DESIGN FIRES FOR MOTELS AND HOTELS

BY

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Abstract

With performance-based building codes, fire protection engineers can apply engineering approaches for fire safety design, rather than merely rely on prescriptive requirements. The development of design fires for different building categories is essential to performance-based approaches. In this project, design fires for one building category, motels and hotels, was studied.

In order to quantify the fire loads and their composition in motels and hotels, a fire load survey was conducted in 10 motels and 12 hotels in Canada's National Capital Region, Ottawa and Gatineau area, in 2007. Based on the field survey, two full-scale fire tests, one representing a bedroom with one bed and the other representing a bedroom with two beds, were designed and conducted at NRCC/Carleton (National Research Council of Canada/Carleton University) Fire Research Lab in 2008. For the two tests, the parameters, such as heat release rate, temperature, heat flux, and gas concentration were measured and/or calculated. Recommended design fire curves are presented.

A field model, Fire Dynamics Simulator (FDS), was used to simulate the full-scale fire tests. Two virtual fuels were developed and used in three different fuel layouts. The results of the model compared well with the experimental data.

To those surveyed motels and hotels

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Nomenclature

A	Total area of the openings (m^2)
A_f	Floor area (m^2)
A_0	Area of opening (m^2)
A_T	Total compartment surface area (m^2)
A_W	Window area (m^2)
b	Square root of thermal inertial ($\text{Ws}^{0.5}/\text{m}^2\text{K}$)
b_{ref}	Reference value of b ($\text{Ws}^{0.5}/\text{m}^2\text{K}$)
c_p	Specific heat of gas ($\text{kJ/kg} \cdot \text{K}$)
E	Heat released per unit mass of oxygen consumed (MJ/kg)
E_{CO}	Heat released per unit mass of oxygen consumed for combustion of CO to CO_2
F	Fire load in equivalent weight (kg)
F_0	Opening factor ($\text{m}^{1/2}$)
F_{ref}	Reference value of opening factor ($\text{m}^{1/2}$)
H	Weighted height of the openings (m)
H_0	Height of opening (m)
h_{c_i}	Calorific value of item i (MJ/kg)
h_k	Effective heat transfer coefficient ($\text{kW/m} \cdot \text{K}$)
k_i	Proportion of content or building component i that can burn
$k\rho c_p$	Thermal inertial ($\text{W}^2\text{s}/\text{m}^4\text{K}^2$)
$M_r(E)$	Relative molecular mass of exhaust gas (kg/kmol)
$M_r(\text{O}_2)$	Relative molecular mass of oxygen (kg/kmol)
m_i	Mass of item i (kg)

$\dot{m}_g$	Gas flow rate out the opening (kg/s)
P_{amb}	Pressure of ambient air (Pa)
psf	Pounds per square foot (lb/ft ²)
Q	Total fire load in a compartment (MJ)
$\dot{Q}$	Rate of heat release (kW), heat release rate of the fire (kW)
$\dot{Q}_o$	Reference heat release rate (kW)
Q_i''	Fire load density (MJ/m ²)
$\dot{q}$	Heat release rate of the fire (kW)
$\dot{q}_{loss}$	Net radiative and convective heat transfer from the upper gas layer (kW)
RH_{amb}	Relative humidity of ambient air (%)
T_g	Temperature of the upper gas layer (K)
$T_{g,max}$	Maximum temperature (K)
T_{amb}	Temperature of ambient air (K)
T_∞	Ambient temperature (K)
T^*	Empirical constant (K)
t	Time after effective ignition (s)
t_o	Time to reach the reference heat release rate (s)
$X_{H_2O}^0$	Mole fraction of H ₂ O in the incoming air
$X_{O_2}^0$	Measured mole fraction of O ₂ in the incoming air
$X_{CO_2}^0$	Measured mole fraction of CO ₂ in the incoming air
X_{CO}^0	Measured mole fraction of CO in the incoming air
X_{O_2}	Measured mole fraction of O ₂ in the exhaust gases
X_{CO_2}	Measured mole fraction of CO ₂ in the exhaust gases
X_{CO}	Measured mole fraction of CO in the exhaust gases

α	Growth rate (kW/s ²), combustion expansion factor
ρ_{∞}	Density of air (kg/m ³)
ε	Emissivity of hot gas
σ	Stefan-Boltzmann constant (kW/m ² ·K ⁴)
θ_1	Burning rate stoichiometry
θ_2	Wall steady-state losses
θ_3	Wall transient losses
θ_4	Opening height effect
θ_5	Combustion efficiency
ϕ	Oxygen depletion factor

Chapter 1: Introduction

1.1 Background

Fire safety is one of the major concerns in building design, and building codes provide a set of safety requirements for designers, engineers, code officials, and other building practitioners to fulfill. The Code of Hammurabi was regarded as the first building code in history, which can be traced back to about 4000 years ago, when King Hammurabi of Babylonia reigned from 1955 BC to 1913 BC [1]. In the United States, the early building and fire regulations adopted in some territories, such as New Amsterdam (1645), Virginia (1662), Boston (1683), and Philadelphia (1696), are prior to the formation of the United States (1776) [2]. The first modern building code of the United States was published in 1905 [2].

There are two main types of building codes: prescriptive-based and performance-based building codes. The prescriptive-based building codes have been used in engineering design for about 100 years around the world, and, for example, the first modern building code of the United States (1905) was a prescriptive-based code. The prescriptive building code is defined by SFPE (Society of Fire Protection Engineers) Engineering Guide [3] as “a code or standard that prescribes fire safety for a generic use

or application. Fire safety is achieved by specifying certain construction characteristics, limiting dimensions, or protection systems without referring to how these requirements achieve a desired fire safety goal”.

During the last twenty or thirty years, the performance-based building codes have aroused worldwide interests, and some countries have changed their building codes from prescriptive-based to performance-based. In fact, the first building code in history, the Code of Hammurabi, was a performance-based code, but the objective was simply the penalty for failure [1].

For the prescriptive-based building code, the goal of a fire safety design is to satisfy specific requirements or code provisions, but for the performance-based design, the goal is to meet code mandated objectives by using accepted means of verification, and designers are allowed to use ‘any’ solutions that meet the objectives [2].

1.1.1 Prescriptive-based Building Code

The first modern building code of the United States, published in 1905, was triggered by the widespread loss of life and property by fire in the late 19th century. With time, the prescriptive-based codes became thicker by the addition of new prescriptive requirements following large building fires to address the specific concerns raised by those fires. For example, before the first performance-based code for England and Wales was adopted in 1985, the document of their prescriptive-based code was 307 pages, while their new performance-based code was only 23 pages [2].

Prescriptive-based building codes have a number of advantages. For prescriptive design, engineers or designers only need to follow the requirements specified in the prescriptive-based building codes, and little analysis, knowledge or even time is needed. It is also easier and more comfortable for AHJs (Authority Having Jurisdiction) to check and accept fire safety designs [4].

Another advantage is that the prescriptive design can cover a broad range of conditions and the diversity of facilities being protected. Even though the inherent safety factors can be so high to cause redundancies, which cost money, it can provide sufficient flexibility for future changes [4], and disaster could be avoided by redundancy. Babrauskas [5] pointed out that most of the major fire disasters occurred because of a series of failures or a string of failures occurred in a row, rather than the failure of any one safety system.

A disadvantage of the prescriptive design is that the design can be unreasonably expensive due to higher inherent safety factors and redundant considerations. Furthermore, the unreasonable expensive design may not protect a particular facility in the most effective way [4].

Another disadvantage is that the prescriptive approach can hinder innovation by not allowing designers to utilize new materials or new technologies that are not accepted in the existing prescriptive-based codes. New versions of national prescriptive-based building codes are expected to be updated and released in 5 years, 10 years, or even

longer periods so they cannot keep up with changes in technologies and construction methods.

1.1.2 Performance-based Building Code

The first adopted performance-based building code in the world was the one for England and Wales in 1985. Later on, countries such as New Zealand (1992), Australia (1996), Japan (2000), and Canada (2005) have adopted performance-based building codes [2, 6]. The National Building Code of China is still prescriptive-based, but performance-based concepts have been accepted in the construction of the 2008 Beijing Olympic venues [6]. The first draft of the IBC (International Building Code) performance-track code was issued in 1998 [5].

All performance-based building codes state a set of objectives which have to be met by the designs; however, different structures are used in different countries. Table 1 presents a summary of the structure system of performance-based codes in New Zealand, Australia, and Canada.

Table 1 Structures of performance-based codes in 3 countries

New Zealand 1992 [2]	Australia 1995 [2]	Canada 2005 [6, 7]
L1 Objectives	L1 Objectives	D-A Objectives: (OS, OH, OA, OP)
L2 Functional Requirements	L2 Functional Statements	D-A Functional Statements
L3 Performance Criteria	L3 Performance Requirements	D-B Acceptable Solution
	L4-A Deem to Satisfy	
	L4-B Verification Methods	

Note: L—Level; D—Division; OS—Safety; OH—Health; OA—Accessibility; OP—Fire and Structural Protection of Buildings

The performance-based New Zealand building code has three levels: objectives, functional requirements, and performance criteria. The performance building code of Australia consists of four levels. The first three levels are similar to the code of New Zealand, and level 4 includes two parts: deem to satisfy solutions and verification methods [2]. The National Building Code of Canada 2005 is an objective-based model code that has three divisions. Division A includes four main objectives, which are Safety (OS), Health (OH), Accessibility (OA), and Fire and Structure Protection of buildings (OP), as well as functional statements that are interconnected with the objectives. Division B provides acceptable solutions, and division C includes administrative provisions [6, 7].

The common points of the three national building codes are the objectives, functional statements and performance requirements, which can be traced back to the early idealized structure of the performance-based regulatory system proposed by the Nordic Committee on Building Regulations (NKB) in 1978 [8], Figure 1.

