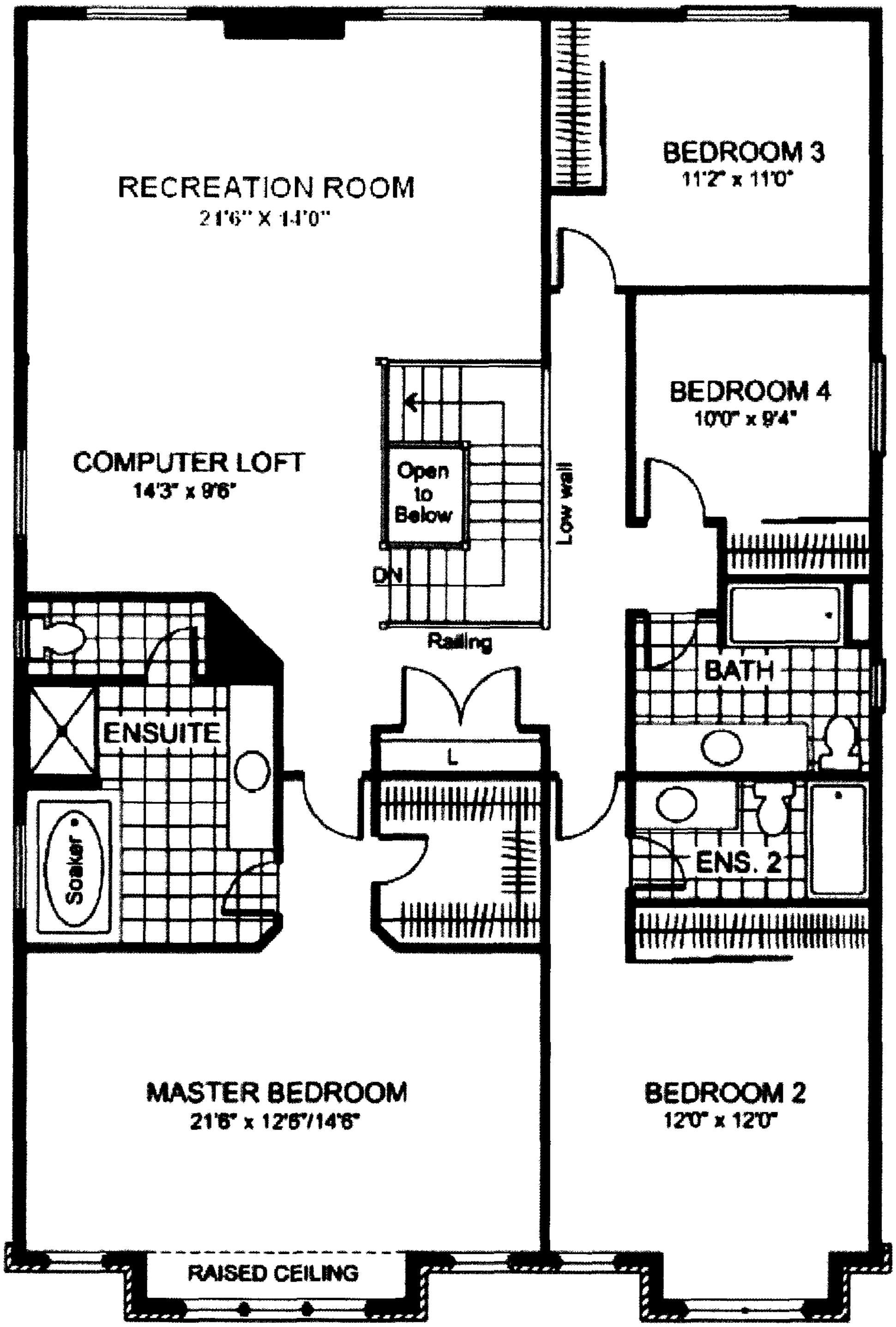
House Geometries

[93]



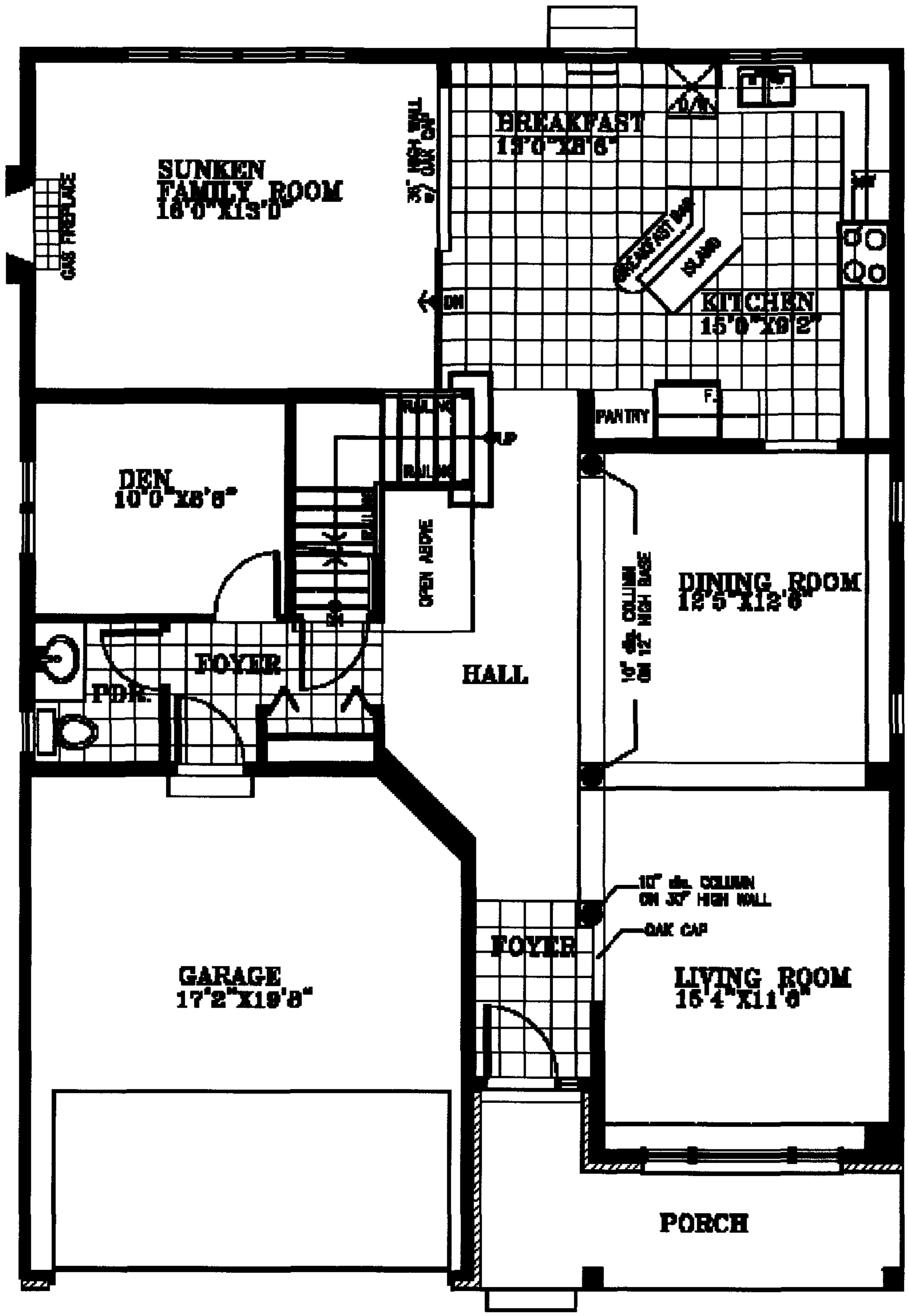
NAME	FLOOR AREA	BUILDER	FLOOR
Westmount	3200 sq ft	Minto	Ground

[93]



SECOND FLOOR
ELEVATION A

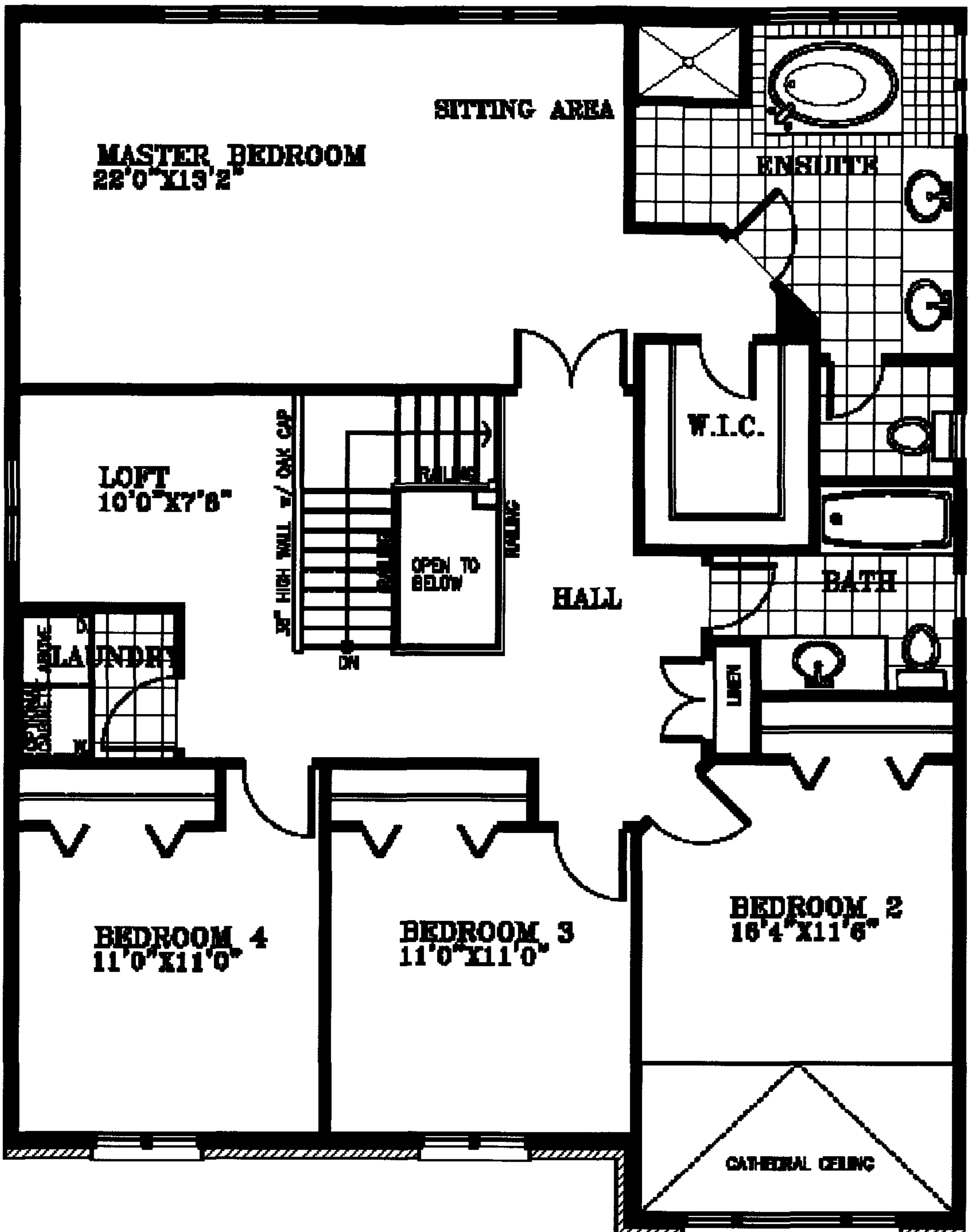
NAME	FLOOR AREA	BUILDER	FLOOR
Westmount	3200 sq ft	Minto	Second



GROUND FLOOR PLAN
1275 sq. ft.

[94]

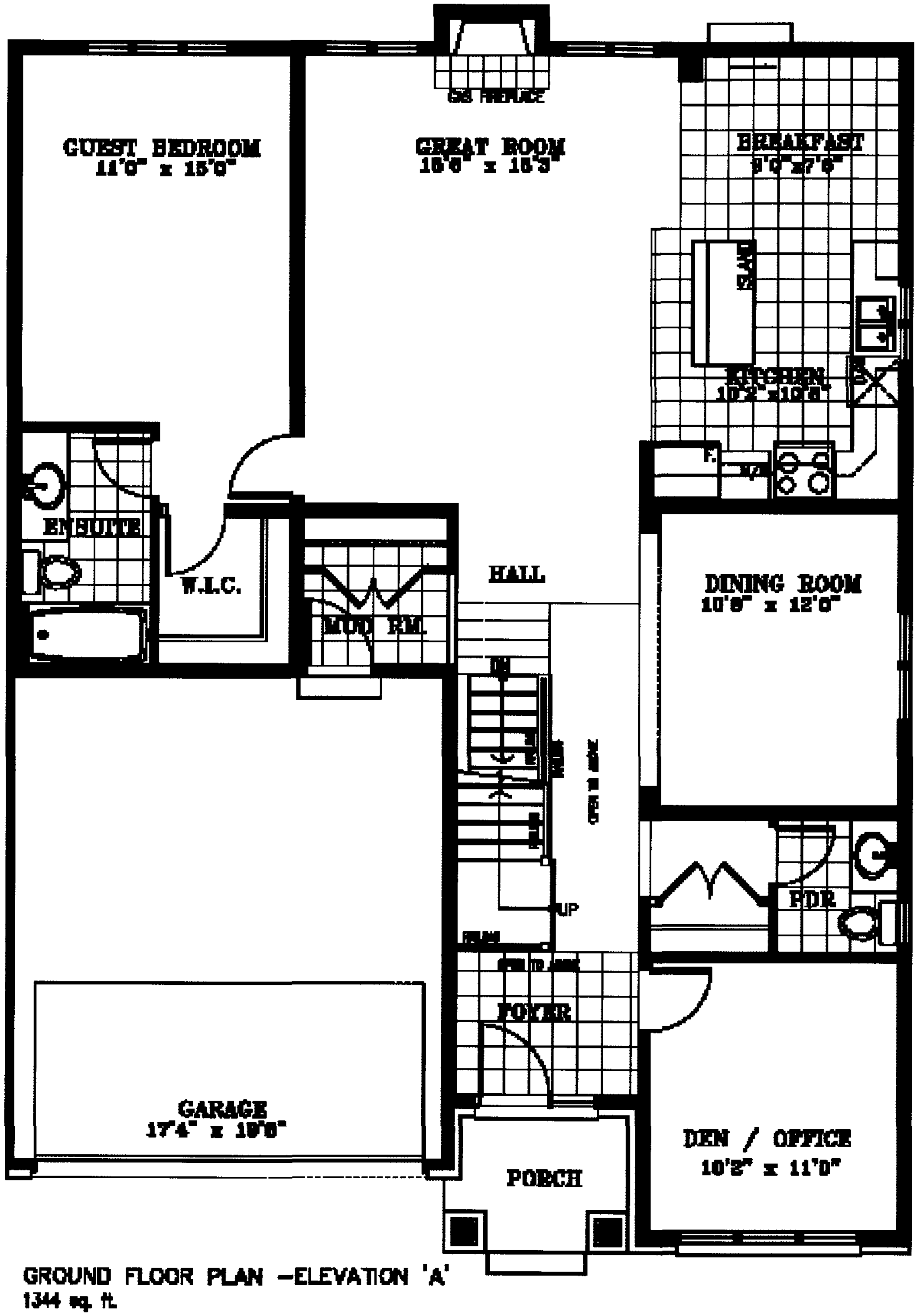
NAME	FLOOR AREA	BUILDER	FLOOR
Jasper	3700 sq ft	Ashcroft Homes	Ground



SECOND FLOOR PLAN – ELEV. "B"
1495 sq. ft. inc. 20 sq. ft. open to below

[94]