Figure 1 The idealized structure of the performance-based regulatory system [8]

The structure of the performance-based building codes illustrates the difference with the prescriptive-based codes, where only the prescriptive solutions are provided. In the performance-based building code, engineers or designers can use ‘any’ solutions that meet the objectives, rather than only a single set or limited solutions allowed in the prescriptive-based codes [2]. Therefore, the performance-based building codes allow designers to use new materials and new technologies by verifying that the new materials or new technologies can meet the mandated objectives.

Another significant advantage of performance-based building codes is that rational designs can be made, especially in unconventional projects that may not be amenable to analysis under prescriptive codes. Performance-based approaches can also provide a rational tool for designers to meet owner’s desire to increase the level of safety over the legal minimum requirements [5].

The disadvantages of performance-based design are the need for time-consuming analysis and the need for more knowledge for both designers and AHJ. These are part of the reasons that the performance-based building codes have only been adopted by few countries in the world.

One of the main concerns for adopting performance-based codes is that they may lead to designs that provide much less fire safety than those under prescriptive codes. While the performance-based building codes are initially applied in the large, high-dollar projects, it could mean that the buildings with larger numbers of people may have relatively lower safety standards than those with small number of people [5].

From an historical overview of the development of building regulations, Hadjisophocleous et al. [9] summarized the advantages and disadvantages of prescriptive-based and performance-based regulations as shown in Table 2. The performance-based codes have superiority over prescriptive codes in economic, flexibility and globalization aspects. The difficulty to prove compliance with the set of objectives in the performance-based approach could be resolved with the development of computer models and engineering tools [9].

Table 2 Prescription vers Performance [9]

Code Type	Advantages	Disadvantages
Prescriptive codes	<ul style="list-style-type: none"> • Straightforward evaluation of compliance with established requirements • No requirements for high level of engineering expertise 	<ul style="list-style-type: none"> • Requirements specified without statement of objectives • Complexity of the structure of codes • No promotion of cost-effective designs • Very little flexibility for innovation • Presumption that there is only one way of providing the level of safety
Performance codes	<ul style="list-style-type: none"> • Establishment of clear safety goals and leaving the means of achieving those goals to the designer • Permit innovative design solutions that meet the performance requirements • Eliminate technical barriers to trade for a smooth flow of products • Facilitate harmonization of international regulation systems • Facilitate use of new knowledge when available • Allow for cost-effectiveness and flexibility in design • Non complex documents • Permit the prompt introduction of new technologies to the market place 	<ul style="list-style-type: none"> • Difficult to define quantitative levels of safety (performance criteria) • Need for education because of lack of understanding especially during first stages of application • Difficult to evaluate compliance with established requirements • Need of computer models for evaluating performance

1.1.3 Fire Protection Design for Buildings

Figure 2 [3] presents a typical basic building design and construction process, which can be used in either prescriptive-based design or performance-based design, or both. In comparison with the prescriptive-based design, the early involvement of performance-based approaches in the designs, such as in the feasibility or conceptual design phase, can provide benefits of flexible design, innovative utilization of new materials and/or new technologies, better fire safety approaches, and maximal benefit/cost ratio.

Recommended steps in the performance-based design process are given in Figure 3, which is reproduced from the SFPE Engineering Guide [3, 10].

Figure 2 Basic building design and construction process [3]

Figure 3 Steps of performance-based design (modified from [3], [10])

1.2 Objective of this Study

Some countries in the world have changed their building codes from prescriptive to performance-based, and other countries around the world are interested to adopt the performance-based approach. One of the most challenging tasks for applying performance-based designs is to develop design fires for different building categories. For this, the fire loads in different building categories need to be well understood, and the engineering tools, such as computer models, need to be reliable and available for use by engineers and designers.

Motels and hotels belong to the residential occupancy group, and are considered as a “sleeping risk” with more fire safety concerns to public. However, very few studies have been conducted in this building category.

The objective of this research is to determine the fire loads for motels and hotels, and also to obtain experimental data through full-scale fire tests, which can be used to compare the results of computer modelling.

1.3 Thesis Organization

This research project deals with design fires for motels and hotels. The scope of this report covers four major aspects: literature review, fire load surveys, experimental tests, and fire modelling. The main contents of each chapter are listed below:

Chapter 1: discusses the advantages and disadvantages of prescriptive-based and performance-based codes, and also introduces the fire protection design using the performance-based approach. The objective of this research is also presented.

Chapter 2: provides a literature review on statistical data of hotel fires; possible design fire scenarios; fire load surveys conducted in office buildings, residential buildings, and hotels; fire tests from heat release rate measurements and room fire tests; an introduction of zone models and field models used in the fire community, and a modelling exercise of room fires.

Chapter 3: presents the fire load survey of 10 motels and 12 hotels conducted in Canada's National Capital Region, Ottawa and Gatineau area, from March 2007 to August 2007.

Chapter 4: discusses the test setup, instrumentation, results and analyses of two full-scale room fire tests, conducted in the NRC/Carleton Fire Research Lab in 2008.

Chapter 5: presents a computer simulation of the hotel room fire tests using the Fire Dynamic Simulator (FDS) model, and a simplified approach used to develop input data files for FDS modelling.

Chapter 6: presents a summary of this research and recommendations for future research work.

Chapter 2: Literature Review

2.1 Hotel Fires

The National Building Code of Canada (NBCC) [7] provides major occupancy classifications so every building can be classified into one of the six groups (Group A, B, C, D, E, and F), or one of the divisions under the specific group. Hotels and motels are categorised into Group C---residential occupancies. Some examples of other classifications are: Educational properties (non-residential schools and colleges) belong to Division 2 of Group A; nursing homes and facilities that care for the aged belong to Division 2 of Group B; business and office properties belong to Group D; stores and other mercantile establishments belong to Group E; low-hazard general item warehouses belong to Division 3 of Group F [11]. Most countries in the world also adopt the classification of hotels as a type of residential premises [12].

Statistical data of fire losses in selected classifications of non-residential, commercial and residential structures in Canada in 2001 are presented in Table 3 [11]. As the table shows, 218 hotel/motel fires were reported in Canada in 2001. The average annual fire losses in similar building categories in the United States from 1980 to 1998 are given in

Table 4 [11], which shows that there was an average of 7400 hotel/motel fires annually during the period of 1980 to 1998 in the United States.

Table 3 2001 Canadian fire losses in selected property classifications of non-residential, commercial and residential structures [11, 13]

Property classification	Property loss			
	Fires	per fire (CD)	Injuries	Deaths
Office	233	47 800	5	0
Hotel, inn, motel, etc.	218	73 600	25	1
Home for Aged	93	4200	7	2
Textile and clothing store	44	32 000	2	0
Furniture, appliance and electronics store	38	98 500	1	0
Department and variety store	105	72 300	1	0
Food and beverage store	202	60 400	9	0
Restaurant or bar	349	51 300	19	0
Church, funeral parlor, etc.	66	57 100	1	0
School, college, university	420	28 400	19	0
Theatre, auditorium, studio, recreation or social club, library, museum, art gallery, amusement or recreational place, etc.	231	34 700	6	0
Warehouse/storage	291	154 300	6	0

Table 4 Average annual* fire losses in selected classifications of non-residential, commercial and residential structures in the United States from 1980 to 1998 [11, 13]

Property classification	Average annual fire losses 1980-1998			
	Fires	Property loss per fire (USD)	Injuries	Deaths
Hotels/motels	7400	9000	408	46
Care homes for aged	3600	1600	228	15
Eating and drinking	14 800	11 700	245	11
Stores and mercantile	25 150	19 500	486	22
Business and office	7950	20 400	113	4
General item warehouse	2280	35 400	28	1
Religious and funeral	2490	24 800	29	3
Educational	9200	10 200	194	2
Other public assembly	5640	16 500	85	7

* The numbers throughout the remainder of this report are the average each year, over the nineteen-period from 1980 through 1998

The major hotel fires around the world from 1909 to 2006 are listed in Appendix A. One of the biggest hotel fires in the United States history is the MGM Grand Hotel fire, in Las Vegas, Nevada, on the early morning of November 21, 1980. The MGM Grand Hotel was a 23-story high-rise building. 85 guests and hotel employees were killed, and about 600 were injured in this fire [14].

2.1.1 When Hotel Fires Occur

From the reported data on fire events and their outcomes in hotels/motels in Canada from 1980 to 1998, Richardson [11] noticed that the greatest percentage of fire injuries was from fires that occurred between midnight and 6:00 am and the greatest percentage of property loss was between 9:00 pm and 6:00 am. The percentage of fires starts to decrease between the 3:00-6:00 am time period. He also noted that Saturdays and Sundays were the peak days in terms of number of fires, and fire injuries.

Hansell and Morgen [15] analysed the U.K. fire statistical data-base for 1978 and 1979. They found that an average of 0.375 casualties per hour from 8:00 am to 23:59 pm, and 9.75 casualties from 0:00 am to 7:59 am. It shows that 26 times more casualties occur during nighttime than during daytime. This illustrates that hotels represent a 'sleeping risk' as they are more heavily populated at night.

2.1.2 Ignition Source and First Ignited Items

According to the U.K. fire statistical data-base for 1978 and 1979, smoker's materials were the major ignition source, and caused about 40% of all fires. The fire incidents

caused by smoker's materials during the night were about twice as many as that during the day (55% to 29%) [15].

In the United States, the NFPA Survey from 1982 to 1986 indicates that smoking materials were also the major ignition source in terms of civilian deaths and injuries from fires in hotels and motels [12]. Table 5 shows the causes of civilian deaths and injuries of hotel and motel fires.

Table 5 Causes of civilian deaths and injuries of hotel and motel fires, 1982-1986: annual average unknown-cause fires allocated proportionally [12]

Cause	Civilian deaths	Civilian injuries
Smoking materials	21	143
Incendiary or suspicious causes	18	138
Cooking equipment	4	43
Heating equipment	4	29
Open flame, embers or torches	3	14
Electrical distribution	2	39
Child playing	2	8
Other equipment	1	18
Other heat	1	7
Natural causes	1	4
Appliances, tools or air conditioning	1	32
Exposure (to other hotel fire)	1	2
Total	59	475
Source: NFIRS (1982-1986)		

Richardson [11] analysed the Canadian fire statistics from 1980 to 1998, and found that the category of 'mattress, pillow or bedding, linen other than bedding, wearing apparel not on a person, unclassified or unknown soft goods or wearing apparel' was the leading type of materials first ignited in terms of number of fires (28.1%) with 75.5 injuries per 1000 fires. The largest number of injuries per 1000 fires was 110.7 with

relatively a small number of fires (3.8%), which was caused by ‘upholstered furniture, cabinetry, unclassified or unknown furniture’. Table 6 shows the type of materials first ignited for fire events in hotels/motels.

Table 6 Type of materials first ignited for fire events in hotels/motels [11]

Type of material first ignited--hotel/motel properties	Fires (per cent)	Injuries (per 1000 fires)	Property loss per fire (USD)
Mattress, pillow or bedding, linen other than bedding, wearing apparel not on a person, unclassified or unknown soft goods or wearing apparel	28.1	75.5	5900
Rubbish, trash or waste, dust, fibre or lint	13.9	25.2	3400
Cooking material	8.9	28.8	2300
Electrical wire or cable insulation	7.6	46.4	7500
Interior wall covering, floor covering or surface, ceiling covering or surface	5.1	60.5	14 000
Structural member or framing, unclassified or unknown type structural member or framing	4.9	44.4	42 200
Upholstered furniture, cabinetry, unclassified or unknown furniture	3.8	110.7	8600
Exterior sidewall covering or finish, exterior roof covering or finish, exterior trim	3.6	14.8	14 400
Percentage of all losses depicted by data	76%	74%	72%

2.2 Design Fires and Design Fire Scenarios

In fire safety design, the design fire(s) needs to be appropriately selected, due to its impact on “all aspects of fire safety performance, including the fire resistance for structures, compartmentation against fire spread, egress systems, manual or automatic detection systems, suppression systems, and smoke control” [16]. As the performance criteria have been established in the performance-based design, the first part of the

engineer's work is to identify the possible fire scenarios and design fire scenarios [3]. The definitions of fire scenario, design fire scenario, design fire, and design fire curve from two source references were summarized by Bwalya in Table 7 [17].

Table 7 Terminology related to design fires [17]

Term	Definition by source reference	
	ISO/TR-13387-2 [58]	SFPE engineering guide [3]
Fire scenario	A qualitative description of the course of a specific fire with time, identifying key events that characterize the fire and differentiate it from other possible fires	A set of conditions that defines the development of fire and the spread of combustion products throughout a building or part of a building
Design fire Scenario	A specific fire scenario on which an analysis will be conducted. It includes a description of the impact on the fire of building features, occupants, fire safety systems and would typically define the ignition source and process, the growth of the fire on the first item ignited, the spread of the fire, the interaction of the fire with the building occupants and the interaction with the features and fire safety systems within the building	A set of conditions that defines or describes the critical factors determining the outcomes of trial Designs
Design fire Design fire curve	<i>Design fire:</i> A quantitative temporal description of assumed fire characteristics based on appropriate fire scenarios. Variables used in the description include: HRR, fire size (including flame length), quantity of fire effluent, temperatures of hot gases, and time to key events such as flashover	<i>Design fire curve:</i> An engineering description of a fire in terms of HRR versus time (or in other terms elaborated in the stated reference) for use in a design fire Scenario

In terms of the temperature or heat release rate development in the compartment, enclosure fires are normally divided into different stages, including ignition, growth, flashover, fully developed and decay. Figure 4 presents the stages of fire development in a room in the absence of an active suppression system [18].

Figure 4 Stages of fire development in a room (modified from [18])

Figure 5 A simple design fire curve [19]

In fire safety engineering design, the fire development can be simplified into two stages: pre-flashover fire and post-flashover fire. The concern in the pre-flashover fire is the safety of humans, while the design objective in the post-flashover fire is to ensure structural stability and safety of firefighters [19]. Figure 5 presents an example of a simple design fire curve [19], which is similar to Figure 4 [18].

2.2.1 Pre-flashover Stage and T-squared Fires

In the pre-flashover stage of a real fire, the heat release rate is practically always increasing, and the growth is commonly quantified as a function of time squared. Equation 2.1 is one of the most widely used equations of the t-squared design fire given by NFPA [20]. Equation 2.2 [19] is similar to Equation 2.1, where the growth factor α , can be derived by substituting the values of reference heat release rate $\dot{Q}_o$, and time to reach the reference heat release rate t_o in Equation 2.1.

$$\dot{Q} = \dot{Q}_o \left(\frac{t}{t_o} \right)^2 \quad (2.1)$$

$$\dot{Q} = \alpha \cdot t^2 \quad (2.2)$$

Where, $\dot{Q}$ = rate of heat release (kW)

$\dot{Q}_o$ = reference heat release rate (kW), usually taken as 1000 kW

t_o = time to reach the reference heat release rate (s)

t = time after effective ignition (s)

α = growth rate coefficient (kW/s²)

Four different growth rates: ultra fast, fast, medium, and slow are presented in Figure 6, and the corresponding values of α and the characteristic time in different design fire scenarios are given in Table 8 [21]. The t-squared fire is typically for a single burning item [21], and a more complex design fire is provided in Figure 7 [19].

Figure 6 Heat release rate for different growth rates [19]

Table 8 Categories of t-squared fires [21]

Growth Rate	Design Fire Scenario	Value of α	Characteristic time, t_0 (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 stacked 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

Figure 7 A more complex design fire [19]

2.2.2 Post-flashover Stage and Flashover

Flashover is normally regarded as the transition from a growth fire to a fully developed fire [18], and also the transition of burning from one or two items to all the combustibles in the compartment. The widely used criteria for flashover are based on the radiation from the hot gas in the compartment [18]. One of the criteria is the temperature of the hot gas between 500 and 600°C, and another important criterion is the heat flux at floor level of the compartment reaching 15-20 kW/m².

A minimum heat release rate required for flashover can be predicted by different methods, such as method of MQH (McCaffrey, Quintiere, and Harkleroad) [22], method of Babrauskas [23], and method of Thomas [24]. All of these methods are based on the conservation of energy in the upper hot layer of a compartment, derived by McCaffrey, Quintiere, and Harkleroad. Equation 2.3 gives the conservation of energy expression to the upper layer.

$$\dot{Q} = \dot{m}_g c_p (T_g - T_\infty) + \dot{q}_{loss} \quad (2.3)$$

Where, $\dot{Q}$ = heat release rate of the fire (kW)

$\dot{m}_g$ = gas flow rate out the opening (kg/s)

c_p = specific heat of gas (kJ/kg · K)

T_g = temperature of the upper gas layer (K)

T_∞ = ambient temperature (K)

$\dot{q}_{loss}$ = net radiative and convective heat transfer from the upper gas layer (kW)

Table 9 summarises the three methods for predicting the minimum heat release rate for flashover with the respectively derived equations (Equation 2.4, 2.5, and 2.6), and the corresponding equations, values and assumptions that were substituted in the same conservation of energy expression, Equation 2.3.

Table 9 Summary of methods for predicting minimum heat release rate for flashover

Methods	Equations, values and assumptions	Minimum $\dot{Q}$ for flashover
MQH [22]	$\dot{m}_g \approx \sqrt{g} \rho_\infty A_0 \sqrt{H_0}$ $\dot{q}_{loss} = h_k A_T (T_g - T_\infty)$ <p>Where $\Delta T_g = T_g - T_\infty = 500$ $c_p = 1.0 \text{ kJ/kg} \cdot \text{K}$ $\rho_\infty = 1.18 \text{ kg/m}^3$ (density of air) A_0 = area of opening (m^2) H_0 = height of opening (m) h_k = effective heat transfer coefficient (kW/mK) A_T = total compartment surface area (m^2)</p>	$\dot{Q} = 610 (h_k A_T A_0 \sqrt{H_0})^{1/2}$ <p>.....(2.4)</p>
Babrauskas [23]	$\dot{m}_g \approx 0.5 A_0 \sqrt{H_0}$ $\dot{q}_{loss} = \varepsilon \sigma (T_g^4 - T_\infty^4) (0.40 A_T)$ <p>Where $T_g = 873 \text{ K}$ $T_\infty = 298 \text{ K}$ $\varepsilon = 0.5$ (emissivity of hot gas) $\sigma = 5.67 \times 10^{-11} \text{ kW/m}^2 \cdot \text{K}^4$ (Stefan-Boltzmann constant) $\frac{A_T}{A_0 \sqrt{H_0}} \approx 50$</p>	<p>Calculated: $\dot{Q} = 600 A_0 \sqrt{H_0}$</p> <p>Revised by tests: $\dot{Q} = 750 A_0 \sqrt{H_0}$(2.5)</p>
Thomas [24]	$\dot{m}_g \approx 0.5 A_0 \sqrt{H_0}$ $\dot{q}_{loss} = h_c (T_g - T_w) \frac{A_T}{2} + \varepsilon \sigma (2T_g^4 - T_w^4 - T_{flr}^4) \left(\frac{A_T}{6} \right)$ $\approx 7.8 A_T$ <p>Where $T_g = 577^\circ \text{C}$ or: $\Delta T_g = 600^\circ \text{C}$ $c_p = 1.26 \text{ kJ/kg} \cdot \text{K}$</p>	$\dot{Q} = 7.8 A_T + 378 A_0 \sqrt{H_0}$ <p>.....(2.6)</p>

After flashover, the major concern shifts from safety of humans to structural stability and safety of firefighters [19, 21], since the prevailing conditions may have exceeded the tenability limits [21]. Correspondingly, the importance of predicting heat release rate at the pre-flashover stage is changed to that of predicting temperature at the post-flashover stage [21].