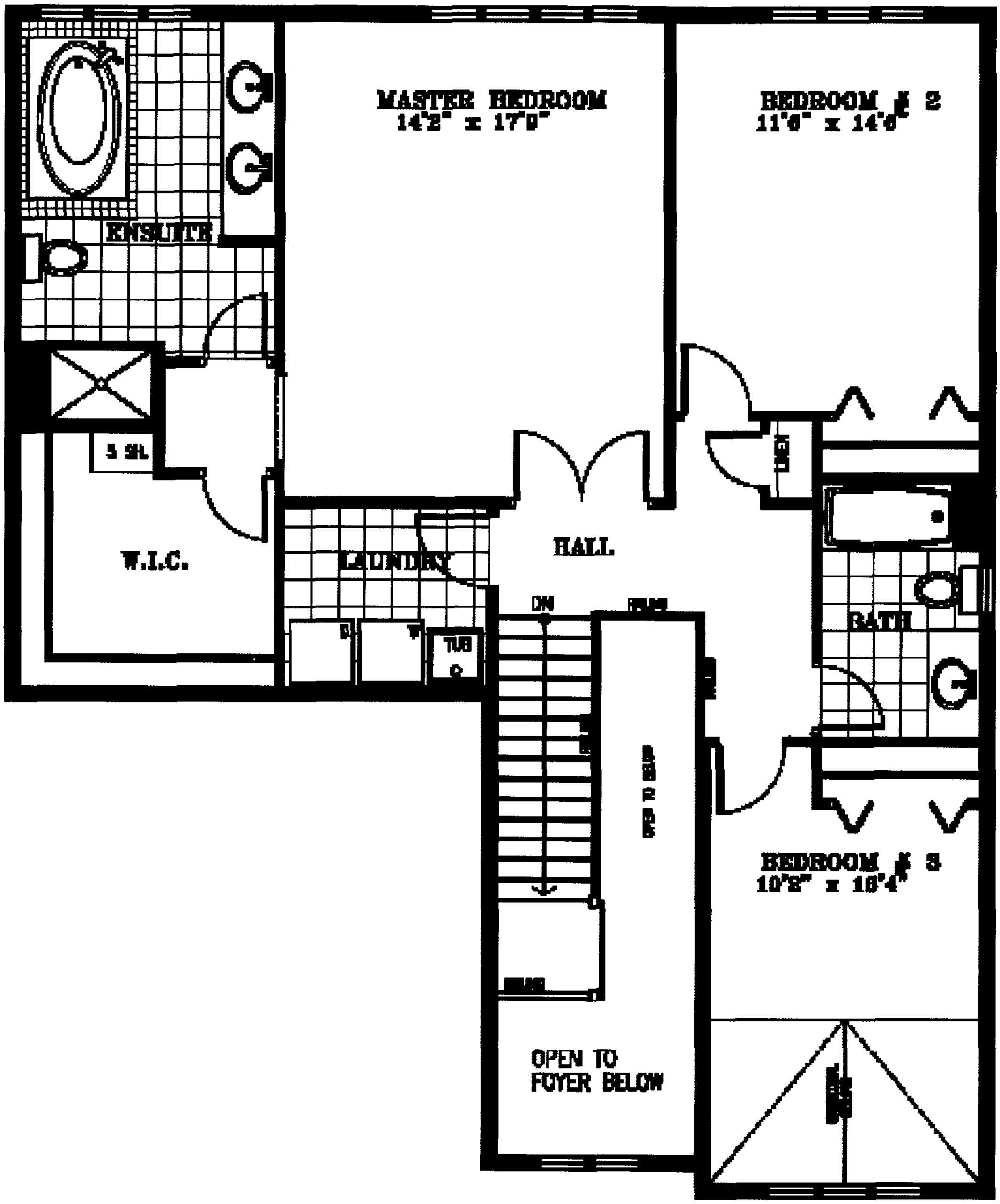
NAME	FLOOR AREA	BUILDER	FLOOR
Jasper	2700 sq ft	Ashcroft Homes	Second



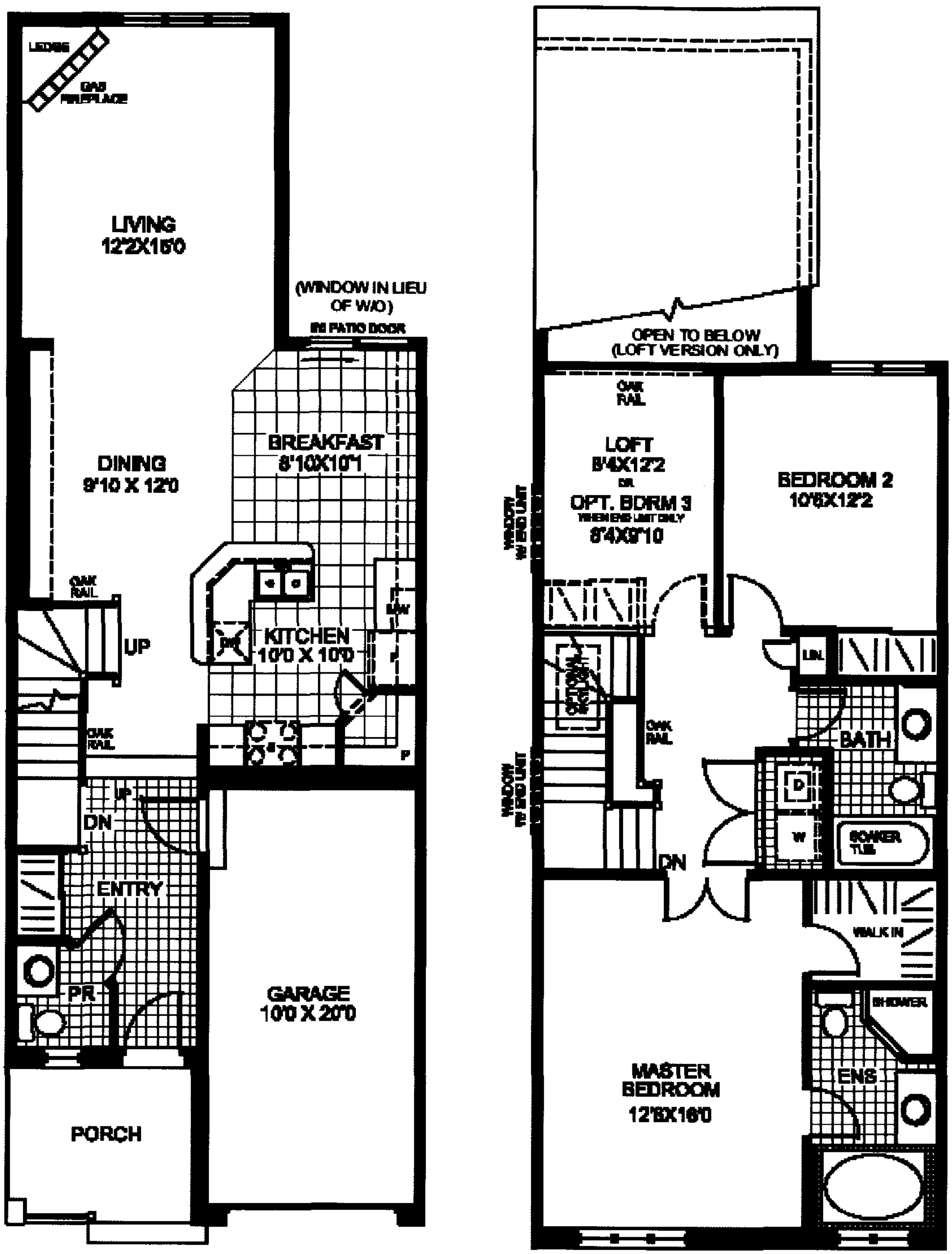
[95]

Name	Floor Area	Builder	Floor
Bonnechere	2418 sq ft	Ashcroft Homes	Ground

[95]

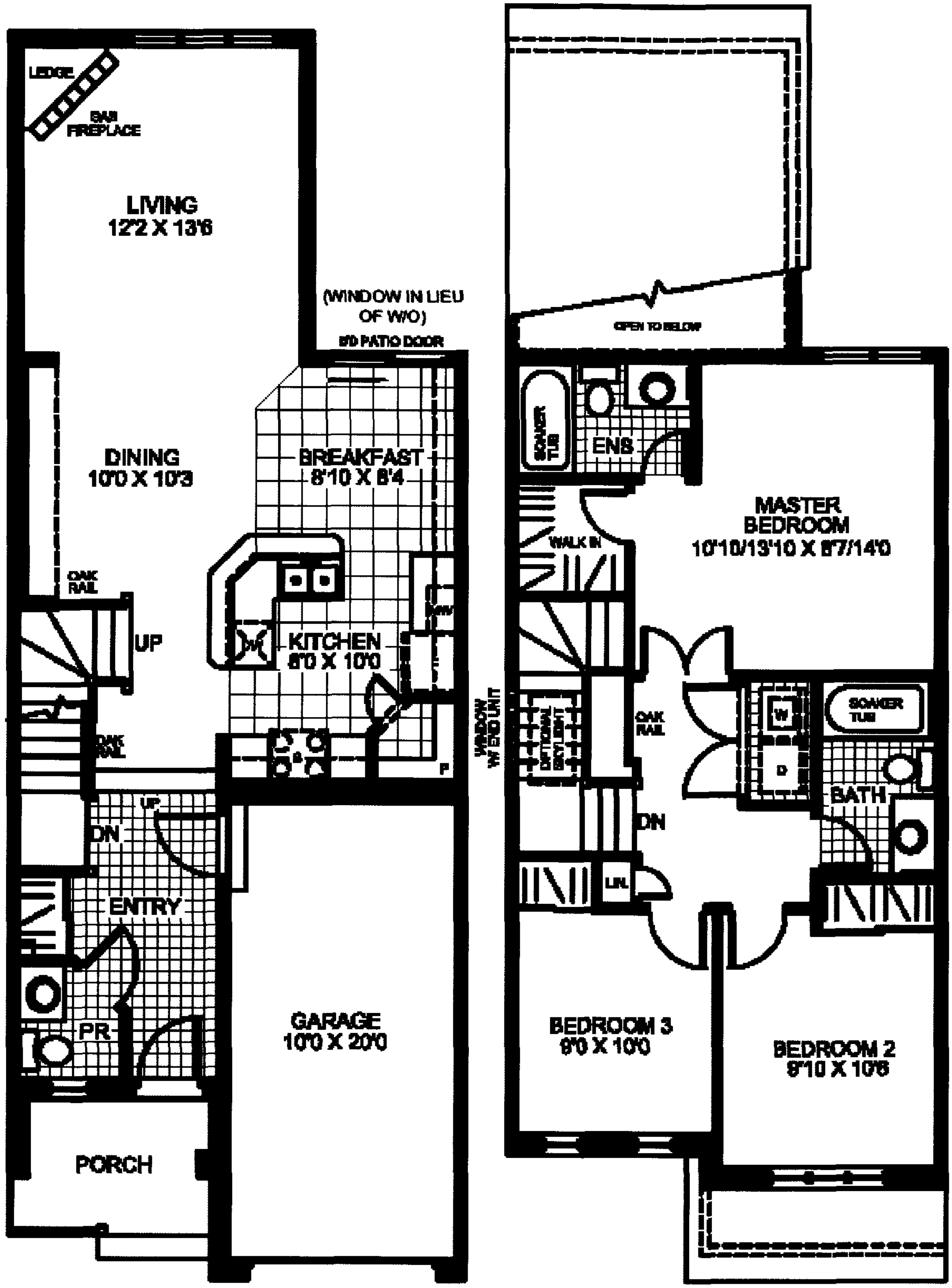


NAME	FLOOR AREA	BUILDER	FLOOR
Bonnechere	2418 sq ft	Ashcroft Homes	Second



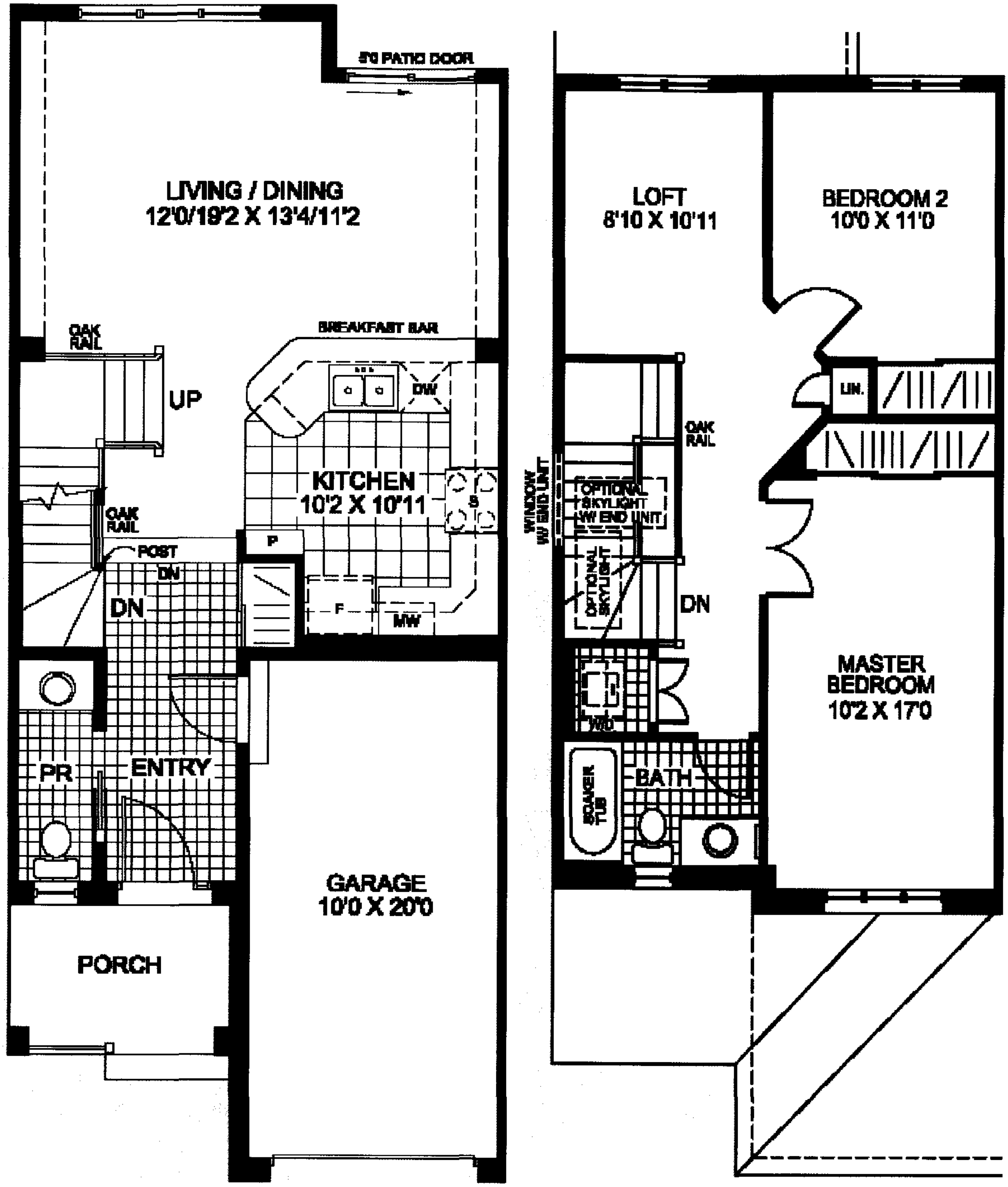
[96]

NAME	**FLOOR AREA**	**BUILDER**
Pasadena	2010 sq ft	Urbandale



[97]

Name	**Floor Area**	**Builder**
Frisco II	1798 sq ft	Urbandale



[98]

NAME	FLOOR AREA	BUILDER
Delmar	1534 sq ft	Urbandale

APPENDIX C

FDS Grid Resolution [99]

$$D^* = \left(\frac{\dot{Q}(kW)}{1100} \right)^{2/5}$$

The maximum recommended cell size to adequately describe a fire of this size would be 56 cm

$$D^* = \left(\frac{15000}{1100} \right)^{2/5}$$

$$D^* = 2.84$$

$$10\% = 28.4$$

$$20\% = 56.8$$

D*: characteristic fire diameter (m)
D: diameter of the fire (m)
Q: heat release rate of the fire (kW)
p: density, 1.204 kg/m^3
c_p: specific heat, 1.005 kJ/kg/K
T: temperature, 293 K
g: acceleration due to gravity, 9.81 m/s^2
R*: ratio of grid size to characteristic fire diameter

$$D^* = \left(\frac{\dot{Q}}{\rho c_p T \sqrt{gD} D^2} \right)^{2/5} D$$

$$D^* = \left(\frac{15000}{1100\sqrt{1.13}(1.13)^2} \right)^{2/5} 1.13$$

$$D^* = 2.84$$

R*<1 good

$$R^* = \frac{\max(\partial z \partial y \partial x)}{D^*} \qquad R^* = \frac{\max(\partial z \partial y \partial x)}{D^*}$$

$$R^* = \frac{30cm}{2.84} \qquad R^* = \frac{15cm}{2.84}$$

$$R^* = 10.6 \qquad R^* = 5.3$$

Past experience has shown that a ratio of 5 to 10 usually produces favorable results at a moderate computational cost.

In short, the greater the ratio D*/δx, the more the fire dynamics are resolved directly, and the more accurate the simulation. Past experience has shown that a ratio of 5 to 10 usually produces favorable results at a moderate computational cost.