Babrauskas [25, 26] developed a method to predict the upper gas temperature in a post-flashover compartment by adding a series of factors in one equation, Equation 2.7. Each factor represents a different physical phenomenon [18], and these factors can be derived from equations or tables presented in the literature [25, 26, and 18].

$$T_g = T_\infty + (T^* - T_\infty) \cdot \theta_1 \cdot \theta_2 \cdot \theta_3 \cdot \theta_4 \cdot \theta_5 \quad (2.7)$$

Where, T_g = temperature of the upper gas layer (K)

T_∞ = ambient temperature (K)

T^* = empirical constant, 1725 K

θ_1 = burning rate stoichiometry

θ_2 = wall steady-state losses

θ_3 = wall transient losses

θ_4 = opening height effect

θ_5 = combustion efficiency

The EUROCODE method [27], which is regarded as the most widely-used method for predicting post-flashover temperature [21], combined the factors that affect the fire

growth and intensity such as fire load density, compartment size, ventilation area, and construction materials [28]. Noticed that the factors used in the EUROCODE method [27] and the method of Babrauskas [25, 26] are different. The EUROCODE method treats the fire development as two phases, the heating phase and the decay phase, and a parametric fire temperature is defined in the heating phase. Table 10 summarizes the equations for the two phases, Equation 2.8 and 2.9, used in the EUROCODE method.

Table 10 Summary of equations used in the EUROCODE method

Phases	Equations for predicting temperatures [27]
Heating	$T = 1325 \left(1 - 0.324e^{-0.2t^*} - 0.204e^{-1.7t^*} - 0.472e^{-19t^*} \right) \dots\dots(2.8)$ <p>Where</p> $t^* = t \left(\frac{(F_0 / F_{ref})}{(b / b_{ref})} \right)^2 = t \left(\frac{F_0}{\sqrt{k\rho c_p}} \right)^2 \left(\frac{1160}{0.04} \right)^2$ <p>$k\rho c_p$ = thermal inertial</p> <p>$b = \sqrt{k\rho c_p}$; $b_{ref} = 1160 \text{ W s}^{0.5}/\text{m}^2\text{K}$</p> <p>$F_0 = \frac{A_0 \sqrt{H_0}}{A_t}$ (opening factor); $F_{ref} = 0.04 \text{ m}^{1/2}$</p>
Decay or Cooling	$T_g = T_{g,\max} - 625(t^* - t_d^*) \quad \text{for } t_d^* \leq 0.5$ $T_g = T_{g,\max} - 250(3 - t_d^*)(t^* - t_d^*) \quad \text{for } 0.5 \leq t_d^* \leq 2.0 \dots\dots(2.9)$ $T_g = T_{g,\max} - 250(t^* - t_d^*) \quad \text{for } t_d^* \geq 2.0$ <p>Where</p> $t_d^* = t_d \left(\frac{F_0}{\sqrt{k\rho c_p}} \right)^2 \left(\frac{1160}{0.04} \right)^2 ; \quad t_d = \frac{0.13 \times 10^{-3} Q_t''}{F_0}$ <p>$T_{g,\max}$ = maximum temperature at $t_d^* = t_d$</p> <p>Q_t'' = fire load density (MJ/m^2)</p>

The equations used in the EUROCODE method were derived from the time-temperature curves provided by Magnusson and Thelandersson [29] in Figure 8. The time-temperature curves can be referenced in structural design for fire resistance by knowing the fire load and the ventilation factors.

Figure 8 Time-temperature curves for different ventilation factors and fire loads [29]

2.3 Fire Load and Fire Load Surveys

In performance-based design, one of the important steps is design fires, which needs knowledge of fire loads and their composition in a variety of buildings. In fact, in applying performance-based design in engineering disciplines, there are two important

elements that need to be well understood, developed, and known; one is the underlying science, and another is the design loads [4]. In comparison with structural engineering that is based on the Newtonian equations for balancing forces [4] and has been applied in structural design for about 200 years, the underlying science of fire protection engineering, or fire science, which is a relatively young engineering discipline, has been highly developed since twenty or thirty years ago [5]. It is also in this twenty or thirty year period that most countries around the world have aroused interests to change their codes from prescriptive to performance-based and some countries have already adopted performance-based building codes.

The design loads in structural engineering are mainly differentiated as ‘dead loads’ and ‘live loads’ [30]. Similarly, in fire safety engineering, the fire loads in a compartment are divided into “fixed fire loads” and “moveable fire loads”. All combustible materials in or on the walls, floor and ceiling are considered as fixed fire loads; and all other combustible items that are brought into the compartment are considered as moveable fire loads.

However, fire loads are different from the loads in structural engineering in that fire is not a real load, since the impact of the fire is not only limited to one compartment, as fire can spread to other rooms and areas in the building or adjacent buildings. In addition, the building itself has a large impact on fire development, especially the openings [16].

In fire safety design, it is a challenge to determine realistic fire loads, because of the numerous possible arrangements of fire loads in most buildings. The worse case fire

loads, or bounding loads, are normally used by fire safety engineers. In some cases, most likely fire loads for many different scenarios are also used [4].

Fire load data are historically established by surveys [16]. Fire load surveys in different building categories can be conducted by either physically entering buildings, or using questionnaires through the internet [31]. For the on-site fire load survey, two methods, the weighing technique and the inventory technique, or a combination of the two, can be used. Culver [32] evaluated the inventory technique, and the results obtained from the inventory technique are reasonable.

The first fire load survey was conducted by Ingberg [16] in the late 1920's. He published his first detailed data in 1942, and a second set of data in 1957. Ingberg [16] also established the relationship between fuel load and fire severity in Table 11.

Table 11 Fire severity for Various Fuel Loads (modified from [16])

Fuel Load (lb/ft ²)	Fire Severity (hours)
5	0.5
10	1
15	1.5
20	2
30	3
40	4.5
50	7
60	8
70	9

2.3.1 Fire Load Survey in Office Buildings

Fire load surveys of office buildings have been conducted by Bryson and Gross in the USA in 1967 [33]; Baldwin et al. in the UK in 1970 [34]; Culver in the USA in 1976 [32]; Kumar and Rao in India in 1997 [35], respectively.

In 1967, Bryson and Gross [33] conducted a survey of live floor loads and fire loads at the same time in two office buildings in the United States. The survey of live floor loads was to provide comprehensive data of the actual loads that are applied to structures for structural design. The survey of fire loads was to update and extend the survey of the combustible contents conducted by Ingberg about 30 years before.

The first surveyed office building was an 11-story reinforced concrete building, and was surveyed from February to May 1967 with the surveyed area of 70,820 ft² (6,579 m²) in 335 rooms. The second surveyed building was a 7-story reinforced concrete building, and was surveyed in July 1967 with the total surveyed area of 125,950 ft² (11,701 m²) in 556 rooms, including a sampling of 55,130 ft² (5,122 m²) of space considered to be representative of 573,000 ft² (53,233 m²). The average survey rates in the first and second office building are 590 ft²/hr (54.8 m²/hr), and 430 ft²/hr (39.9 m²/hr), respectively.

Bryson and Gross [33] divided fire loads into two categories---‘moveable contents’ and ‘interior finish’, which corresponds to two categories of ‘moveable fire loads’ and ‘fixed fire loads’ that are normally used in recent years. The major data they recorded in the survey were room use and dimensions, number of assigned personnel and sex, item weight, location, and description. The direct weighting method was mainly used to

determine the weights of items, and where the items could not be weighed, the weights were obtained by estimating the thickness and area.

By converting all weights to equivalent weights of combustibles having a calorific value of 8000 Btu/lb (18608 kJ/kg), Bryson and Gross [33] presented the surveyed fire loads in pounds per square foot (*psf*), with the mean value of the total fire load of 6.0 and 4.8 *psf* in the first and the second surveyed office building, respectively. The corresponding fire loads in mega joule (MJ) per square metre are 545 and 435 MJ/m².

Also at the end of the 1960s, Baldwin and his colleagues [34] conducted a survey of fire loads in two office buildings in the United Kingdom, and published a paper in March 1970. Unlike Bryson et al., they randomly chose two office buildings from a total of about 100. One building was 5 storeys with a plan area of 245 m², and the other building was 6 storeys with a plan area of 490 m².

Baldwin and his colleagues [34] analysed the data of fire loads in terms of fire-load per unit window area (F/A_w) and fire load per unit floor area (F/A_f). The fire-load per unit window area (F/A_w) can be used as a criterion to distinguish the fire by ventilation controlled or fire-load controlled. In a fairly shallow compartment, with a depth to height ratio of 1.22, the fire can be treated as ventilation controlled when the fire-load per unit window area (F/A_w) is greater than 150 kg/m² (30 lb/ft²), and otherwise the fire is fire-load controlled. The fire-load per unit floor area (F/A_f) is widely used as the fire load density.

From the analysis of the 93 surveyed rooms in the two buildings, Baldwin and his colleagues [34] derived the mean values of the fire-load per unit window area and the fire-load per unit floor area, which are 55 kg/m^2 (11.3 lb/ft^2) and 20 kg/m^2 (4.13 lb/ft^2), respectively. The percentage of floor area covered by furnishings, as the distribution of the fuel, is 27 percent on average. They also noticed that there is no correlation between the fire-load density and the size of the room.

In 1973, a comprehensive survey of fire loads and live loads in office buildings was initiated in the United States by the General Services Administration (GSA), the National Academy of Sciences (NAS), and the National Bureau of Standards (NBS). A total of 2433 rooms were surveyed in the twenty-three office buildings from August 1974 to August 1975 [32].

The survey samples of the buildings were randomly selected from the available lists throughout the country by considering three building characteristics: geographic location, height and building age. Only twelve of the twenty originally selected private buildings were given survey permission due to apprehension concerns on the disruption of the normal business activities in the offices and the potential use of the survey results. Also because of the difficulties in obtaining survey permission, only 4 additional private buildings were surveyed by working through city building officials. The total of sixteen private buildings, plus six randomly selected government buildings and one NBS Administration Building composes the survey samples of a total of twenty-three office buildings located in various regions throughout the United States [32].

The inventory method, rather than the direct weighting, which was normally used before, was used in this survey [32]. The measurement error by using the inventory technique is about 10 percent, but it represents only a relatively small fraction of the variability of live loads. The magnitude of the loads in the surveyed rooms was not affected by the three building characteristics: geographic location, height, and building age, but the use of the room had a significant influence on both fire loads and live loads. File rooms, libraries, and storage rooms had larger values.