APPENDIX D

Sample FDS Input File

```
3200.fds
Generated by PyroSim - Version 2010.1.0928
12-Aug-2010 11:01:46 AM

&HEAD CHID='3200'/
&TIME T_END=1.8000000E003, DT=1.00/
&DUMP RENDER_FILE='3200.ge1'/
&MISC SURF_DEFAULT='Walls', CO_PRODUCTION=.TRUE./

&MESH ID='Living Room', IJK=74,46,18, XB=0.00,11.10,8.10,15.00,-0.1000,2.60/
&MESH ID='1st Storey', IJK=37,27,9, XB=0.00,11.10,0.00,8.10,-0.1000,2.60/
&MESH ID='2nd Storey', IJK=31,28,9, XB=0.00,9.30,6.60,15.00,2.60,5.30/

&PART ID='Tracer',
    MASSLESS=.TRUE.,
    COLOR='BLACK',
    AGE=60.00/
&PART ID='Water',
    WATER=.TRUE.,
    AGE=60.00/

&REAC ID='POLYURETHANE',
    FYI='NFPA Babrauskas',
    C=6.30,
    H=7.10,
    O=2.10,
    N=1.00,
    SOOT_YIELD=0.1000/

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    FYI='NBSIR 88-3752 - ATF NIST Multi-Floor Validation',
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    CONDUCTIVITY=0.1700,
    DENSITY=930.00/
&MATL ID='YELLOW PINE',
    FYI='Quintiere, Fire Behavior - NIST NRC Validation',
    SPECIFIC_HEAT=2.85,
    CONDUCTIVITY=0.1400,
    DENSITY=640.00/
&MATL ID='Wood Furniture02',
```

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    SPECIFIC_HEAT=1.70,
    CONDUCTIVITY=0.1000,
    DENSITY=640.00,
    HEAT_OF_COMBUSTION=1.9000000E004,
    N_REACTIONS=1,
    HEAT_OF_REACTION=400.00,
    NU_FUEL=1.00,
    N_S=3.00,
    A=1.0000000E015,
    E=2.0000000E005/
&MATL ID='FOAM02',
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et al., "FDS simulation of fire spread..."',
    SPECIFIC_HEAT=1.50,
    CONDUCTIVITY=0.80,
    DENSITY=30.00,
    HEAT_OF_COMBUSTION=3.0000000E004,
    N_REACTIONS=2,
    HEAT_OF_REACTION=1.5000000E003,1.5000000E003,
    NU_FUEL=1.00,1.00,
    N_S=1.00,1.16,
    A=1.6860000E008,8.7460000E009,
    E=1.3500000E005,1.7500000E005/

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    MATL_MASS_FRACTION(1,1)=1.00,
    THICKNESS(1)=0.0127/
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    BACKING='INSULATED',
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    MATL_MASS_FRACTION(1,1)=1.00,
    THICKNESS(1)=8.0000000E-003/
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    PART_ID='Tracer'/
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&RAMP ID='Burner_RAMP_Q', T=1.00, F=9.3200000E-006/
&RAMP ID='Burner_RAMP_Q', T=100.00, F=0.0932/
&RAMP ID='Burner_RAMP_Q', T=150.00, F=0.2097/
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```

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&RAMP ID='Burner_RAMP_Q', T=350.00, F=1.00/
&RAMP ID='Burner_RAMP_Q', T=400.00, F=1.00/
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&RAMP ID='Burner_RAMP_Q', T=2.1000000E003, F=0.0666/
&RAMP ID='Burner_RAMP_Q', T=2.2000000E003, F=0.00/
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    RGB=23,19,0,
    BURN_AWAY=.TRUE.,
    BACKING='EXPOSED',
    MATL_ID(1,1)='Wood Furniture02',
    MATL_MASS_FRACTION(1,1)=1.00,
    THICKNESS(1)=0.0150/
&SURF ID='SOFA',
    RGB=102,0,102,
    BURN_AWAY=.TRUE.,
    BACKING='INSULATED',
    MATL_ID(1,1)='FOAM02',
    MATL_MASS_FRACTION(1,1)=1.00,
    THICKNESS(1)=0.1000/

&PROP ID='Default', QUANTITY='LINK TEMPERATURE',
ACTIVATION_TEMPERATURE=300.00/
&PROP ID='Cleary Ionization I1',
    QUANTITY='CHAMBER OBSCURATION',
    ALPHA_E=2.50,
    BETA_E=-0.70,
    ALPHA_C=0.80,
    BETA_C=-0.90/
&PROP ID='Default_Water Spray',
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    QUANTITY='SPRINKLER LINK TEMPERATURE',
    ACTIVATION_TEMPERATURE=74.00,
    PART_ID='Water',
    FLOW_RATE=0.00,
    DROPLET_VELOCITY=5.00/
&DEVC ID='LR a CO', QUANTITY='VOLUME FRACTION', SPEC_ID='carbon
monoxide', XYZ=4.60,10.00,1.70/
&DEVC ID='LR a CO2', QUANTITY='VOLUME FRACTION', SPEC_ID='carbon
dioxide', XYZ=4.60,10.00,1.70/
&DEVC ID='LR a FED', QUANTITY='FED', XYZ=4.60,10.00,1.70/
&DEVC ID='LR a HD', PROP_ID='Default', XYZ=4.60,10.00,2.50/
&DEVC ID='LR a Heat FLux', QUANTITY='RADIATIVE HEAT FLUX GAS',
XYZ=4.60,10.00,1.70/
&DEVC ID='LR a LAYER ->HEIGHT', QUANTITY='LAYER HEIGHT',
XB=4.60,4.60,10.00,10.00,0.2000,2.60, SETPOINT=1.70/
&DEVC ID='LR a LAYER ->LTEMP', QUANTITY='LOWER TEMPERATURE',
XB=4.60,4.60,10.00,10.00,0.2000,2.60, SETPOINT=121.00/
&DEVC ID='LR a LAYER ->UTEMP', QUANTITY='UPPER TEMPERATURE',
XB=4.60,4.60,10.00,10.00,0.2000,2.60, SETPOINT=183.00/
&DEVC ID='LR a O2', QUANTITY='VOLUME FRACTION', SPEC_ID='oxygen',
XYZ=4.60,10.00,1.70/
&DEVC ID='LR a SD', PROP_ID='Cleary Ionization I1', XYZ=4.60,10.00,2.40/
&DEVC ID='LR a Visibility', QUANTITY='VISIBILITY', XYZ=4.60,10.00,1.70/
&DEVC ID='LR a2 CO', QUANTITY='VOLUME FRACTION', SPEC_ID='carbon
monoxide', XYZ=4.60,10.00,1.20/
&DEVC ID='LR a2 CO2', QUANTITY='VOLUME FRACTION', SPEC_ID='carbon
dioxide', XYZ=4.60,10.00,1.20/
&DEVC ID='LR a2 FED', QUANTITY='FED', XYZ=4.60,10.00,1.20/
&DEVC ID='LR a2 Heat Flux', QUANTITY='RADIATIVE HEAT FLUX GAS',
XYZ=4.60,10.00,1.20/
&DEVC ID='LR a2 O2', QUANTITY='VOLUME FRACTION', SPEC_ID='oxygen',
XYZ=4.60,10.00,1.20/
&DEVC ID='LR a2 Visibility', QUANTITY='VISIBILITY', XYZ=4.60,10.00,1.20/
&DEVC ID='LR a3 Heat Flux', QUANTITY='RADIATIVE HEAT FLUX GAS',
XYZ=4.60,10.00,0.2000/
&DEVC ID='LR b CO', QUANTITY='VOLUME FRACTION', SPEC_ID='carbon
monoxide', XYZ=2.10,11.00,1.70/
&DEVC ID='LR b CO2', QUANTITY='VOLUME FRACTION', SPEC_ID='carbon
dioxide', XYZ=2.10,11.00,1.70/
&DEVC ID='LR b FED', QUANTITY='FED', XYZ=2.10,11.00,1.70/
&DEVC ID='LR b HD', PROP_ID='Default', XYZ=2.10,11.00,2.40/
&DEVC ID='LR b Heat Flux', QUANTITY='RADIATIVE HEAT FLUX GAS',
XYZ=2.10,11.00,1.70/
&DEVC ID='LR b LAYER->HEIGHT', QUANTITY='LAYER HEIGHT',
XB=2.10,2.10,11.00,11.00,0.2000,2.60, SETPOINT=1.70/
&DEVC ID='LR b LAYER->LTEMP', QUANTITY='LOWER TEMPERATURE',
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XB=2.10,2.10,11.00,11.00,0.2000,2.60, SETPOINT=121.00/
&DEVC ID='LR b LAYER->UTEMP', QUANTITY='UPPER TEMPERATURE',
XB=2.10,2.10,11.00,11.00,0.2000,2.60, SETPOINT=183.00/
&DEVC ID='LR b O2', QUANTITY='VOLUME FRACTION', SPEC_ID='oxygen',
XYZ=2.10,11.00,1.70/
&DEVC ID='LR b SD', PROP_ID='Cleary Ionization I1', XYZ=2.10,11.00,2.40/
&DEVC ID='LR b Visibility', QUANTITY='VISIBILITY', XYZ=2.10,11.00,1.70/
&DEVC ID='LR b2 CO', QUANTITY='VOLUME FRACTION', SPEC_ID='carbon
monoxide', XYZ=2.10,11.00,1.20/
&DEVC ID='LR b2 CO2', QUANTITY='VOLUME FRACTION', SPEC_ID='carbon
dioxide', XYZ=2.10,11.00,1.20/
&DEVC ID='LR b2 FED', QUANTITY='FED', XYZ=2.10,11.00,1.20/
&DEVC ID='LR b2 Heat Flux', QUANTITY='RADIATIVE HEAT FLUX GAS',
XYZ=2.10,11.00,1.20/
&DEVC ID='LR b2 O2', QUANTITY='VOLUME FRACTION', SPEC_ID='oxygen',
XYZ=2.10,11.00,1.20/
&DEVC ID='LR b2 Visibility', QUANTITY='VISIBILITY', XYZ=2.10,11.00,1.20/
&DEVC ID='LR b3 Heat Flux', QUANTITY='RADIATIVE HEAT FLUX GAS',
XYZ=2.10,11.00,0.2000/
&DEVC ID='LR c CO', QUANTITY='VOLUME FRACTION', SPEC_ID='carbon
monoxide', XYZ=4.40,12.70,1.70/
&DEVC ID='LR c CO2', QUANTITY='VOLUME FRACTION', SPEC_ID='carbon
dioxide', XYZ=4.40,12.70,1.70/
&DEVC ID='LR c FED', QUANTITY='FED', XYZ=4.40,12.70,1.70/
&DEVC ID='LR c HD', PROP_ID='Default', XYZ=4.40,12.70,2.50/
&DEVC ID='LR c Heat Flux', QUANTITY='RADIATIVE HEAT FLUX GAS',
XYZ=4.40,12.70,1.70/
&DEVC ID='LR c LAYER->HEIGHT', QUANTITY='LAYER HEIGHT',
XB=4.40,4.40,12.70,12.70,0.2000,2.60, SETPOINT=1.70/
&DEVC ID='LR c LAYER->LTEMP', QUANTITY='LOWER TEMPERATURE',
XB=4.40,4.40,12.70,12.70,0.2000,2.60, SETPOINT=121.00/
&DEVC ID='LR c LAYER->UTEMP', QUANTITY='UPPER TEMPERATURE',
XB=4.40,4.40,12.70,12.70,0.2000,2.60, SETPOINT=183.00/
&DEVC ID='LR c O2', QUANTITY='VOLUME FRACTION', SPEC_ID='oxygen',
XYZ=4.40,12.70,1.70/
&DEVC ID='LR c O202', QUANTITY='VOLUME FRACTION', SPEC_ID='oxygen',
XYZ=4.40,12.70,1.20/
&DEVC ID='LR c SD', PROP_ID='Cleary Ionization I1', XYZ=4.40,12.70,2.50/
&DEVC ID='LR c Visibility', QUANTITY='VISIBILITY', XYZ=4.40,12.70,1.70/
&DEVC ID='LR c2 CO', QUANTITY='VOLUME FRACTION', SPEC_ID='carbon
monoxide', XYZ=4.40,12.70,1.20/
&DEVC ID='LR c2 CO2', QUANTITY='VOLUME FRACTION', SPEC_ID='carbon
dioxide', XYZ=4.40,12.70,1.20/
&DEVC ID='LR c2 FED', QUANTITY='FED', XYZ=4.40,12.70,1.20/
&DEVC ID='LR c2 Heat Flux', QUANTITY='RADIATIVE HEAT FLUX GAS',
XYZ=4.40,12.70,1.20/
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&DEVC ID='LR c2 Visibility', QUANTITY='VISIBILITY', XYZ=4.40,12.70,1.20/
&DEVC ID='LR c3 Heat Flux', QUANTITY='RADIATIVE HEAT FLUX GAS',
XYZ=4.40,12.70,0.2000/
&DEVC ID='SPRK 1', PROP_ID='Default_Water Spray', XYZ=8.75,12.65,2.50/
&DEVC ID='SPRK 2', PROP_ID='Default_Water Spray', XYZ=8.75,10.15,2.50/
&DEVC ID='SPRK 3', PROP_ID='Default_Water Spray', XYZ=4.90,10.80,2.50/
&DEVC ID='SPRK 4', PROP_ID='Default_Water Spray', XYZ=2.20,10.80,2.50/
&DEVC ID='SPRK 5', PROP_ID='Default_Water Spray', XYZ=4.90,14.85,2.50/
&DEVC ID='SPRK 6', PROP_ID='Default_Water Spray', XYZ=2.20,14.85,2.50/
&DEVC ID='UP CO', QUANTITY='VOLUME FRACTION', SPEC_ID='carbon
monoxide', XYZ=5.20,8.50,4.40/
&DEVC ID='UP CO2', QUANTITY='VOLUME FRACTION', SPEC_ID='carbon
dioxide', XYZ=5.20,8.50,4.40/
&DEVC ID='UP FED', QUANTITY='FED', XYZ=5.20,8.50,4.40/
&DEVC ID='UP HD', PROP_ID='Default', XYZ=5.20,8.50,5.20/
&DEVC ID='UP Heat Flux', QUANTITY='RADIATIVE HEAT FLUX GAS',
XYZ=5.20,8.50,4.40/
&DEVC ID='UP LAYER->HEIGHT', QUANTITY='LAYER HEIGHT',
XB=5.20,5.20,8.50,8.50,2.90,5.30, SETPOINT=4.40/
&DEVC ID='UP LAYER->LTEMP', QUANTITY='LOWER TEMPERATURE',
XB=5.20,5.20,8.50,8.50,2.90,5.30, SETPOINT=121.00/
&DEVC ID='UP LAYER->UTEMP', QUANTITY='UPPER TEMPERATURE',
XB=5.20,5.20,8.50,8.50,2.90,5.30, SETPOINT=183.00/
&DEVC ID='UP O2', QUANTITY='VOLUME FRACTION', SPEC_ID='oxygen',
XYZ=5.20,8.50,4.40/
&DEVC ID='UP SD', PROP_ID='Cleary Ionization I1', XYZ=5.20,8.50,5.20/
&DEVC ID='UP Visibility', QUANTITY='VISIBILITY', XYZ=5.20,8.50,4.40/
&DEVC ID='UP3 Heat Flux', QUANTITY='RADIATIVE HEAT FLUX GAS',
XYZ=5.20,8.50,2.90/
&DEVC ID='x SD UP', PROP_ID='Cleary Ionization I1', XYZ=3.20,9.50,5.20/
&DEVC ID='x SD02', PROP_ID='Cleary Ionization I1', XYZ=7.40,12.70,2.50/
&DEVC ID='x THCP DR', QUANTITY='THERMOCOUPLE', XYZ=10.70,6.60,1.70,
SETPOINT=250.00/
&DEVC ID='x THCP KD-1', QUANTITY='THERMOCOUPLE', XYZ=8.10,14.80,1.70,
SETPOINT=250.00/
&DEVC ID='x THCP KD-2', QUANTITY='THERMOCOUPLE', XYZ=8.80,14.80,1.70,
SETPOINT=250.00/
&DEVC ID='x THCP LAUNDRY', QUANTITY='THERMOCOUPLE',
XYZ=0.4000,6.80,1.70, SETPOINT=250.00/
&DEVC ID='x THCP LR', QUANTITY='THERMOCOUPLE', XYZ=0.4000,9.05,1.70,
SETPOINT=250.00/
&DEVC ID='x THCP LR W', QUANTITY='THERMOCOUPLE',
XYZ=9.80,0.4000,1.70, SETPOINT=250.00/
&DEVC ID='x THCP W1-1', QUANTITY='THERMOCOUPLE', XYZ=0.70,14.80,1.70,
SETPOINT=250.00/
&DEVC ID='x THCP W1-2', QUANTITY='THERMOCOUPLE', XYZ=1.40,14.80,1.70,
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SETPOINT=250.00/
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SETPOINT=250.00/
&DEVC ID='x THCP W2-1', QUANTITY='THERMOCOUPLE', XYZ=4.80,14.80,1.70,
SETPOINT=250.00/
&DEVC ID='x THCP W2-2', QUANTITY='THERMOCOUPLE', XYZ=5.50,14.80,1.70,
SETPOINT=250.00/
&DEVC ID='x THCP W2-3', QUANTITY='THERMOCOUPLE', XYZ=6.20,14.80,1.70,
SETPOINT=250.00/
&DEVC ID='x THCP W3-1', QUANTITY='THERMOCOUPLE',
XYZ=10.70,14.10,1.70, SETPOINT=250.00/
&DEVC ID='x THCP W3-2', QUANTITY='THERMOCOUPLE',
XYZ=10.70,13.60,1.70, SETPOINT=250.00/
&DEVC ID='x THCP W3-3', QUANTITY='THERMOCOUPLE',
XYZ=10.70,13.10,1.70, SETPOINT=250.00/
&DEVC ID='x THCP W3-4', QUANTITY='THERMOCOUPLE',
XYZ=10.70,12.60,1.70, SETPOINT=250.00/
&DEVC ID='x THCP W3-5', QUANTITY='THERMOCOUPLE',
XYZ=10.70,12.10,1.70, SETPOINT=250.00/
&DEVC ID='x THCP W3-6', QUANTITY='THERMOCOUPLE',
XYZ=10.70,11.60,1.70, SETPOINT=250.00/
&DEVC ID='X UP LOFT', QUANTITY='THERMOCOUPLE', XYZ=0.4000,8.85,4.40,
SETPOINT=250.00/
&DEVC ID='x UP OPEN 1', QUANTITY='THERMOCOUPLE', XYZ=1.30,14.80,4.60,
SETPOINT=250.00/
&DEVC ID='x UP OPEN 2', QUANTITY='THERMOCOUPLE', XYZ=5.30,14.80,4.60,
SETPOINT=250.00/
&DEVC ID='xx FED', QUANTITY='FED', XYZ=2.50,13.00,1.70/
&DEVC ID='xx FED02', QUANTITY='FED', XYZ=2.50,13.00,0.70/
&DEVC ID='xx LR THCP01', QUANTITY='TEMPERATURE', XYZ=4.40,12.70,2.55/
&DEVC ID='xx LR THCP02', QUANTITY='TEMPERATURE', XYZ=4.40,12.70,2.40/
&DEVC ID='xx LR THCP03', QUANTITY='TEMPERATURE', XYZ=4.40,12.70,2.25/
&DEVC ID='xx LR THCP04', QUANTITY='TEMPERATURE', XYZ=4.40,12.70,2.10/
&DEVC ID='xx LR THCP05', QUANTITY='TEMPERATURE', XYZ=4.40,12.70,1.80/
&DEVC ID='xx LR THCP06', QUANTITY='TEMPERATURE', XYZ=4.40,12.70,1.50/
&DEVC ID='xx LR THCP07', QUANTITY='TEMPERATURE', XYZ=4.40,12.70,1.20/
&DEVC ID='xx LR THCP08', QUANTITY='TEMPERATURE', XYZ=4.40,12.70,0.90/
&DEVC ID='xx up THCP01', QUANTITY='TEMPERATURE', XYZ=5.10,8.40,5.15/
&DEVC ID='xx up THCP02', QUANTITY='TEMPERATURE', XYZ=5.10,8.40,5.00/
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&DEVC ID='xx up THCP05', QUANTITY='TEMPERATURE', XYZ=5.10,8.40,4.40/
&DEVC ID='xx up THCP06', QUANTITY='TEMPERATURE', XYZ=5.10,8.40,4.10/
&DEVC ID='xx up THCP07', QUANTITY='TEMPERATURE', XYZ=5.10,8.40,3.80/
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W2-2'/
&CTRL ID='W2-1', FUNCTION_TYPE='ALL', LATCH=.TRUE., INPUT_ID='x THCP
W2-1'/
&CTRL ID='LR', FUNCTION_TYPE='ALL', LATCH=.TRUE., INPUT_ID='x THCP
LR'/
&CTRL ID='W1-3', FUNCTION_TYPE='ALL', LATCH=.TRUE., INPUT_ID='x THCP
W1-3'/
&CTRL ID='W1-2', FUNCTION_TYPE='ALL', LATCH=.TRUE., INPUT_ID='x THCP
W1-2'/
&CTRL ID='W1-1', FUNCTION_TYPE='ALL', LATCH=.TRUE., INPUT_ID='x THCP
W1-1'/
&CTRL ID='W2-3', FUNCTION_TYPE='ALL', LATCH=.TRUE., INPUT_ID='x THCP
W2-3'/
&CTRL ID='DR', FUNCTION_TYPE='ALL', LATCH=.TRUE., INPUT_ID='x THCP
DR'/
&CTRL ID='Laundry', FUNCTION_TYPE='ALL', LATCH=.TRUE., INPUT_ID='x
THCP LAUNDRY'/
&CTRL ID='KD-2', FUNCTION_TYPE='ALL', LATCH=.TRUE., INPUT_ID='x THCP
KD-2'/
&CTRL ID='KD-1', FUNCTION_TYPE='ALL', LATCH=.TRUE., INPUT_ID='x THCP
KD-1'/
&CTRL ID='UP W 2', FUNCTION_TYPE='ALL', LATCH=.TRUE., INPUT_ID='x UP
OPEN 2'/
&CTRL ID='UP W 1', FUNCTION_TYPE='ALL', LATCH=.TRUE., INPUT_ID='x UP
OPEN 1'/
&CTRL ID='LOFT', FUNCTION_TYPE='ALL', LATCH=.TRUE., INPUT_ID='X UP
LOFT'/
&CTRL ID='w3-4', FUNCTION_TYPE='ALL', LATCH=.TRUE., INPUT_ID='x THCP
W3-4'/
&CTRL ID='W3-5', FUNCTION_TYPE='ALL', LATCH=.TRUE., INPUT_ID='x THCP
W3-5'/
&CTRL ID='w3-3', FUNCTION_TYPE='ALL', LATCH=.TRUE., INPUT_ID='x THCP
W3-3'/
&CTRL ID='w3-6', FUNCTION_TYPE='ALL', LATCH=.TRUE., INPUT_ID='x THCP
W3-6'/
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W3-2'/
&CTRL ID='W3-1', FUNCTION_TYPE='ALL', LATCH=.TRUE., INPUT_ID='x THCP
W3-1'/

&OBST XB=2.90,5.50,6.30,6.40,0.00,2.60, SURF_ID='Walls'/ Obstruction
&OBST XB=2.80,2.90,5.50,7.50,0.00,2.60, SURF_ID='Walls'/ Obstruction
&OBST XB=0.00,3.40,10.50,10.80,0.00,2.60, SURF_ID='Walls'/ Obstruction
&OBST XB=5.40,5.50,5.50,6.40,0.00,2.59, REMOVABLE=.FALSE., SURF_ID='Walls'/
Wall
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&OBST XB=5.50,6.10,2.60,2.70,0.00,2.59, SURF_ID='Walls'/ Wall[1]
&OBST XB=6.00,6.10,2.60,4.30,0.00,2.59, SURF_ID='Walls'/ Wall[1][1]
&OBST XB=6.00,11.00,8.10,8.40,0.00,2.60, SURF_ID='Walls'/ Wall[1][1]
&OBST XB=6.80,6.90,8.00,10.80,0.00,2.60, SURF_ID='Walls'/ Wall[1]
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&OBST XB=5.00,6.60,7.70,8.00,2.60,4.00, SURF_ID='Walls'/ Obstruction[1][1][1]
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&OBST XB=0.00,11.10,0.00,15.00,2.60,2.90, COLOR='INVISIBLE', SURF_ID='Floor'/
2nd Storey Floor
&OBST XB=0.00,11.10,0.00,15.00,5.30,5.50, COLOR='INVISIBLE', SURF_ID='Floor'/
2nd Floor Ceiling
&OBST XB=10.80,11.10,0.00,15.00,0.00,5.30, COLOR='INVISIBLE',
SURF_ID='Walls'/ W Wall
&OBST XB=5.30,5.40,0.70,6.90,0.00,2.60, SURF_ID='Walls'/ E Wall
&OBST XB=7.60,11.00,0.00,0.3000,0.00,2.60, SURF_ID='Walls'/ N Wall
&OBST XB=0.00,11.10,14.85,15.00,0.00,5.30, SURF_ID='Walls'/ S Wall
&OBST XB=0.00,5.50,5.30,5.60,0.00,2.60, BNDF_OBST=.FALSE., SURF_ID='Walls'/
N Wall[1]
&OBST XB=0.00,0.1500,5.30,15.00,0.00,5.30, SURF_ID='Walls'/ W Wall[1]
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&OBST XB=0.00,11.10,0.00,0.3000,2.60,5.30, SURF_ID='Walls'/ N Wall[1]
&OBST XB=0.00,2.90,4.50,4.80,2.60,5.20, SURF_ID='Walls'/ N Wall[1][1]
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&OBST XB=2.90,11.10,6.50,6.80,2.60,5.20, SURF_ID='Walls'/ N Wall[1][1][1][1]
&OBST XB=0.00,2.90,7.40,7.70,2.60,5.20, SURF_ID='Walls'/ N Wall[1][1][1]
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&OBST XB=9.00,11.10,4.90,5.20,2.60,5.20, SURF_ID='Walls'/ N Wall[1][1][1][1][1]
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&OBST XB=0.00,0.1500,0.00,5.30,0.00,5.30, SURF_ID='Walls'/ W Wall[1][1]
&OBST XB=5.90,6.80,9.57,10.60,0.80,1.00, SURF_ID='INERT'/ Stair[6]
&OBST XB=5.77,6.03,9.70,10.60,0.75,0.93, SURF_ID='INERT'/ Stair[9]
```

```
&OBST XB=5.52,5.77,9.70,10.60,0.57,0.75, SURF_ID='INERT'/ Stair[10]
&OBST XB=5.27,5.52,9.70,10.60,0.3819,0.57, SURF_ID='INERT'/ Stair[11]
&OBST XB=5.01,5.27,9.70,10.60,0.1979,0.3820, SURF_ID='INERT'/ Stair[12]
&OBST XB=4.76,5.01,9.70,10.60,0.0139,0.1980, SURF_ID='INERT'/ Stair[13]
&OBST XB=5.80,6.80,8.10,8.80,1.75,2.00, SURF_ID='INERT'/ Stair[9][1]
&OBST XB=5.80,6.80,8.67,8.92,1.57,1.75, SURF_ID='INERT'/ Stair[10][1]
&OBST XB=5.80,6.80,8.92,9.18,1.38,1.57, SURF_ID='INERT'/ Stair[11][1]
&OBST XB=5.80,6.80,9.18,9.43,1.20,1.38, SURF_ID='INERT'/ Stair[12][1]
&OBST XB=5.80,6.80,9.43,9.68,1.01,1.20, SURF_ID='INERT'/ Stair[13][1]
&OBST XB=5.05,5.30,8.10,8.90,2.20,2.60, SURF_ID='INERT'/ Stair[11][1][1]
&OBST XB=5.30,5.55,8.10,8.90,2.20,2.38, SURF_ID='INERT'/ Stair[12][1][1]
&OBST XB=5.55,5.81,8.10,8.90,2.00,2.20, SURF_ID='INERT'/ Stair[13][1][1]
&OBST XB=5.40,6.30,12.00,13.80,1.10,1.25, SURF_ID='Wood Furniture02'/
Wall[1][1][1][1][1]
&OBST XB=3.90,4.80,14.55,14.70,0.80,1.40, SURF_ID='SOFA'/ back
&OBST XB=3.90,4.80,14.10,14.70,0.50,0.80, SURF_ID='SOFA'/ seat
&OBST XB=3.90,4.80,14.10,14.70,0.3500,0.50, SURF_ID='Wood Furniture02'/ frame
&OBST XB=8.70,9.60,12.30,14.10,1.10,1.25, SURF_ID='Wood Furniture02'/
Wall[1][1][1][1][1][1]
&OBST XB=1.20,3.30,11.40,13.80,0.00,0.50, SURF_ID='INERT'/ Obstruction
&OBST XB=10.20,10.80,8.40,11.40,0.2000,1.10, SURF_ID='Wood Furniture02'/
Wall[1][1][1][1][1]
&OBST XB=10.20,10.80,8.40,11.40,1.85,2.60, SURF_ID='Wood Furniture02'/
Wall[1][1][1][1][1]
&OBST XB=8.10,10.20,8.40,9.00,0.2000,1.10, SURF_ID='Wood Furniture02'/
Wall[1][1][1][1]
&OBST XB=8.10,10.20,8.40,9.00,1.85,2.60, SURF_ID='Wood Furniture02'/
Wall[1][1][1][1][1][1]
&OBST XB=8.70,10.20,10.80,11.40,0.2000,1.10, SURF_ID='Wood Furniture02'/
Wall[1][1][1][1][1]
&OBST XB=2.70,3.00,7.50,7.50,-0.1000,2.60, SURF_ID='Walls'/ Obstruction[1]
&OBST XB=3.00,3.30,7.80,7.80,-0.1000,2.60, SURF_ID='Walls'/ Obstruction[1]
&OBST XB=3.00,3.00,7.50,7.80,-0.1000,2.60, SURF_ID='Walls'/ Obstruction[1]
&OBST XB=3.30,3.30,7.80,8.10,-0.1000,2.60, SURF_ID='Walls'/ Obstruction[1]

&HOLE
XB=2.8000000E000,3.0000000E000,6.5000000E000,7.3000000E000,2.0000000E-
001,2.1000000E000/ Door[1]
&HOLE
XB=3.6000000E000,4.4000000E000,6.3000000E000,6.4000000E000,0.0000000E000,2.
0000000E000/ Back Door 2[1]
&HOLE
XB=7.1000000E000,7.9000000E000,8.1000000E000,8.4000000E000,0.0000000E000,2.
0000000E000/ Back Door 2[1][1]
&HOLE
XB=5.1000000E000,5.8000000E000,1.4800000E001,1.5300000E001,1.0000000E000,2.
```

2000000E000, CTRL_ID='W2-2'/ LR Window[1]
&HOLE
XB=4.4000000E000,5.1000000E000,1.4800000E001,1.5300000E001,1.0000000E000,2.
2000000E000, CTRL_ID='W2-1'/ LR Window[1]
&HOLE XB=-1.0000000E-001,4.0000000E-
001,9.0000000E000,9.5000000E000,1.0000000E000,2.0000000E000, CTRL_ID='LR'/
LR Window[1][1]
&HOLE
XB=1.8000000E000,2.5000000E000,1.4800000E001,1.5300000E001,1.0000000E000,2.
2000000E000, CTRL_ID='W1-3'/ 1st Floor BR
&HOLE
XB=1.1000000E000,1.8000000E000,1.4800000E001,1.5300000E001,1.0000000E000,2.
2000000E000, CTRL_ID='W1-2'/ 1st Floor BR
&HOLE XB=4.0000000E-
001,1.1000000E000,1.4800000E001,1.5300000E001,1.0000000E000,2.2000000E000,
CTRL_ID='W1-1'/ 1st Floor BR
&HOLE XB=-1.0000000E-001,4.0000000E-
001,8.5000000E000,9.0000000E000,1.0000000E000,2.0000000E000, CTRL_ID='LR'/
LR Window 1
&HOLE
XB=5.8000000E000,6.5000000E000,1.4800000E001,1.5300000E001,1.0000000E000,2.
2000000E000, CTRL_ID='W2-3'/ LR Window[1][1]
&HOLE XB=9.4000000E000,9.9000000E000,-2.0000000E-001,4.0000000E-
001,1.0000000E000,2.0000000E000, CTRL_ID='LR'/ DR Window
&HOLE XB=8.9000000E000,9.4000000E000,-2.0000000E-001,4.0000000E-
001,1.0000000E000,2.0000000E000, CTRL_ID='LR'/ DR Window
&HOLE XB=9.9000000E000,1.0400000E001,-2.0000000E-001,4.0000000E-
001,1.0000000E000,2.0000000E000, CTRL_ID='LR'/ DR Window[1]
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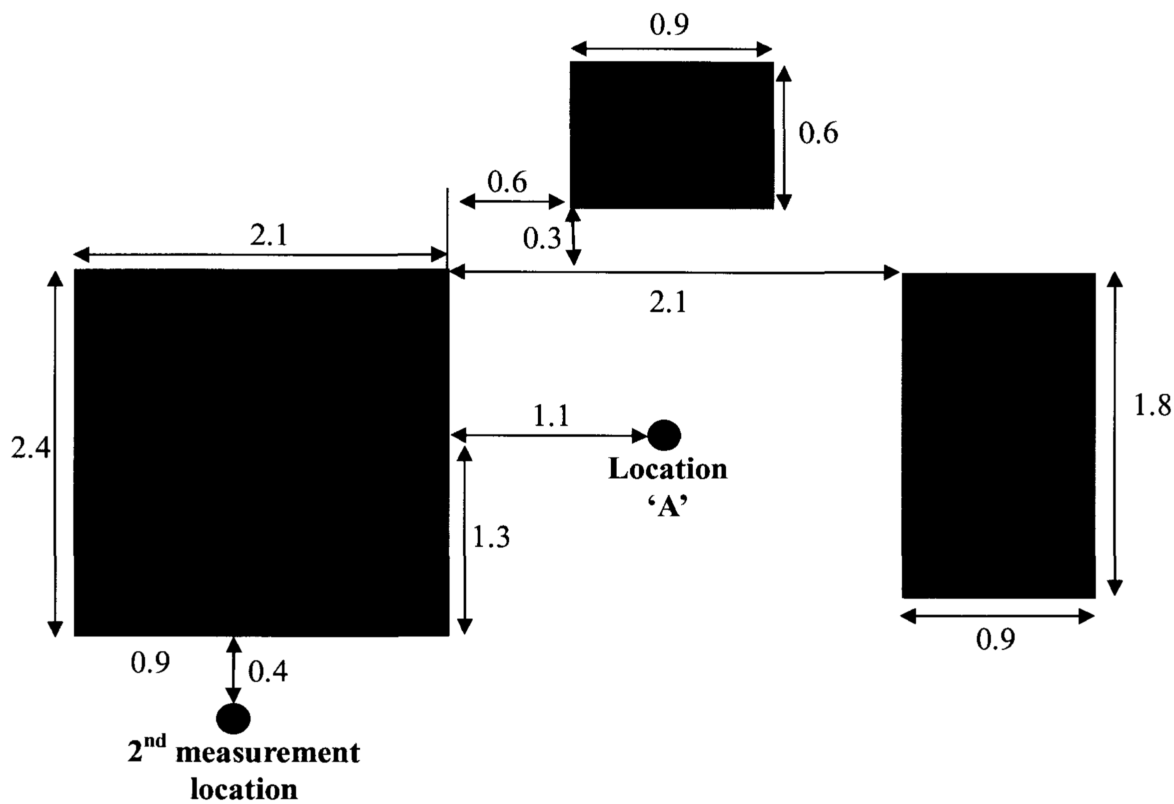
XB=1.0600000E001,1.1300000E001,6.3000000E000,6.8000000E000,1.0000000E000,2.
0000000E000, CTRL_ID='DR'/ DR window
&HOLE XB=-1.0000000E-001,4.0000000E-
001,6.6000000E000,7.1000000E000,1.0000000E000,2.0000000E000,
CTRL_ID='Laundry'/ DR window 2[1]
&HOLE
XB=1.0600000E001,1.1300000E001,6.8000000E000,7.3000000E000,1.0000000E000,2.
0000000E000, CTRL_ID='DR'/ DR window[1]
&HOLE
XB=8.4000000E000,9.2000000E000,1.4800000E001,1.5300000E001,2.0000000E-
001,2.2000000E000, CTRL_ID='KD-2'/ Back Door 1
&HOLE
XB=7.6000000E000,8.4000000E000,1.4800000E001,1.5300000E001,2.0000000E-
001,2.2000000E000, CTRL_ID='KD-1'/ Back Door 2
&HOLE
XB=5.1000000E000,5.6000000E000,1.4600000E001,1.5300000E001,4.1000000E000,5.
1000000E000, CTRL_ID='UP W 2'/ Master Window

&HOLE
XB=4.6000000E000,5.1000000E000,1.4600000E001,1.5300000E001,4.1000000E000,5.
1000000E000, CTRL_ID='UP W 2'/ Master Window
&HOLE
XB=1.3000000E000,1.8000000E000,1.4600000E001,1.5300000E001,4.1000000E000,5.
1000000E000, CTRL_ID='UP W 1'/ Master Window[1]
&HOLE XB=8.0000000E-
001,1.3000000E000,1.4600000E001,1.5300000E001,4.1000000E000,5.1000000E000,
CTRL_ID='UP W 1'/ Master Window[1]
&HOLE
XB=5.6000000E000,6.1000000E000,1.4600000E001,1.5300000E001,4.1000000E000,5.
1000000E000, CTRL_ID='UP W 2'/ Master Window[1]
&HOLE
XB=1.8000000E000,2.3000000E000,1.4600000E001,1.5300000E001,4.1000000E000,5.
1000000E000, CTRL_ID='UP W 1'/ Master Window[1][1]
&HOLE XB=-1.0000000E-001,4.0000000E-
001,8.6000000E000,9.1000000E000,3.9000000E000,4.9000000E000,
CTRL_ID='LOFT'/ DR window 2[1][1][1]
&HOLE
XB=4.6000000E000,6.7000000E000,8.1000000E000,1.0400000E001,2.5000000E000,3.
0000000E000/ Stairway 2
&HOLE
XB=1.0800000E001,1.1300000E001,1.2300000E001,1.2800000E001,1.2000000E000,2.
2000000E000, CTRL_ID='w3-4'/ Kitchen Window
&HOLE
XB=1.0800000E001,1.1300000E001,1.1800000E001,1.2300000E001,1.2000000E000,2.
2000000E000, CTRL_ID='W3-5'/ Kitchen Window 2
&HOLE
XB=1.0800000E001,1.1300000E001,1.2800000E001,1.3300000E001,1.2000000E000,2.
2000000E000, CTRL_ID='w3-3'/ Kitchen Window[1]
&HOLE
XB=1.0800000E001,1.1300000E001,1.1300000E001,1.1800000E001,1.2000000E000,2.
2000000E000, CTRL_ID='w3-6'/ Kitchen Window 2[1]
&HOLE
XB=1.0800000E001,1.1300000E001,1.3300000E001,1.3800000E001,1.2000000E000,2.
2000000E000, CTRL_ID='w3-2'/ Kitchen Window[1][1]
&HOLE
XB=1.0800000E001,1.1300000E001,1.3800000E001,1.4300000E001,1.2000000E000,2.
2000000E000, CTRL_ID='W3-1'/ Kitchen Window[1][1][1]
&HOLE
XB=2.6999950E000,3.3000050E000,7.4999950E000,7.8000050E000,1.9999500E-
001,2.0000050E000/ Door
&HOLE
XB=2.9999950E000,3.3000050E000,7.7999950E000,8.1000050E000,1.9999500E-
001,2.0000050E000/ Door