The mean value of the percentage of the room floor area occupied by the furniture shows a slight decrease with room area. For rooms less than 100 ft² (9.29 m²), the mean value is about 40 percent of the floor area occupied, and for the majority of the surveyed rooms larger than 100 ft² (9.29 m²), the mean percentage of floor area occupied by furniture is between 20 to 30 percent. The interior finish fire load (or fixed fire load) ranges from 1.0 psf (4.88 kg/m²) to 1.9 psf (9.28 kg/m²), and has a contribution to the total fire load in the range from less than five percent to about fifty percent [32].

From July 1992 to July 1993, Kumar and Rao [35] conducted a fire load survey in 388 rooms of eight government office buildings with height up to four stories in India. The total surveyed floor area was about 11,720 m². The fire load was divided into two categories, 'non-moveable contents' and moveable contents'. For all surveyed rooms, the average fire load and the standard deviation were 348 MJ/m² and 262 MJ/m² respectively. The storage and file rooms had the maximum fire load of 1860 MJ/m², and the corridors had the minimum fire load of 153 MJ/m². The percentage of non-moveable fire loads and

moveable fire loads were 11.7% and 88.3%, respectively. The composition of furniture was 68.1% of steel, 31.6% of wood and 0.3% of plastic by their weights. There was no definite relationship between fire load and floor level of buildings.

2.3.2 Fire Load Survey in Residential Buildings

In comparison with the numbers of fire load surveys conducted in office buildings, surveys conducted in residential buildings are fewer, due to the difficulty to obtain permission in private dwellings because of privacy and other considerations [36].

Kumar and Rao [36] conducted a fire load survey in 35 residential buildings in India from September 1991 to May 1992. The 35 residential buildings were randomly selected, and all of them were located in the city area of an Indian city, Kanpur. The total surveyed floor area was 4256.6 m² in a total of 413 rooms, and the mean floor area was 10.3 m². The inventory technique was used in the survey, because of the difficulty to get permission from residents to directly weigh items in their homes. The inventory technique was proven to be a convenient and time-saving method.

For all surveyed rooms, the mean value and standard deviation of fire load was 116.5 Mcal/m² (487.0 MJ/m²) and 61.0 Mcal/m² (255.0 MJ/m²), respectively. The highest mean value of fire load was 203.9 Mcal/m² (852.3 MJ/m²) for the store rooms, and the lowest mean value of fire load was 66.7 Mcal/m² (278.8 MJ/m²) for the verandah. The fixed fire loads and moveable fire loads were 52.66% and 47.34%, respectively [36].

One specific feature of the fire loads in residential buildings, which was observed to be different from that in office buildings, was that the mean value of fire loads decreases as the number of rooms occupied by one family increases. In the survey results of residential buildings [36] and office buildings [32, 35], there was no definite relationship between the load magnitude and building height. The room use has a significant effect on the composition and magnitude of the fire load in residential buildings.

A recent survey of fire loads in Canadian homes was conducted by the National Research Council of Canada (NRCC) [31]. The survey method was done by distributing questionnaires through the internet. A questionnaire consisted of 64 questions. The survey results show that a mean value of fire load density for main floor living rooms is 600 MJ/m^2 , and that for basement living rooms is 500 MJ/m^2 .

2.3.3 Fire Load Survey in Motels and Hotels

Motels and hotels, as a type of residential premises, have the features of regular residential buildings, and also some features of office buildings. The difficulty to obtain permission to conduct fire load surveys in motels and hotels could be similar to or even harder than that for residential buildings. Very few papers on fire load surveys in motels and hotels could be found.

In a 1983 report prepared for the Fire Commission of the Conseil International du Batiment (CIB W14), the 80th percentile of the moveable fire load density for hotel bedrooms was given as 420 MJ/m^2 [37]. In New Zealand, Yii [38] conducted a recent

survey in some offices, residential buildings and motels, and he provided a summary of the mean values of the total fire loads for the three categories shown in Table 12. The mean value of total fire load density for motels is 552 MJ/m^2 , and those for offices and bedrooms are 950 MJ/m^2 and 724 MJ/m^2 , respectively.

Table 12 Summary of the mean value of the total fire load comparisons [39]

Building Occupancy	Surveyed		Robertson & Gross, 1970		Barnett, 1984		Narayanan, 1994	
	(kg/m ²)	(MJ/m ²)	(kg/m ²)	(MJ/m ²)	(kg/m ²)	(MJ/m ²)	(kg/m ²)	(MJ/m ²)
Offices	57	950	35-212	585-3540	22	436	37.8	681
Residence (bedroom)	43	724	40-69	668-1152	/	/	/	/
Motel	33	552	/	/	/	/	/	/

2.4 Fire Tests

In history, the first controlled fire tests, testing of walls, were conducted in 1891 in Germany, and the fire test facility used for the tests was established in 1884. Britain was the second country in the world to conduct fire tests of walls in 1899. In the United States, the earliest fire tests of nonload-bearing walls were conducted in 1901, and the first formal test station was established in 1902 by Columbia University [39], both of which were earlier than the first modern building code in North American that was released in 1905.

2.4.1 Room Fire Tests

Prior to the 1970s, most of the fire tests were conducted on the fire endurance of individual elements of the room, such as walls, doors, floors and columns, and there was little need to perform experimental studies of room fires [40]. This situation changed in

the 1970s with the development of mathematical theories of room fires. The first room calorimeter, the Monsanto Room Calorimeter, for measuring heat release rate in full scale was developed in 1978 by Warren Fitzgerald in the United States. The dimension of the small test room was 2.7 x 2.7 x 2.7 m, and the test samples were relatively small, free standing combustible items. Later, a standard room fire test was developed by ASTM in 1982, with a room size of 2.45 x 3.67 x 2.45 m, and a single doorway opening size of 0.76 x 2.03 m, shown in Figure 9 [41]. In 1986, the Nordic countries in Europe published the NORDTEST method for room fire tests, which was later adopted by ISO (the International Organization for Standardization). The ISO test room has a room dimension of 2.4 x 3.6 x 2.4 m high and an opening size of 0.8 x 2.0 m. The flow rate capacity of the exhaust system is from 0.5 kg/s to 4.0 kg/s [40].

Figure 9 The dimensions of the room and hood for the original (1982) ASTM proposed room fire test (modified from [41])

Except for the standard test rooms discussed above, other dimensions of test rooms were also used to conduct room fire tests. In the United States, a test room with dimensions of 2.26 x 3.94 x 2.31 m was built in the large-scale fire test facility at the National Institute of Standards and Technology (NIST) at Gaithersburg, MD, where four tests with furniture were conducted [41]. The plan view and the elevation view of the test room are presented in Figure 10.

Figure 10 Plan view of experimental room for single room tests with furniture [41]

Figure 11 Elevation view of experimental room for single room tests with furniture [41]

A love seat or armchair was used in each of the four tests. Figure 12 presents the heat release rates in the four tests. Three of them have very close peak values at 2.5 MW, and another one has a slightly lower peak value with a little earlier development. Gas concentrations of O_2 , CO_2 , and CO were also measured and provided in Figure 13.

Figure 12 Heat release rate during single room tests with furniture [41]

Figure 13 Gas concentrations measured during single room tests with furniture [41]

In 1996, two full-scale room fire experiments were conducted at the University of Maryland (UM) [42]. The test room had dimensions of 3.66 x 3.66 x 2.44 m, and was located on the first floor of the burn tower. The two tests used the same size of door, 0.91 x 2.09 m, and the same size of window frame of 1.07 x 0.93 m with 2 panes of glass for each window. The major difference of the two tests was a 90° counter clock wise rotation of the room in Test 2 due to the characteristics of the burn tower enclosure [42]. This change made Test 2 have more fresh air availability at the window, and less air at the door than Test 1. Figure 14 and Figure 15 provides the diagrams of the floor plans, furnishings and instrumentation for Test 1 and Test 2, respectively.

Figure 14 Diagram of furnishings and instrumentation for Test 1 [42]

Figure 15 Diagram of furnishings and instrumentation for Test 2 [42]

For each of the two full-scale room fire experiments, four thermocouple trees, three gas sampling probes and two heat flux meters were used to measure temperature, gas concentration and heat flux, but there was no heat release rate measurement. Figure 16 and Figure 17 provide the temperatures measured in the middle of the room for the two tests. In both tests, the temperatures reached a first peak value of 900°C at about 350 seconds. Figure 18 and Figure 19 present the heat flux measured at the doorway and in the middle of the room. Both measuring locations were placed 0.15 m from the floor. Figure 20 and Figure 21 provide the oxygen concentration measured by two systems, UM and NIST. CO and CO₂ were only measured at the SW corner above the dresser by NIST, but data was not provided in the report.

Figure 16 Temperature in the middle of room vs time for Test 1 [42]

Figure 17 Temperature in the middle of room vs time for Test 2 [42]

Figure 18 Heat flux vs time for Test 1 [42]

Figure 19 Heat flux vs time for Test 2 [42]

Figure 20 Oxygen concentration vs time for Test 1 [42]

Figure 21 Oxygen concentration vs time for Test 2 [42]

2.4.2 Heat Release Rate Measurements

The heat release rate is one of the most important fire parameters, which is widely used to define how fast fires develop and how big they are. However, a direct measurement of the heat release rate of a fire is very difficult because of the dynamic and vigorous characteristic of the fires, and the influence of the compartment and its opening.

In order to measure heat release rate in full scale fire tests, the first room calorimeter, was developed in 1978 by Warren Fitzgerald in the United States [40]. The theory of this application was initially from a discovery by Thornton in 1917, who found that almost the same amount of heat is produced per unit mass of oxygen consumed in fires for a large number of organic materials [43]. Thornton's rule, named as the oxygen consumption principle, was later developed and quantified by many researchers, such as Hinkley et al. in 1968, [44], Parker in 1977 [45], and Huggett in 1980 [46].