```
&VENT SURF_ID='OPEN', XB=0.00,0.00,0.00,10.50,-0.1000,2.60,
COLOR='INVISIBLE'/ Vent Min X for 1st Storey
&VENT SURF_ID='OPEN', XB=11.10,11.10,0.00,10.50,-0.1000,2.60,
COLOR='INVISIBLE'/ Vent Max X for 1st Storey
&VENT SURF_ID='OPEN', XB=0.00,11.10,0.00,0.00,-0.1000,2.60,
COLOR='INVISIBLE'/ Vent Min Y for 1st Storey
&VENT SURF_ID='OPEN', XB=11.10,11.10,10.50,15.00,-0.1000,2.60,
COLOR='INVISIBLE'/ Vent Max X for Living Room
&VENT SURF_ID='OPEN', XB=0.00,11.10,15.00,15.00,-0.1000,2.60,
COLOR='INVISIBLE'/ Vent Max Y for Living Room
&VENT SURF_ID='OPEN', XB=0.00,0.00,0.00,15.00,2.60,5.30, COLOR='INVISIBLE'/
Vent Min X for 2nd Storey
&VENT SURF_ID='OPEN', XB=11.10,11.10,0.00,15.00,2.60,5.30,
COLOR='INVISIBLE'/ Vent Max X for 2nd Storey
&VENT SURF_ID='OPEN', XB=0.00,11.10,0.00,0.00,2.60,5.30, COLOR='INVISIBLE'/
Vent Min Y for 2nd Storey
&VENT SURF_ID='OPEN', XB=0.00,11.10,15.00,15.00,2.60,5.30,
COLOR='INVISIBLE'/ Vent Max Y for 2nd Storey
&VENT SURF_ID='Burner', XB=1.20,3.30,11.40,13.80,0.50,0.50/ Vent