In 1991, Janssen [47] proposed a set of equations for calculating heat release rate that were developed especially for full-scale fire test applications. One of the main simplifying assumptions in his analysis is that the amount of energy released by complete combustion per unit mass of oxygen consumed is taken as a constant, and the value is an average of $E = 13.1 \text{ MJ/kg of O}_2$ proposed by Huggett. Figure 22 presents the schematic of a full-scale fire test calorimeter. The minimum requirement for heat release rate calculation is to measure the O_2 concentration and mass flow rate. The accuracy of the calculation can be improved by additional measurements of the concentration of CO_2 , CO , and H_2O . He provided the calculation procedures and equations for four different

cases: only O₂ measured; both O₂ and CO₂ measured; O₂, CO₂, and CO measured; and O₂, CO₂, CO, and H₂O measured.

Figure 22 Schematic of a full-scale fire test combustion system [47]

Janssen's equations were also used in the Large Fire Research Facility at the National Institute of Standards and Technology (NIST) for heat release rate calculations [48]. The equations shown below that are the equations for the third case in Janssen's paper where O₂, CO₂, and CO are measured. The set of equations for heat release rate calculation [48]:

$$\dot{q} = \left(E\phi - (E_{CO} - E) \frac{1-\phi}{2} \frac{X_{CO}}{X_{O_2}} \right) \frac{\dot{m}_e}{1+\phi(\alpha-1)} \frac{M_r(O_2)}{M_r(E)} (1 - X_{H_2O}^0) X_{O_2}^0 \quad (2.10)$$

$$\phi = \frac{X_{O_2}^0 (1 - X_{CO_2} - X_{CO}) - X_{O_2} (1 - X_{CO_2}^0)}{X_{O_2}^0 (1 - X_{O_2} - X_{CO_2} - X_{CO})} \quad (2.11)$$

$$X_{H_2O}^0 = \frac{RH_{amb}}{100} \frac{(0.6107 + 0.06052T_{amb} - 0.0002088T_{amb}^2 + 0.00007376T_{amb}^4)}{P_{amb}} \quad (2.12)$$

where

- $\dot{q}$ = heat release rate of the fire (kW)
- ϕ = oxygen depletion factor
- T_{amb} = temperature of ambient air (293.13 K)
- P_{amb} = pressure of ambient air (101.3 kPa)
- RH_{amb} = relative humidity of ambient air (50 %)
- α = combustion expansion factor (1.105)
- E = heat released per unit mass of oxygen consumed (13.1 MJ/kg of O₂)
- E_{CO} = heat released per unit mass of oxygen consumed for combustion of CO to CO₂ (≈ 17.6 MJ/kg of O₂)
- $M_r(E)$ = relative molecular mass of exhaust gas (≈ 28.97 kg/kmol)
- $M_r(O_2)$ = relative molecular mass of oxygen (≈ 32 kg/kmol)
- $X_{H_2O}^0$ = mole fraction of H₂O in the incoming air
- $X_{O_2}^0$ = measured mole fraction of O₂ in the incoming air*
- $X_{CO_2}^0$ = measured mole fraction of CO₂ in the incoming air*
- X_{CO}^0 = measured mole fraction of CO in the incoming air*
- X_{O_2} = measured mole fraction of O₂ in the exhaust gases*
- X_{CO_2} = measured mole fraction of CO₂ in the exhaust gases*
- X_{CO} = measured mole fraction of CO in the exhaust gases*

* as measured in the gas analyzer located downstream of the cold traps and desiccant

2.5 Fire Modelling

With the emergence of performance-based building codes and the development of computer technologies, computer models for fire simulation have been increasingly used in fire research and fire safety design. Fire models can be divided into two main categories: probabilistic and deterministic models. The probabilistic models can predict

statistical probabilities about the transition from one stage of fire growth to another, but can not directly use the physical and chemical principles involved in fires. However, the pure probabilistic models can be combined with deterministic models to form hybrid models. Deterministic models can predict the movement of smoke and heat in enclosures, and they can be subdivided into two types: zone models, and field models or computational fluid dynamics (CFD) models [49].

2.5.1 Zone Models

In fire protection engineering, zone models were developed to simulate enclosure fires. Some of the zone models can be only used for the fire room, while other models can be used for several rooms [49]. Zone models, also called two-zone models, normally treat the room as two gaseous layers, upper hot layer and lower cold layer. The conservation of mass, species, and energy are applied to the control volumes of the two gaseous layers. Figure 23 shows the two gaseous layers used in two-zone models [50].

Figure 23 Two-zone model [50]

CFAST (Consolidated Model of Fire and Smoke Transport) is a two-zone fire model that can be used to predict the evolving distribution of smoke, fire gases and temperature throughout compartments during a fire [50]. The fire itself needs to be prescribed by the user. In CFAST, each compartment is treated as two gas layers. CFAST can be applied to the compartments with space from 1 m³ to 1000 m³, and the size of the compartment governs the appropriate size of the fire that can be modelled [50]. The computational time of zone models is of the order of seconds for a modern personal computer.

2.5.2 Field Models and FDS

In contrast to zone models, which were developed and applied within the fire community, field models or computational fluid dynamics (CFD) models were developed as a tool for solving general fluid flow problems. The development of CFD technology can be traced back to the early 1920s, when the feasibility of using numerical methods to solve the governing equations of fluid flow was first demonstrated by Lewis Richardson, whose purpose was weather prediction [51].

The Fire Dynamics Simulator (FDS) is a CFD model developed for fire and smoke modelling. FDS solves numerically a form of the Navier-Stokes equations, which is appropriate for low-speed, thermally-driven flow that focuses on smoke and heat transport from fires. The Smagorinsky form of Large Eddy Simulation (LES) is the default mode to treat turbulence, and if the underlying numerical mesh is fine enough, a Direct Numerical Simulation (DNS) can be performed [52 and 53]. In comparison with

other CFD models, FDS has fast computational speed and relatively modest requirements in terms of computational hardware [54].

The first version of FDS was released by the National Institute of Standards and Technology (NIST) in February 2000. Gradual improvements of FDS have been made in version 2 (2001), version 3 (2002), and version 4 (2004) [54]. The latest version 5 was first released in October 2007, and from version 5, a formal revision management system has been implemented [53]. Until now, the newest version number, FDS 5.2.4, indicates the FDS revision management system of the fifth major release, second significant upgrade, and fourth minor upgrade.

One of the important changes in FDS version 5 is that multiple layers of materials can be modelled by specifying them in a new namelist group called *MATL*, while a single homogeneous layer was assumed in the previous versions. This change can provide a better prediction of a room fire with ordinary furniture, but the FDS user's guide also addressed the difficulty of simulating a room fire with ordinary furniture as one of the most challenge applications of FDS, due to the sensitivity of the model to the thermal and material properties of real materials [52].

A fire can be designated in two ways in FDS. The first is to specify a heat release rate per unit area. The second way is to specify a `HEAT_OF_REACTION`, and other thermal parameters, in which case the burning rate of the fuel depends on the net feedback to the surface. The mixture fraction combustion model is automatically invoked and used in both cases. For the solid fuels, the parameter of heat release rate per unit area, ignition

temperature, heat of vaporization, and heat of combustion can be used to control the burning rate by the modeller [52].

The grid size is the most important numerical parameter in CFD models. McGrattan [55] pointed out that using grid cells of the order of 10 cm could be good enough to simulate a house fire, but the resolution of about 1 mm might be required for simulating the details of the flame, such as its temperature. Figure 24 shows a large number of rectilinear volumes, called *meshes*, used in FDS modelling [49].

Figure 24 Field model for enclosure fire [49]

2.5.3 Model Application in Room Fire

An extensive round-robin exercise to model a large scale compartment fire test has been conducted in England, recently. The fire test used for modelling is the Dalmarnock Test One, a post-flashover compartment fire experiment held on July 25th, 2006, in a two-

bedroom single-family flat, which was located on the 4th floor of a 23-storey reinforced concrete building in Dalmarnock, Glasgow [56]. Six international independent teams participated, and all of them worked in fire and used fire modelling as part of their professional practice. A total of ten simulations were submitted, including eight models using FDS, and two models using CFAST. The same information about the test setup, such as the compartment layout shown in Figure 25, was given to all of the teams [57]. Table 13 summarizes the information and some predictions of their modelling.

Figure 25 Layout of the main compartment in Dalmarnock Test One [57]

Table 13 Summary of model information and prediction (modified from 2 tables of [57])

Model Information				Model Prediction	
#	Fire Model	ERT* (h)	Grid (mm)	Time to Flashover (s)	Maximum Smoke Layer Temp.(°C)
A1	CFAST	0.01	--	850	792
A2	FDS4	153	50	780	1026
B	FDS4	23	5-500	841	1070
C	CFAST	0.01	--	no flashover	211
D1	FDS4	19	100	200	720
D2	FDS4	128	50-100	77	1153
E1	FDS4	55	100	180	900
E2	FDS4	33	100	180	1170
F1	FDS4	170	90	720	590
F2	FDS4	170	90	850	650
Ave:				591	828
Exp*:				300	750

* ERT—Estimated Running Time in the computer; Exp—Experimental data

From two simulations using CFAST, one did not predict flashover, and the predicted maximum smoke layer temperature was very low at 211°C; the other had a good prediction of the maximum smoke layer temperature at 792°C, but the predicted time to flashover was quite long at 850 seconds. For the eight simulations using FDS, different grid sizes were used. Three of them used 100 mm, two used 90 mm, one used 50mm, and another used multiple meshes. Simulation number D1 had relatively a good prediction with 200 seconds to flashover and 720°C of the maximum smoke layer temperature. Simulation A2 had the lower mesh size, but did not show good prediction results. The average time to flashover of the ten simulations was about double of the experimental data, and the reason could be the involvement of window breakage, which made the

simulation even harder. The average value of the predicted maximum smoke layer temperature is relatively good with only about 10% higher than the experimental data.