&BNDF QUANTITY='RADIATIVE HEAT FLUX'/

&SLCF QUANTITY='TEMPERATURE', PBX=3.80/
&SLCF QUANTITY='TEMPERATURE', PBY=12.50/


&TAIL /
```

APPENDIX E

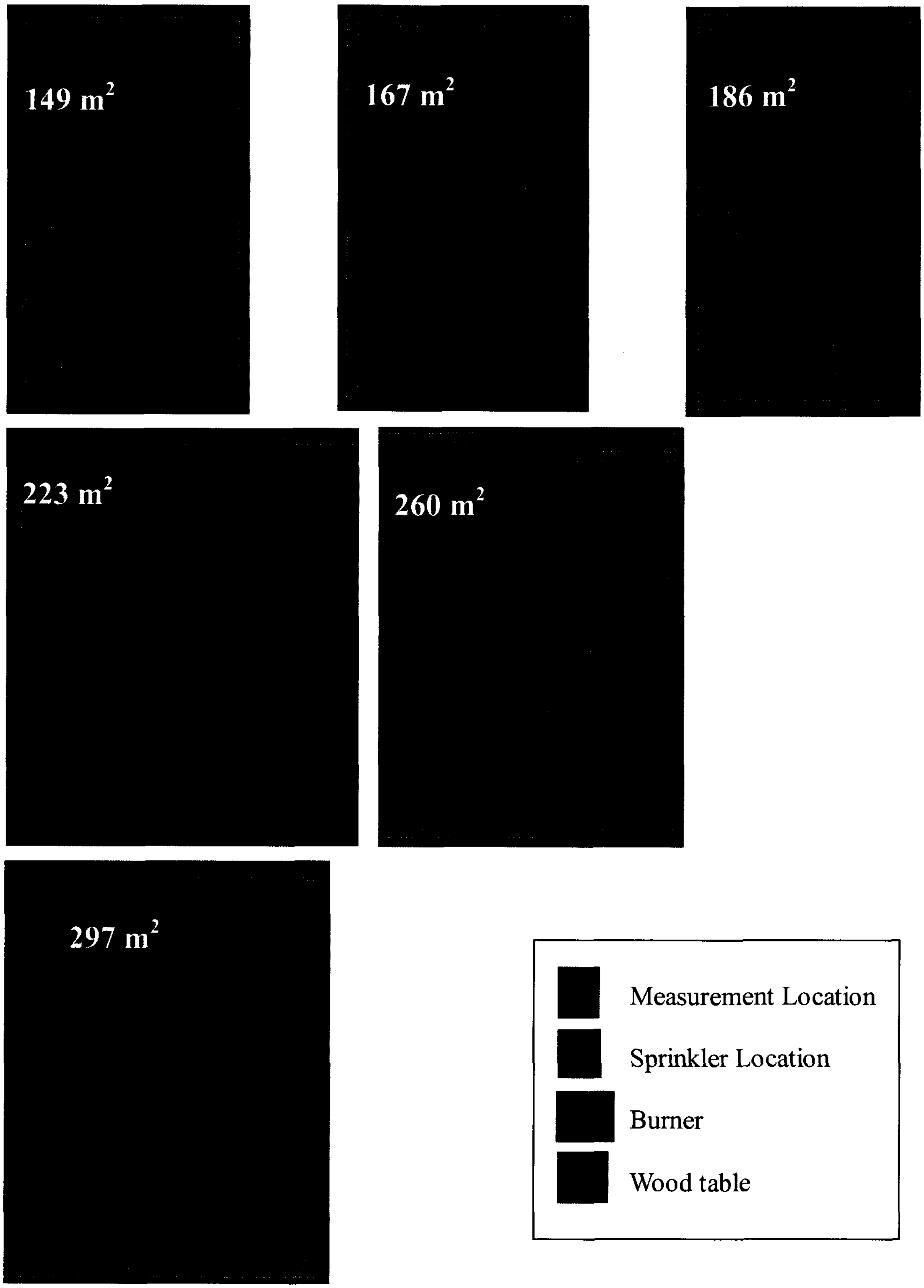
Furniture Configuration



All units in metres

APPENDIX F

Burner Placement in Bedroom Simulations



APPENDIX G

Tenability Graphs

Living Room Toxicity Graphs

Detached Homes

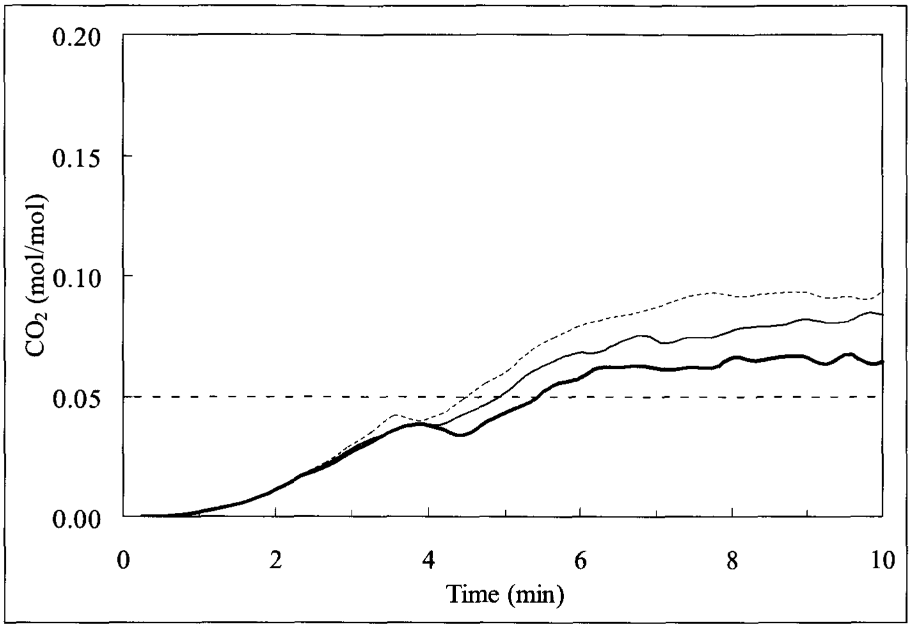


Figure E-1: CO_2 concentration at Location 'A' for a 297-m^2 home

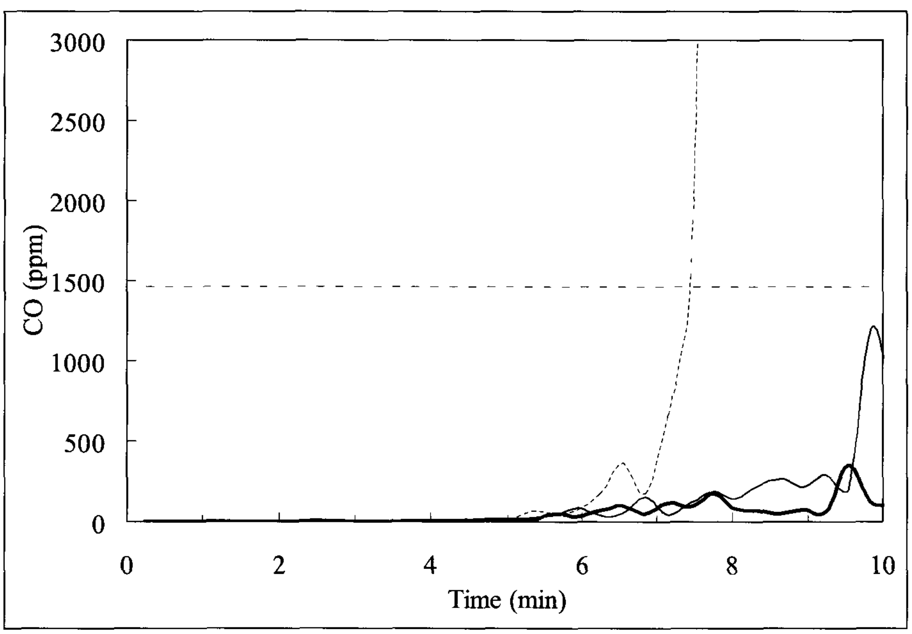


Figure E-2: CO concentration at Location 'A' for a 297-m^2 home

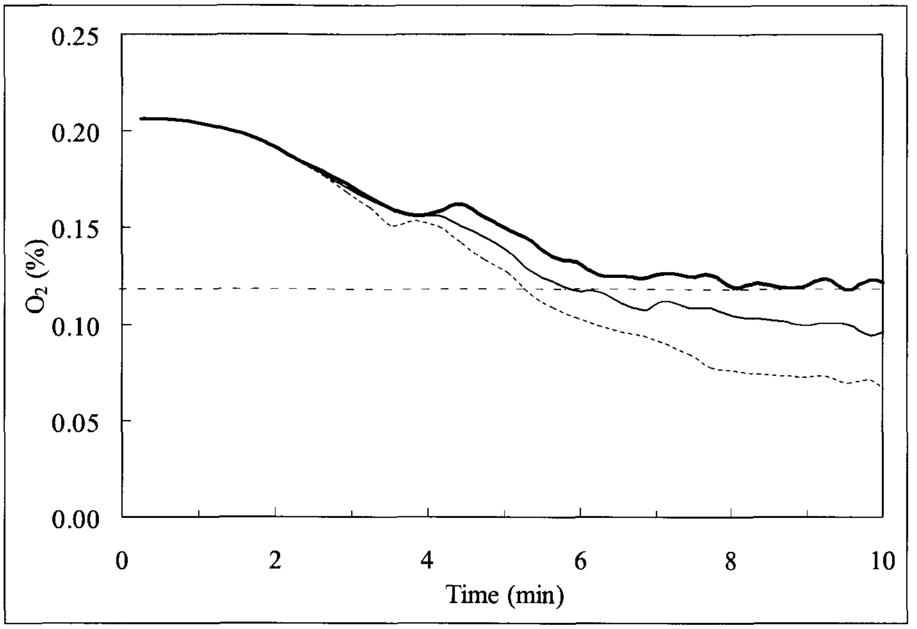


Figure E-3: O2 concentration at Location 'A' for a 297-m^2 home

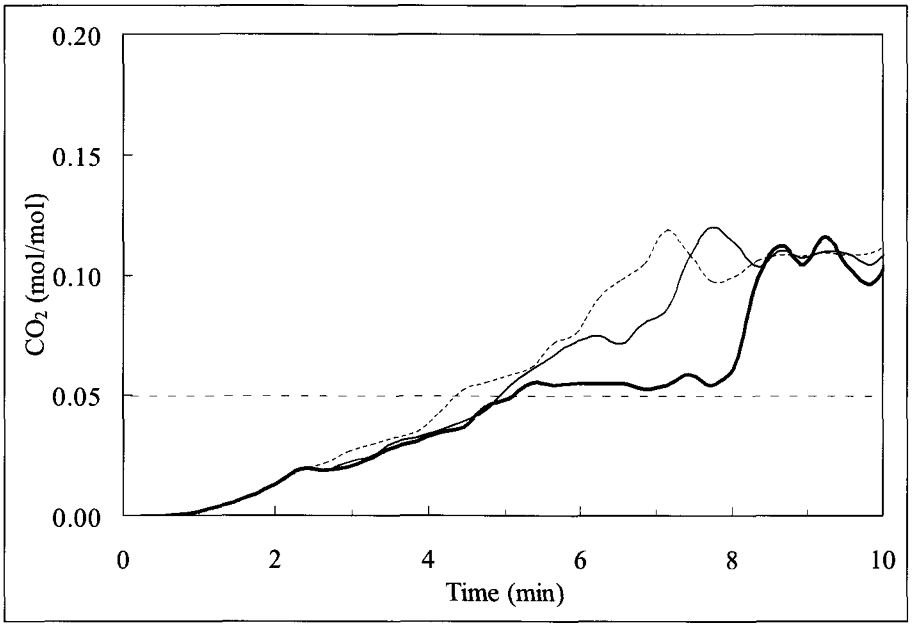


Figure E-4: CO_2 concentration at Location 'A' for a 260-m^2 home

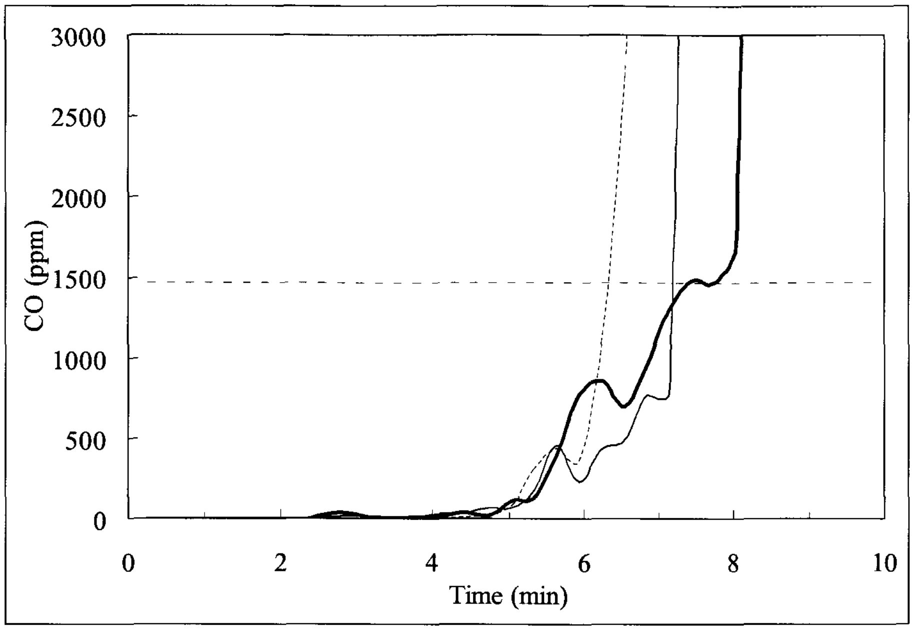


Figure E-5: CO concentration at Location 'A' for a 260-m^2 home

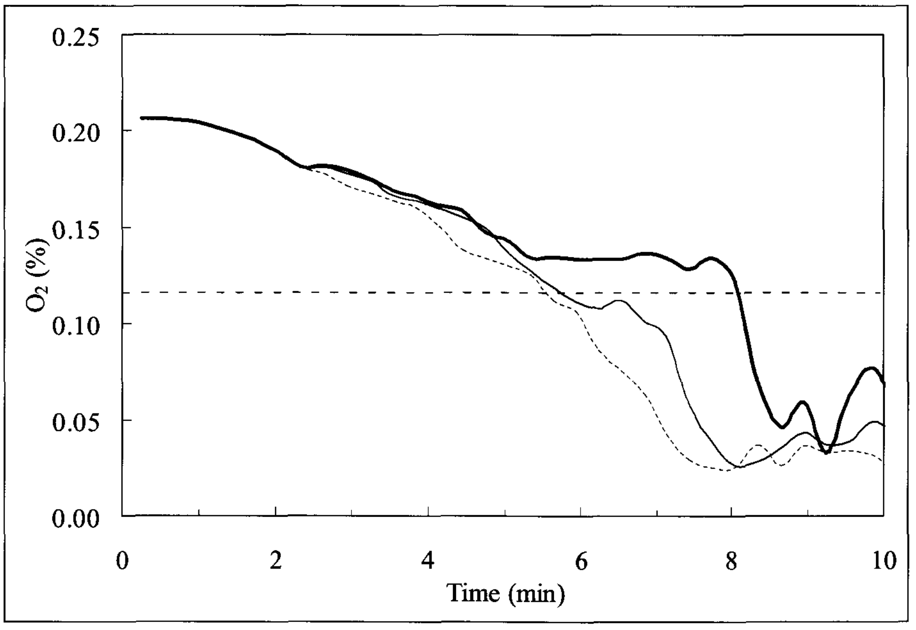


Figure E-6: O_2 concentration at Location 'A' for a 260-m^2 home

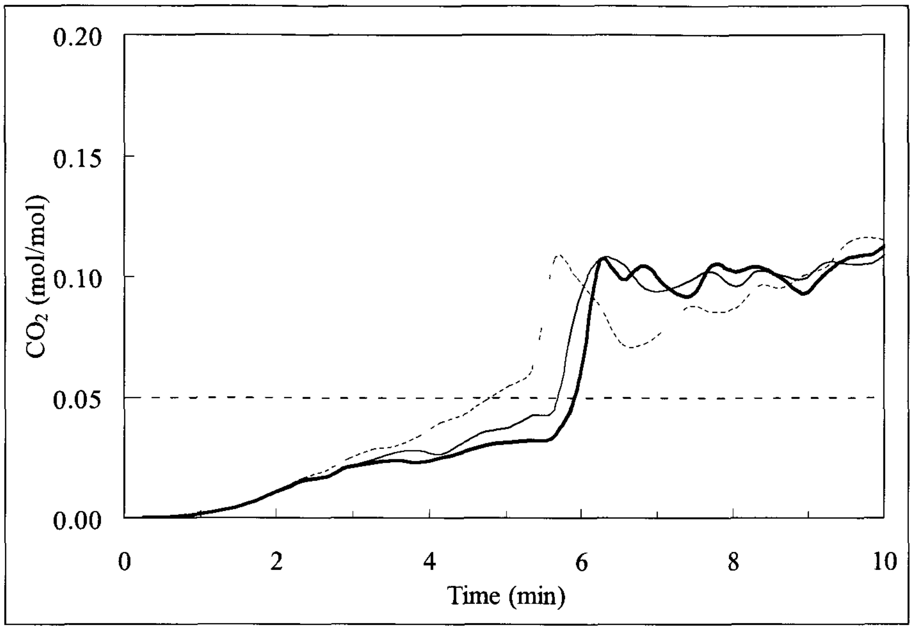


Figure E-7: CO_2 concentration at Location 'A' for a 223-m^2 home

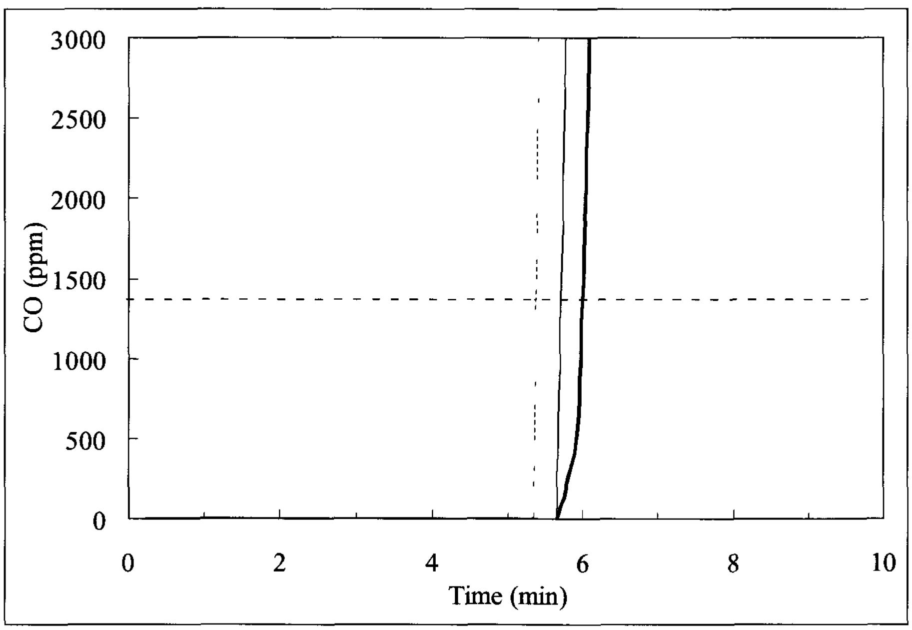


Figure E-8: CO concentration at Location 'A' for a 223-m^2 home

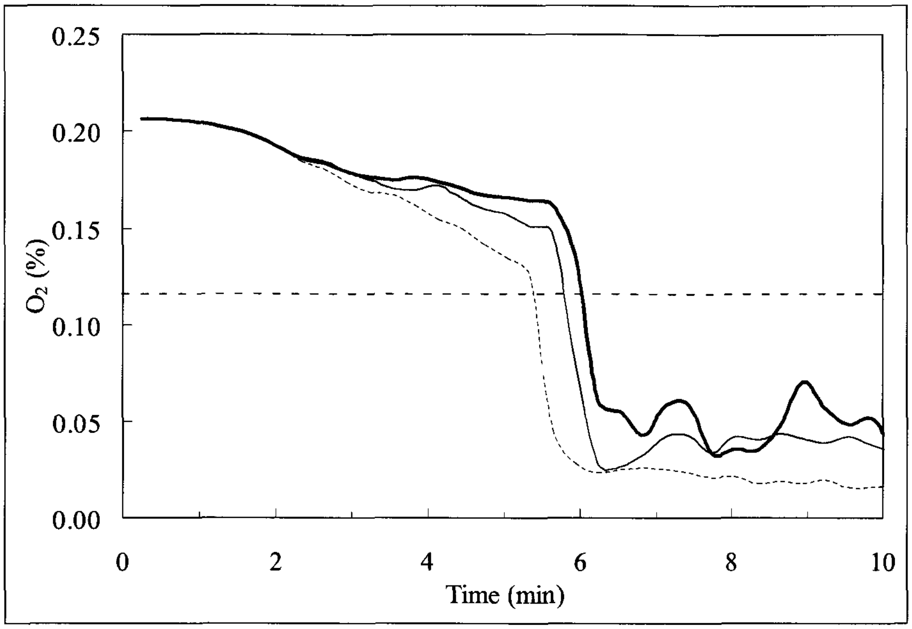