Figure 26 depicts the predicted heat release rate of the ten simulations, and also the experimental data. Both of the two models that use CFAST had lower prediction of the heat release rate. For the eight models using FDS, the simulation number E1 had a good prediction, but others did not have good results. One overpredicted the fire by about 100% and the other six predictions were lower [57].

Figure 26 Predicted heat release rate in the whole compartment [57]

Chapter 3: Fire Load Survey

3.1 Introduction

In prescriptive-based building codes, the goal of a fire safety design is to satisfy code provisions [5]; hence there is no need for designers to consider fire loads in building design. By contrast, in structural engineering, it is impossible and unimaginable to design buildings without considering dead loads and live loads. As countries around the world change their codes from prescriptive to performance-based, fire safety engineers started to apply the engineering approach for fire safety design, rather than merely rely on empirical technology. One of the important steps in performance-based approaches is design fires, which are defined as “an idealization of real fires that may occur in the building”, in ISO/TR 13387-2 [58]. The cornerstone of design fires is the determination of fire loads and their composition in a variety of buildings.

In this research, fire load surveys for motels and hotels have been conducted in Canada’s National Capital Region---Ottawa and Gatineau area, from March 2007 to August 2007. “The National Capital Region has a total population of 1,130,761 (2006), and consists of an area of 5,318.36 square kilometers that straddles the boundary between the provinces of Ontario and Quebec” [59].

The survey was conducted in 10 motels and 12 hotels. The surveyed motels were either one-storey or two-storey buildings, except for one three-storey building. Most of the surveyed hotels were high-rise buildings, covering hotel ratings from 2-star to 5-star, building age from 6 years to over 100 years, and storeys from 3 to 24.

Data related to fire load were collected in the field survey. The dimensions of the surveyed guest rooms were measured and recorded for calculating fire load densities and determining fuel arrangements. The dimensions of openings were also measured due to their important role in enclosure fire development.

3.2 Survey Methodology

As loads in structural engineering are usually differentiated as ‘dead loads’ and ‘live loads’[30], the fire load in a compartment can be divided into a fixed fire load and a moveable fire load. The fixed fire load consists of all combustible materials in or on the walls, floor and ceiling; and the moveable fire load consists of all other combustible items that are brought into the compartment.

The total fire load in a compartment can be calculated by using the following equation [35, 60]:

$$Q = \sum k_i m_i h_{c_i} \quad (3.1)$$

Where, Q = total fire load in a compartment (MJ),

k_i = proportion of content or building component i that can burn,

m_i = mass of item i (kg), and

h_{c_i} = calorific value of item i (MJ/kg).

The goal of a fire load survey is to determine the mass of each item m_i , and their calorific values h_{c_i} . For determining the mass of each item, either the weighing technique or inventory technique, or a combination of the two can be used during the survey. As the types of combustibles are identified through the survey, their calorific values can be derived from the literature [35, 60].

To facilitate the survey process, a specific survey form for motels and hotels was developed, and provided in Appendix B. The survey form was divided into the following 6 sections: (1) brief information of surveyed motels and hotels that includes hotel name, address, building age, number of rooms and stories, and survey date; (2) draft floor plan; (3) room dimensions; (4) opening dimensions; (5) fixed fire loads; (6) moveable fire loads: this section was further divided into 4 categories: furniture, bedding, electronics, and others including paper, curtain, rubbish bins and Christmas trees.

A similar survey procedure was applied to all of the surveyed motels and hotels. Building information was collected, and data related to fire load in the surveyed room were measured and/or recorded following the sequence of the specific hotel survey form. Digital photos were taken in the surveyed rooms for assisting data analysis and reproducing furniture arrangements for the tests.

In the survey process, the inventory technique was the main method used, and weighing items in the surveyed guest rooms was seldom used because of the fact that most of the surveyed rooms were already cleaned and ready for renting. Some common items, such as telephone books and rubbish bins, were pre-weighed. In some hotels, the bedding items were weighed in their storage rooms or in other guest rooms while housekeepers were doing the cleaning. The inventory technique was applied to most of the furniture by measuring their dimensions and taking pictures. For some standard common furniture, their masses were determined by matching target furniture to the data sheets obtained from manufacturers or from information found on the internet. The mass of other furniture was derived by calculating the volume of wood, and multiplying it by the corresponding densities. When the wood species was unknown, a density of 550 kg/m^3 was assumed. Assumptions have been made on the mass of some items, such as plastics contained in TVs, microwaves, coffee makers, and fridges, shown in Appendix C. The calorific values of different combustible materials or assumptions used in calculating the fire loads are also provided in Appendix C.

3.3 Surveyed Motels and Hotels

The fire load survey was conducted in 10 motels and 12 hotels in Canada's National Capital Region---Ottawa and Gatineau area, from March 2007 to August 2007. Two of the ten surveyed motels were located in Gatineau, which is situated on the northern bank of the Ottawa River. The other eight motels were located in Ottawa----6 motels were located at the east, west, south and downtown of Ottawa city area, separately; 2 motels

located at a rural area, 60 kilometres west from downtown Ottawa. Except for one three-storey building, the surveyed motels were either one-storey or two-storey buildings.

Most hotels in the city are high-rise buildings, and they are either located in the downtown area for convenience or close to tourist sites. The surveyed hotels were selected from different hotel rating groups. They included three 2-star, five 3-star (including two “pure” suite hotels), two 4-star, and two 5-star hotels. Two surveyed hotels were located in Gatineau, and the other ten hotels are located in downtown Ottawa. The surveyed hotel buildings cover ages from 6 years to 100+ years, and storeys from 3 to 24. The geographic locations of the surveyed motels and hotels are shown in Figure 27. Typical pictures of the surveyed motels and hotels are presented in Figures 28 to 31.

Figure 27 Map of surveyed motels and hotels

[▲ Motel, ☆ Hotel, ○ Downtown area]

[*2 motels, about 60km west of downtown Ottawa are not shown on this map]

Figure 28 A surveyed 1-storey motel

Figure 29 A surveyed 2-storey motel

Figure 30 A surveyed hotel having building age of 100+ years

Figure 31 A surveyed hotel having building age of 6 years

One specific feature of motel and hotel buildings is that one type of guest room in a building represents many rooms with the same layout, interior finish and inside items, which are named “representing rooms” and recorded in this research. This feature of motel and hotel buildings makes them different than any other building, like offices, dwellings, schools and hospitals. The hotel rating, building age, storeys, number of surveyed rooms, and representing rooms are given in Table 14.

Table 14 Features of surveyed motels and hotels

	No.	Rating (Star)	Building Age (yr)	Building Stories	Surveyed Rooms	Representing Rooms
Motel	1		~50	2	3	20
	2		unknown	2	2	38
	3		~32	2	1	19
	4		~43	2	3	26
	5		~40	1; 2	4	45
	6		~45	1	2	19
	7		~40	2	3	27
	8		~28	2; 3	3	78
	9		~50	1	2	25
	10		~42	2	2	18
Sum					25	315
Hotel	1	2	100+	6	4	20
	2	2	44	3	1	3
	3	2	18	19	2	212
	4	3	~15	22	6	120
	5	3	20~30	12	1	98
	6	3	34; 15	8; 12	4	131
	7	3	29	13	4	241
	8	3	20	21	2	281
	9	4	30	10; 18	4	280
	10	4	35	18	3	236
	11	5	22	24	2	176
	12	5	6	20	3	243
Sum					36	2041

In the 10 surveyed motels, 25 guest rooms with a total floor area of 567 m² were surveyed, which may represent 315 motel guest rooms with a total representing floor area of 7,108 m². In the 12 surveyed hotels, a total of 36 hotel guest rooms, including 10 suites were surveyed, which may represent 2,041 hotel guest rooms with a total surveyed floor area of 1,094 m² and a total representing floor area of 58,395 m².

3.4 Data Analysis

The fire load survey was conducted only in the guest rooms or suites of motels and hotels. Other areas such as atria, corridors, stairwells, storage rooms, offices, and banquet and/or meeting rooms were not included in the survey.

In the field survey, some doors of bathrooms, kitchens, and bedrooms in suites were noticed to be closed, and some were open, which could be the same in the real scenario that some guests may likely keep the inside doors closed, and some guests may likely leave the doors open. In the following data analysis of this research, the assumption was made that all the doors inside the guest rooms are closed, including the doors of bedrooms, living rooms, bathrooms, and kitchens. A suite room was divided into 2 rooms, bedroom and living room, if there was a door in between. Therefore, the bathrooms, and kitchens with doors, were excluded from the following calculations and analysis. Typical floor plans for a regular hotel guest room with one bed and a hotel suit room with one bed are given in Figure 32 and Figure 33.

Figure 32 Floor plan of a typical hotel guest room with one bed

Figure 33 Floor plan of a hotel suite room with one bed [61]

The surveyed hotels were selected by hotel ratings. From observation in the field survey and description of hotel ratings, the hotels with rating of 2-star and 3-star have a slight difference, and the hotels with rating over 3-star are relatively luxurious. In this research, surveyed hotels were categorized into 3 groups---two in terms of hotel ratings: “standard hotels” with hotel rating below 3-star and “luxury hotels” with rating over 3.5-star; and another one group is “hotel suites” for those suites that consist of one or two

bedrooms and one living room. A bedroom in a hotel guest room has either one bed or two beds. A hotel suite has one bedroom (or two bedrooms) and a living room with or without a door in between, and may or may not have a kitchen.

Recorded survey data and the number of surveyed rooms were used to calculate fire load density in each bedroom and living room, and to determine the contribution of different combustible materials to the fire load. In addition, data was collected to calculate typical floor area, area of openings and percentage of floor area covered by furnishings for bedrooms with one bed and two beds, and living rooms of suites in different hotel categories.

3.4.1 Calibration of Measuring Tools

For length measurements, two measuring tools were used in the survey. One is a regular tape rule, and another is an ultrasonic measuring device. The tape rule is convenient and accurate to measure the dimensions of openings, furniture, and other items; and the ultrasonic measuring device is ideal and fast for measuring interior room dimensions. The specifications of the ultrasonic measuring device are provided in Table 15.