Figure E-9: O_2 concentration at Location 'A' for a 223-m^2 home

Townhomes

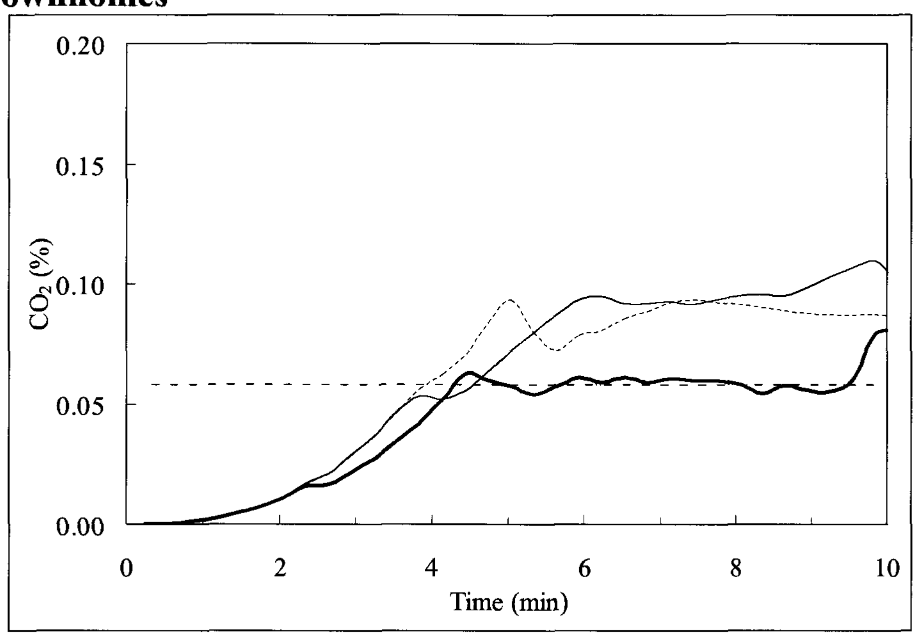


Figure E-10: CO_2 concentration at Location 'A' for a 186-m^2 home

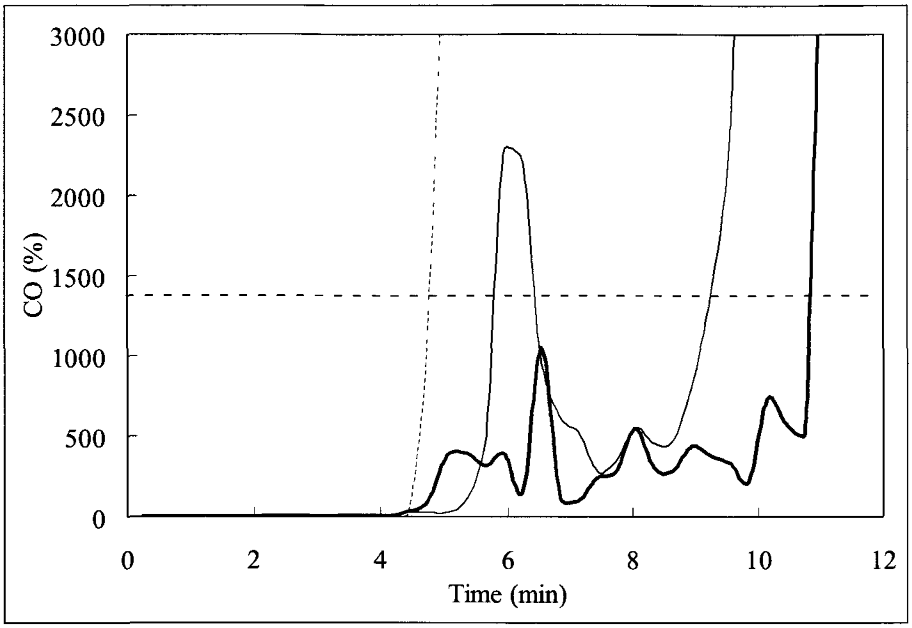


Figure E-11: CO concentration at Location 'A' for a 186-m^2 home

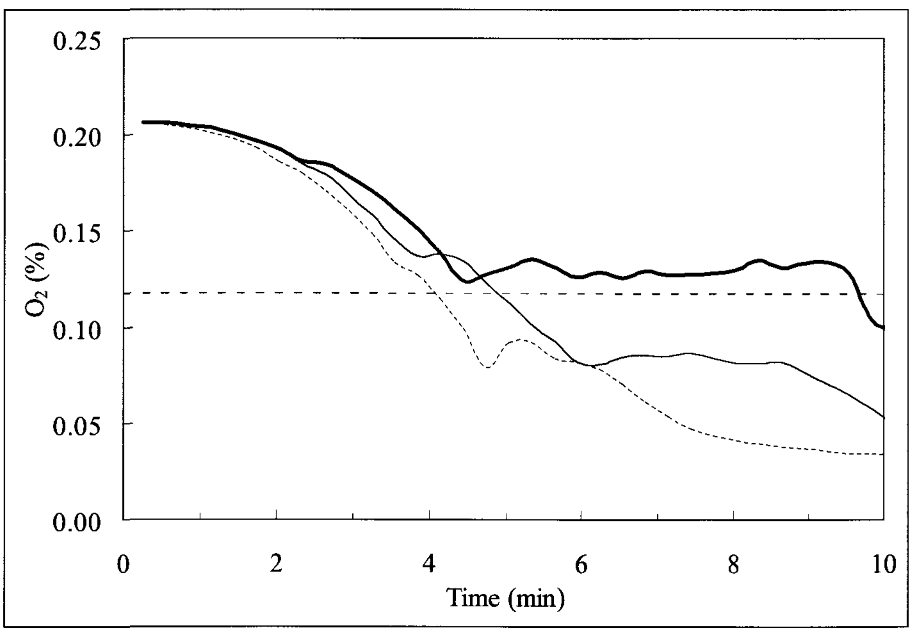


Figure E-12: O_2 concentration at Location 'A' for a 186-m^2 home

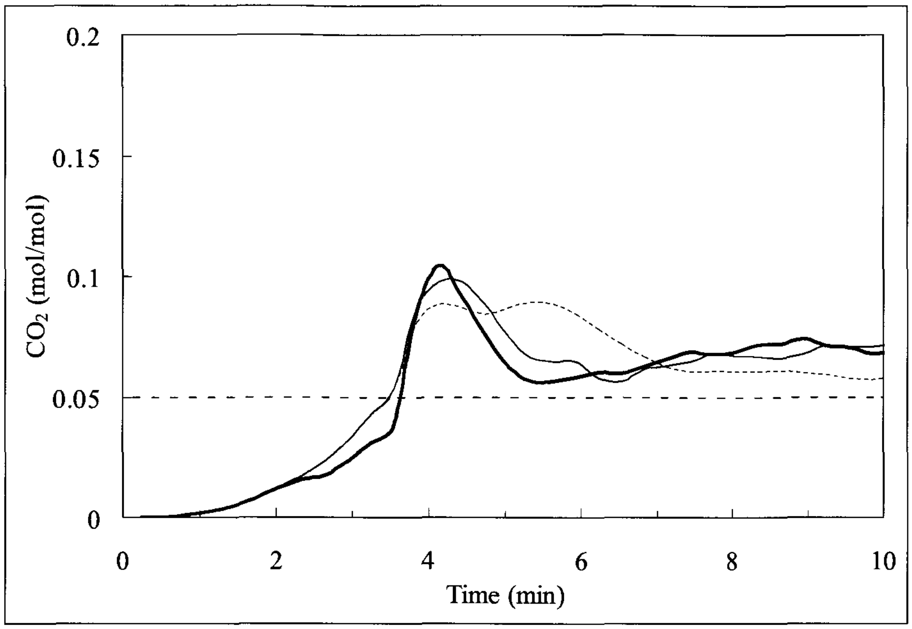


Figure E-13: CO_2 concentration at Location 'A' for a 167-m^2 home

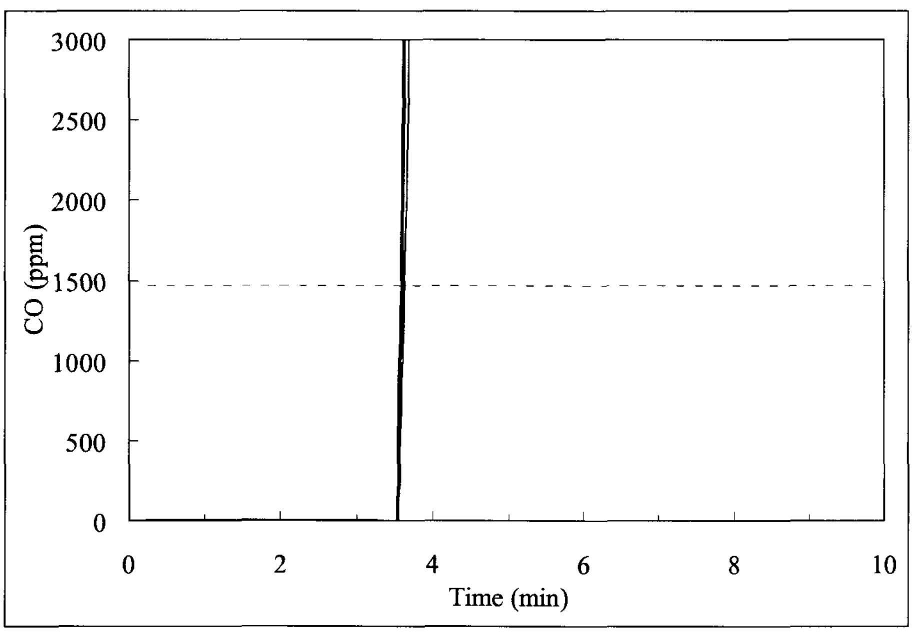


Figure E-14: CO concentration at Location 'A' for a 167-m^2 home

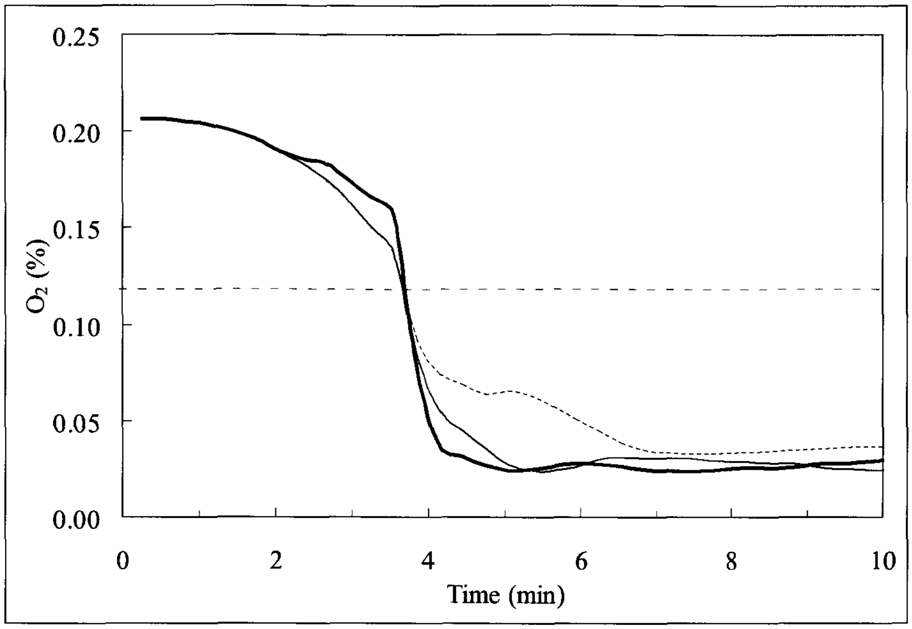


Figure E-15: O_2 concentration at Location 'A' for a 167-m^2 home

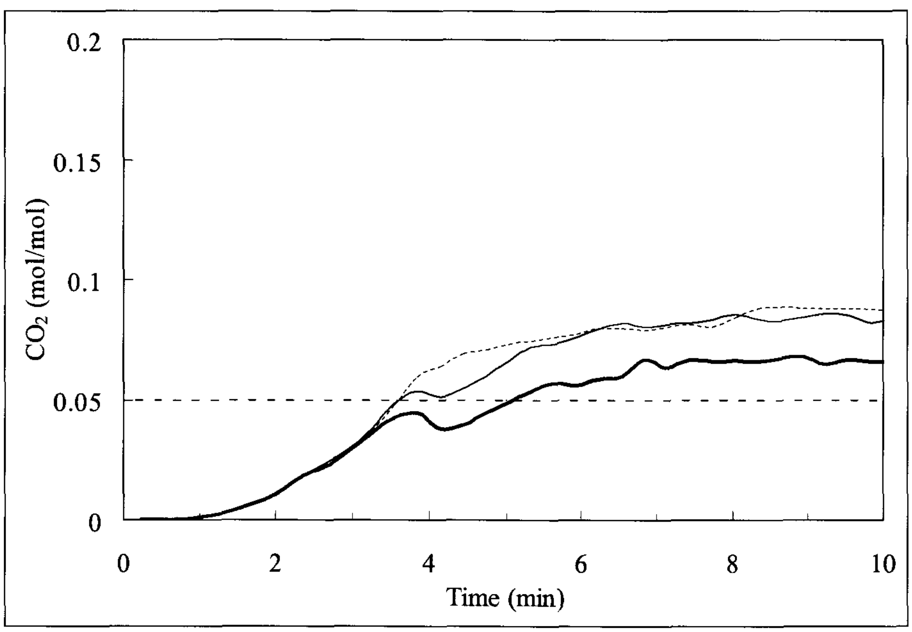


Figure E-16: CO_2 concentration at Location 'A' for a 149-m^2 home

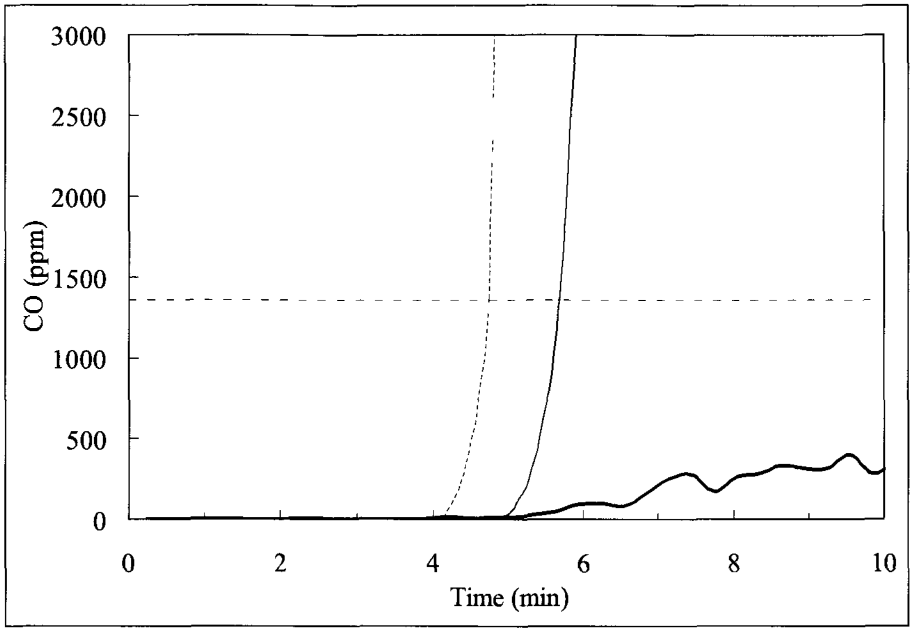


Figure E-17: CO concentration at Location 'A' for a 149-m^2 home

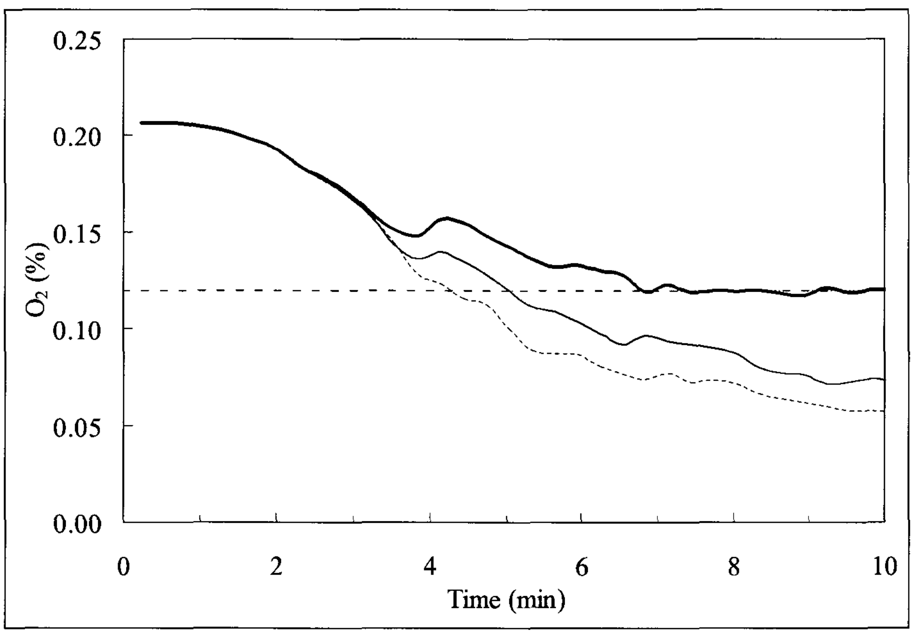


Figure E-18: O_2 concentration at Location 'A' for a 149-m^2 home

Bedroom Toxicity Graphs

Detached Homes

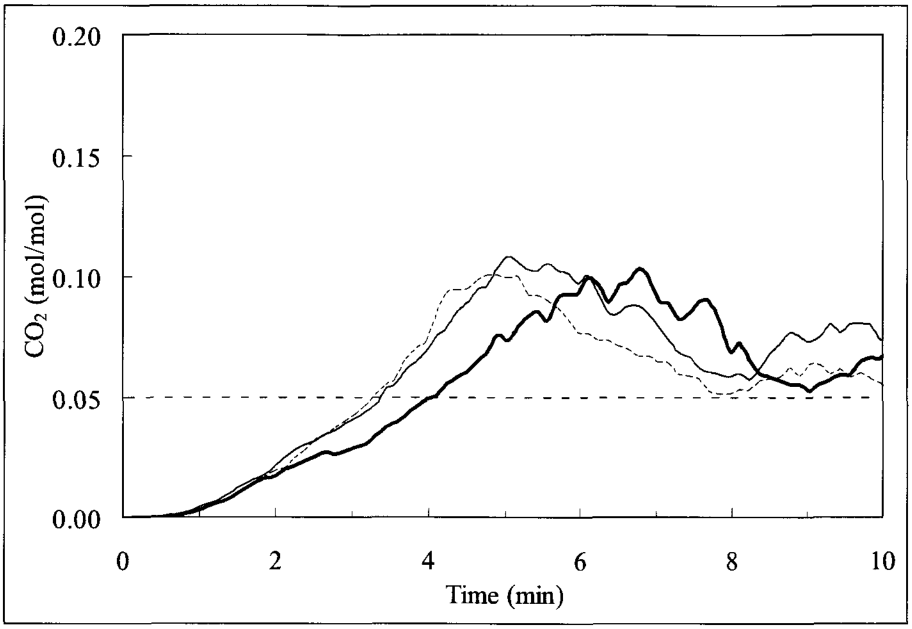


Figure E-19: CO_2 concentration at Location ‘A’ for a 297-m^2 home

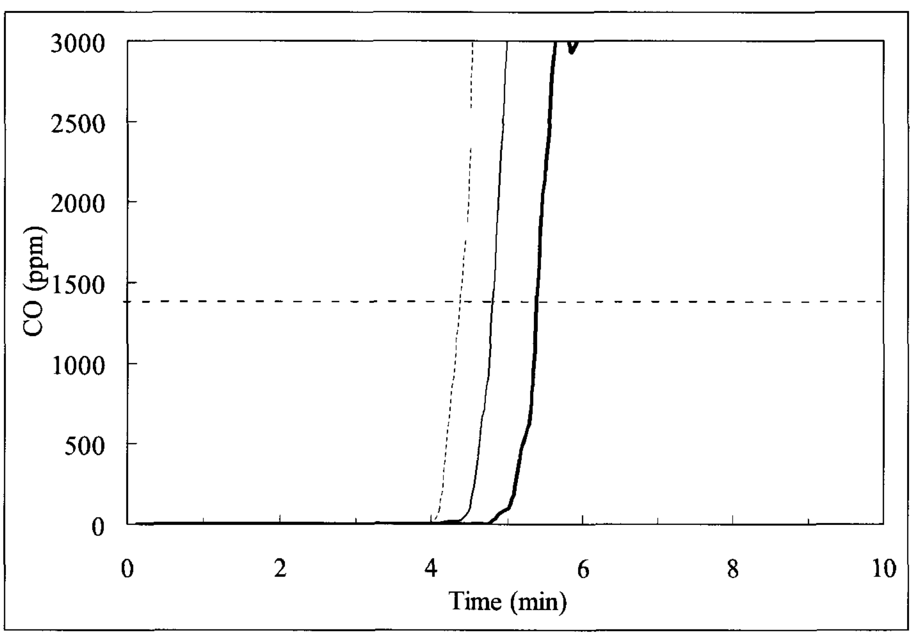


Figure E-20: CO concentration at Location ‘A’ for a 297-m^2 home

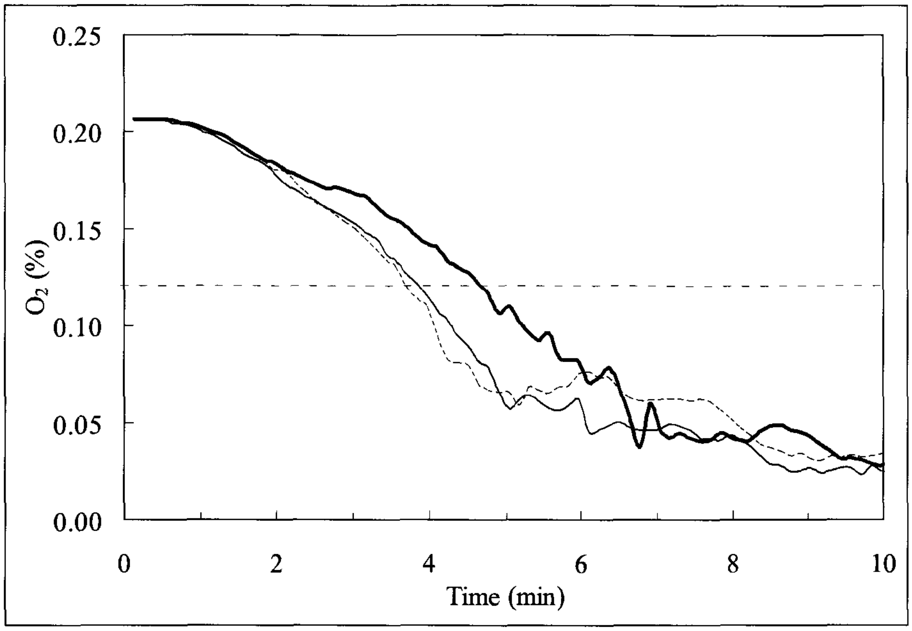


Figure E-21: O_2 concentration at Location 'A' for a 297-m^2 home

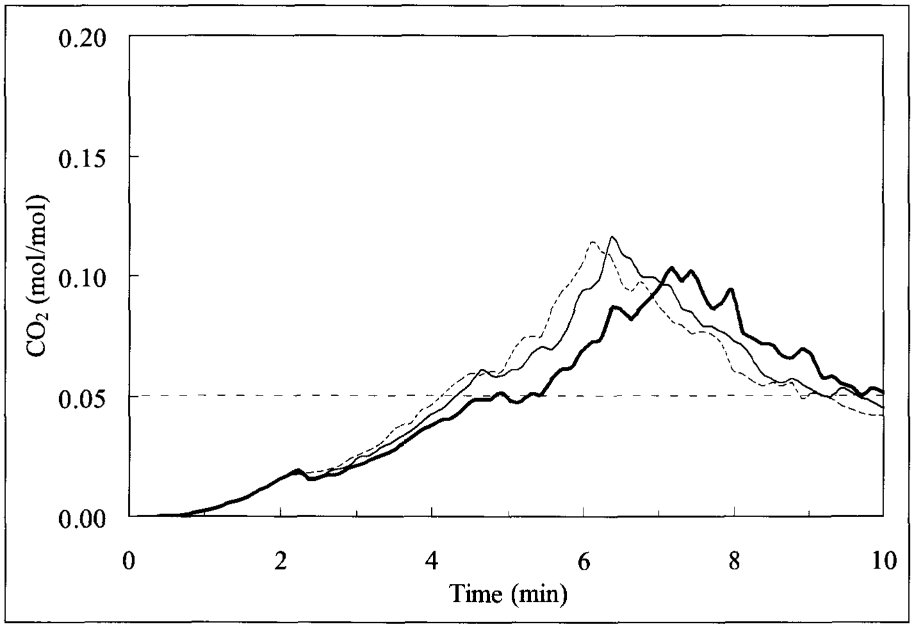


Figure E-22: CO_2 concentration at Location 'A' for a 260-m^2 home

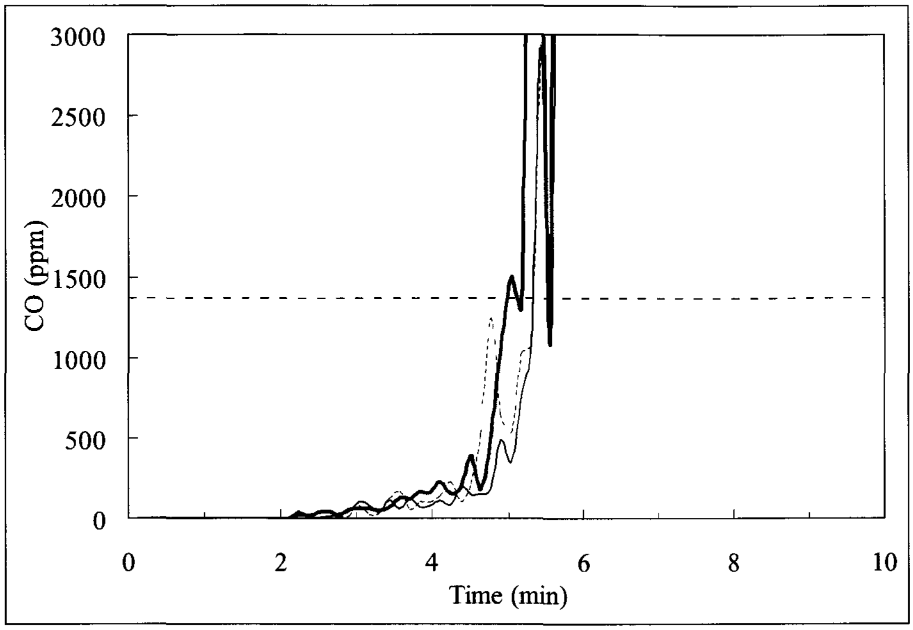


Figure E-23: CO_2 concentration at Location 'A' for a 260-m^2 home

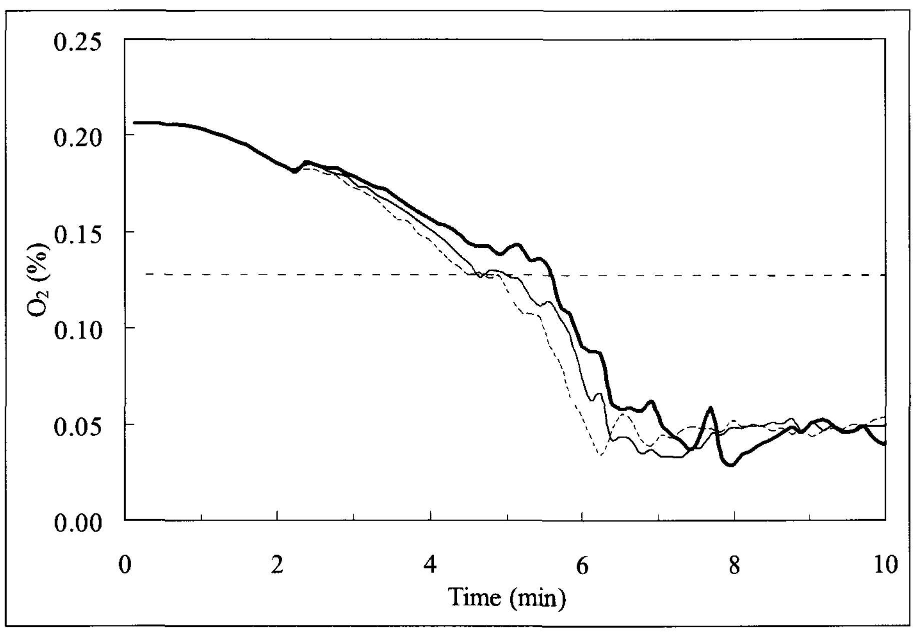


Figure E-24: O_2 concentration at Location 'A' for a 260-m^2 home

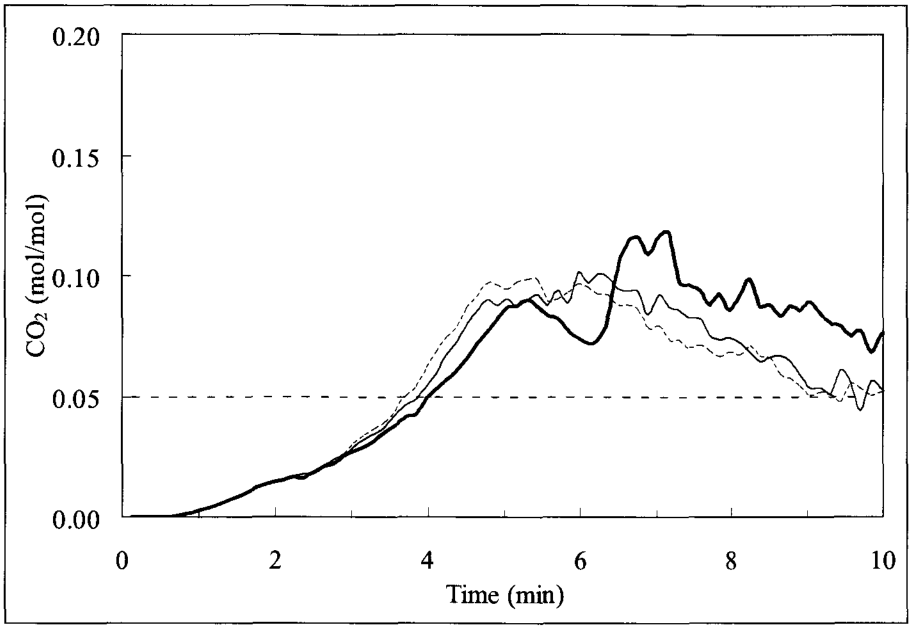


Figure E-25: CO_2 concentration at Location 'A' for a 223-m^2 home

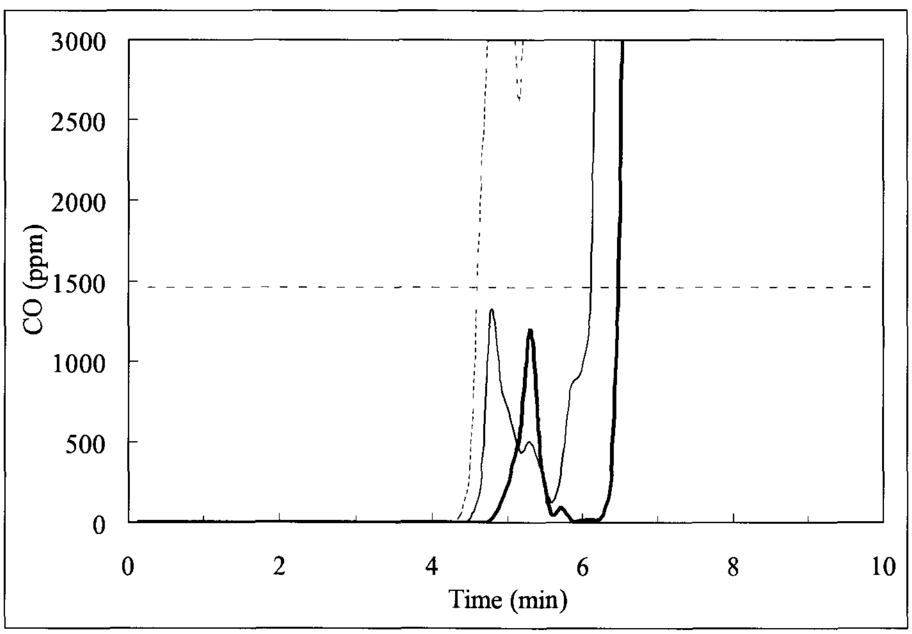


Figure E-26: CO concentration at Location 'A' for a 223-m^2 home

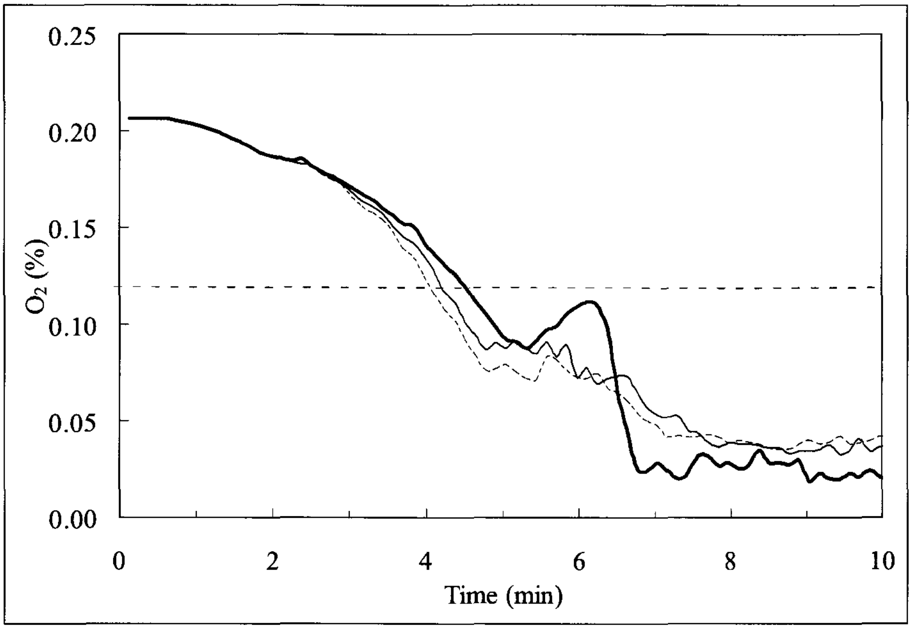


Figure E-27: O_2 concentration at Location 'A' for a 223-m^2 home

Townhomes

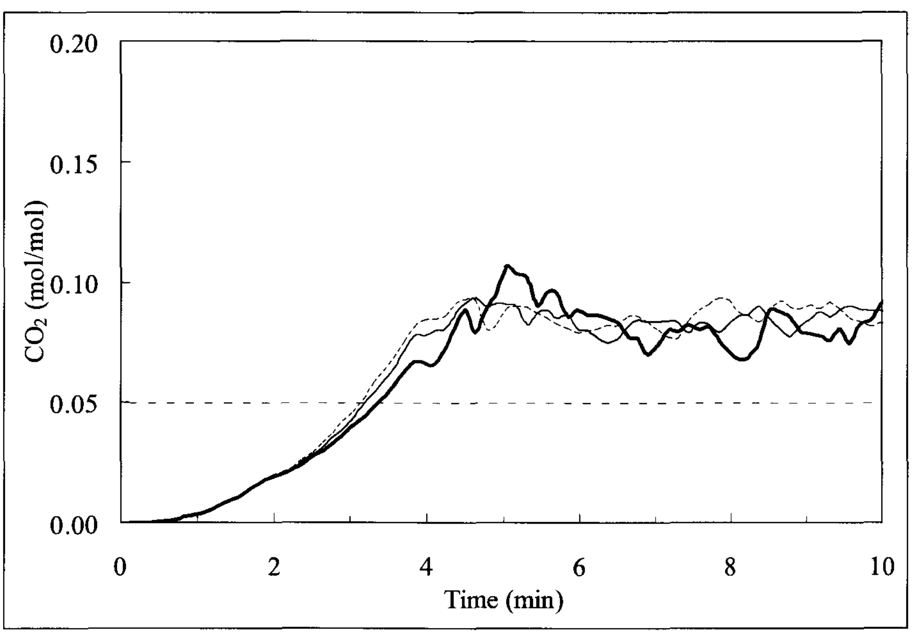


Figure E-28: CO_2 concentration at Location 'A' for a 186-m^2 home

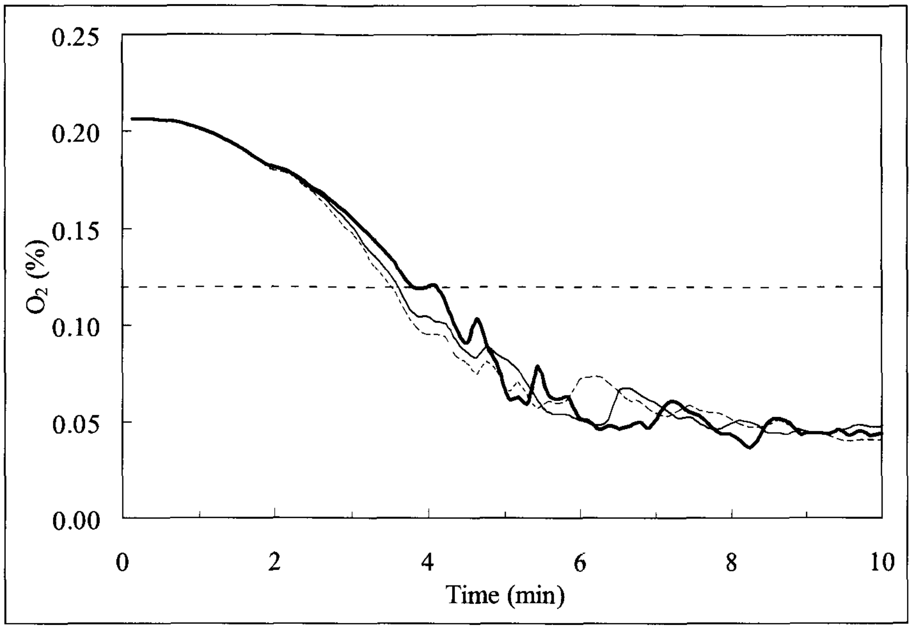


Figure E-29: O_2 concentration at Location 'A' for a 186-m^2 home

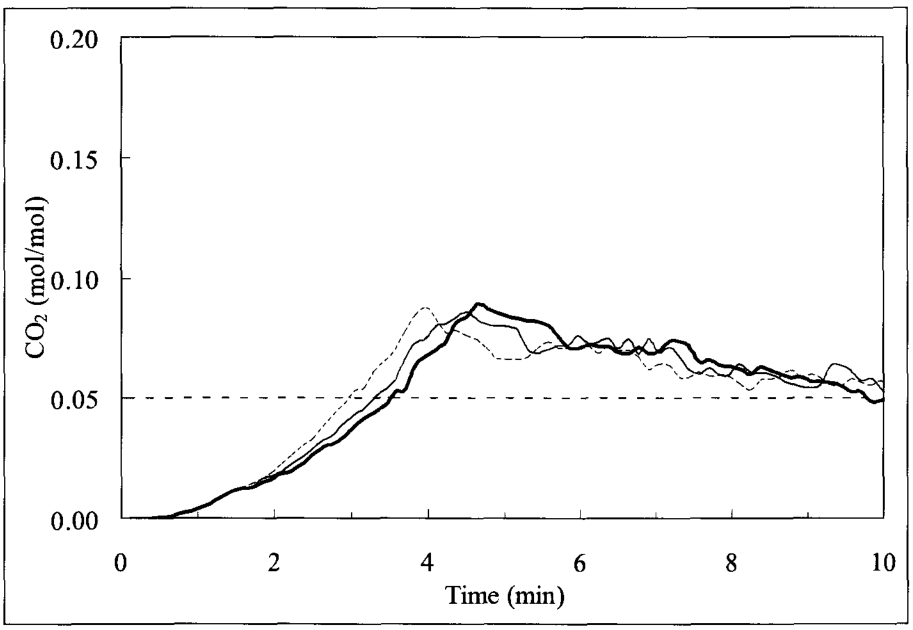


Figure E-30: CO_2 concentration at Location 'A' for a 149-m^2 home

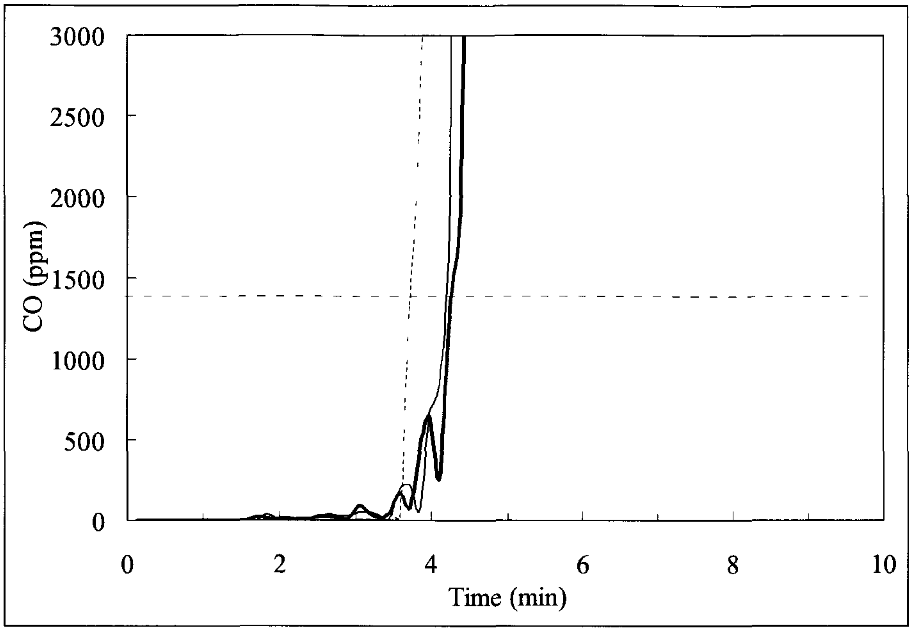


Figure E-31: CO concentration at Location 'A' for a 149-m^2 home

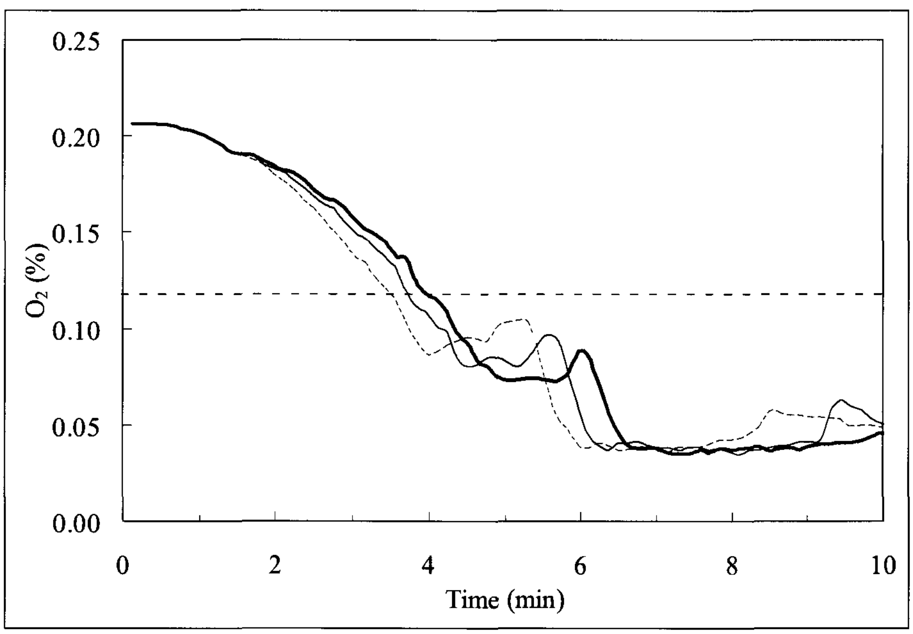


Figure E-32: O_2 concentration at Location 'A' for a 149-m^2 home