In the field survey, the ultrasonic measuring device was only used for measuring room dimensions, and the tape rule was used for all of other dimension measurements. The accuracy of the ultrasonic measuring device was tested by measuring the distance to three walls with the ultrasonic measuring device and the tape rule. Test data are given in Appendix D. Calibration of the ultrasonic measuring device was made according to the

measuring difference of the ultrasonic measuring tool, which is given in Table 16. Figure 34 shows the calibration results of the two measuring tools.

Table 15 Specifications of the ultrasonic measuring device (modified from [62])

Dimensions:	1.2 in. H x 2.8 in. W x 4.4 in. L (3.1 cm x 7.2 cm x 11 cm)
Weight:	3.5 oz. (100 g) without battery
Battery Type:	9-Volt alkaline
Battery Life:	Up to 100,000 continuous accurate readings
Accuracy:	Within $\pm 0.5\% \pm 1$ digit (in still air)
Measurement Range:	1 ft. 10 in. to 41 ft. (55 cm to 12.5 m)
Aperture Angle:	Approximately ± 5 degrees
Display:	5 digit liquid crystal display

Figure 34 Difference of the two measuring tools before and after calibration

Table 16 Calibration of the ultrasonic measuring tool

Measurement (m)	Calibration (m)
1.0-2.0	-0.010
2.0-4.0	-0.020
4.0-8.0	-0.030
8.0-9.0	-0.035

3.4.2 Floor Area

In the 10 selected motels, the survey was conducted in 25 typical guest rooms, including 13 bedrooms with one bed; 10 bedrooms with two beds; 1 bedroom with two double beds and one single bed; and 1 suite room having a bedroom with two beds and a kitchen within the living room. The 25 surveyed guest rooms had a total floor area of 567 m² and may represent 315 guest rooms with a total represented floor area of 7,108 m².

Figure 35 shows the floor area of the surveyed motel rooms. The floor area of bedrooms with one bed has a minimum, maximum, mean, and 95th percentile values of 15.5; 33.2; 20.4; and 29.4 m² respectively, and a standard deviation of 5.67 m². The floor area of motel bedrooms with two beds has a minimum, maximum, mean and 95th percentile values of 15.7; 33.2.0; 22.9; and 29.8 m² respectively, and a standard deviation of 4.75. The mean and 95th percentile floor areas of the surveyed motel rooms with two beds are slightly higher than that of the guest rooms with one bed. The maximum floor areas of rooms with one bed and two beds are the same because the rooms had the same floor plan regardless of bed types. In a suite having a living room with a kitchen inside,

the floor area of the bedroom with two beds is 17.8 m² which is 5.1 m² lower than the mean value of the regular guest bedrooms with two beds.

Figure 35 Floor area of surveyed motel rooms

[*2 beds (suite): a motel bedroom with 2 beds in a suite; 2+1 beds: a motel bedroom with 2 double beds and 1 single bed; Kitchen+LR: a motel living room with kitchen inside]

The 12 surveyed hotels consist of three 2-star, five 3-star (including two suite hotels), two 4-star, and two 5-star hotels. The survey was conducted in 36 hotel guest rooms including 10 suites, with a total floor area of 1,094 m², which may represent about 2,041 hotel guest rooms with a total represented floor area of 58,395 m².

Figure 36 shows the floor areas of the surveyed hotel rooms. The floor areas of bedrooms with one bed for standard hotels, luxury hotels, and hotel suites have a minimum value of 17.0, 20.1, and 11.2 m²; a maximum value of 29.4, 32.8, and 15.0 m²; a mean value of 22.8, 26.2, and 13.2 m²; a 95th percentile of 28.3, 32.1, and 15.0 m²; and

a standard deviation of 4.41, 4.83, and 1.96, respectively. The floor areas of bedrooms with two beds for standard hotels, luxury hotels, and hotel suites have a minimum value of 20.3, 26.0, and 11.2 m²; a maximum value of 32.9, 32.8, and 17.2 m²; a mean value of 26.0, 28.4, and 14.6 m²; a 95th percentile value of 31.9, 32.2, and 17.0 m², and a standard deviation of 5.32, 2.92, and 3.07, respectively.

Figure 36 Floor area of surveyed hotel rooms

[*(SH): standard hotels including 2, 3 star; (LH): luxury hotels above 3 star; (suite): hotel suite bedrooms having doors to living rooms; Bedroom+LR: suite bedrooms plus living rooms without doors in between]

The floor areas of luxury hotel bedrooms with one bed have minimum, maximum, mean and 95th percentile values higher than those of standard hotel rooms. The floor area of luxury hotel bedrooms with two beds also have minimum and mean values higher than those of standard hotel rooms, but have similar maximum and 95th percentile values as

those of standard hotel rooms. All the values of the floor areas of hotel suites are significantly lower than those of standard hotels and luxury hotels, because of the extra area of the living room beside the bedroom in a suite.

The floor areas of living rooms with doors to the bedrooms have a minimum, maximum, mean and 95th percentile values of 22.6; 40.5; 29.9; and 39.2 m² respectively, and a standard deviation of 6.69. The floor areas of bedrooms plus living rooms without doors in between have a minimum, maximum, mean and 95th percentile values of 28.9; 54.6; 38.7; and 51.8 m² respectively, and a standard deviation of 11.07.

3.4.3 Area of Openings

As the assumption was made before that all the doors in the guest rooms are closed, the areas of doors were not considered as openings in this research, except some doors to balconies having small windows, which were counted to the areas of windows in the guest rooms. The window area of the surveyed motel and hotel rooms are discussed below.

Figure 37 shows the window area of the surveyed motel rooms. The window area of motel bedrooms with one bed has a minimum, maximum, mean and 95th percentile values of 1.65; 3.79; 2.54; and 3.34 m² respectively, and a standard deviation of 0.60. The window area of bedrooms with two beds has a minimum, maximum, mean and 95th percentile values of 1.62; 3.79; 2.51; and 3.41 m² respectively, and a standard deviation of 0.60. The window area of motel bedrooms with one bed and two beds did not show

much difference. The maximum window area is significantly higher than all of other windows because of the large window and glass door to the back balcony.

Figure 37 Window area of surveyed motel rooms

[*2 beds (suite): a motel bedroom with 2 beds in a suite; 2+1 beds: a motel bedroom with 2 double beds and 1 single bed; Kitchen+LR: a motel living room with kitchen inside]

The window area of the surveyed hotel rooms is shown in Figure 38. The window areas of bedrooms with one bed for standard hotels, luxury hotels, and suite hotels have a minimum value of 2.03, 3.13, and 1.32 m²; a maximum value of 6.60, 10.00, and 3.00 m²; a mean value of 3.98, 5.92, and 1.87 m²; a 95th percentile value of 6.39, 9.18, and 2.80 m²; and a standard deviation of 1.56, 2.55, and 0.76 respectively. The window areas of bedrooms with two beds for standard hotels, luxury hotels, and suite hotels have a minimum value of 2.03, 3.13, and 1.59 m²; a maximum value of 6.00, 10.00, and 2.67 m²; a mean value of 2.95, 5.26, and 1.98 m²; a 95th percentile value of 5.20, 9.34, and 2.57 m²; and a standard deviation of 1.42, 3.06, and 0.60 respectively. The window

areas of bedrooms with one bed and with two beds in luxury hotels have minimum, maximum, mean and 95th percentile values higher than those of two type bedrooms at standard hotel rooms.

Figure 38 Window area of surveyed hotel rooms

[*(SH): standard hotels including 2, 3 star; (LH): luxury hotels above 3 star; (suite): hotel suite bedrooms having doors to living rooms; Bedroom+LR: suite bedrooms plus living rooms without doors in between]

The window areas of living rooms with doors to bedrooms have minimum, maximum, mean and 95th percentile values of 2.30; 5.22; 3.76; and 4.92 m² respectively, and a standard deviation of 1.00. The window areas of bedrooms plus living rooms without doors in between have minimum, maximum, mean and 95th percentile values of 5.50; 23.84; 13.22; and 22.16 m², respectively, and a standard deviation of 7.70. All the values of window areas in bedrooms plus living rooms without doors in between are much higher than those of other hotel room categories.

3.4.4 Percentage of Floor Area Covered by Furnishings

For both motels and hotels, the percentage of floor area covered by furniture, electronics, and other movable objects, was calculated and given in Figure 39 and Figure 40. In the surveyed motels, the amount of floor space occupied by furniture and equipment in bedrooms with one bed has a mean value of 33.0% and a 95th percentile value of 40.2%; and in bedrooms with two beds, a mean value of 40.3% and a 95th percentile value of 48.2%. The standard deviations are 5.12 and 5.69 respectively. This shows that the percentage of floor coverage for motel bedrooms with two beds is higher than that for motel bedrooms with one bed. The percentage of floor coverage in a living room with kitchen inside is 36%, which is higher than the mean value for the motel bedrooms with one bed, and lower than the mean value for the motel bedrooms with two beds.

Figure 39 Percentage of floor coverage in surveyed motel rooms

[*2 beds (suite): a motel bedroom with 2 beds in a suite; 2+1 beds: a motel bedroom with 2 double beds and 1 single bed; Kitchen+LR: a motel living room with kitchen inside]

Figure 40 Percentage of floor coverage in surveyed hotel rooms

[*(SH): standard hotels including 2, 3 star; (LH): luxury hotels above 3 star; (suite): hotel suite bedrooms having doors to living rooms; Bedroom+LR: suite bedrooms plus living rooms without doors in between]

In the surveyed hotels, the mean value of the percentage of floor area covered by furniture and other contents in bedrooms with one bed in standard hotels, luxury hotels, hotel suites is 34.5%, 35.3%, and 37.5% respectively, and in bedrooms with two beds is 38.1%, 34.5%, and 47.1% respectively. The mean value of the percentage of floor area covered by furniture and contents in living rooms is 28.4%; and the mean value in bedrooms plus living rooms without doors in between is 34.8%. The percentage of floor coverage in the living rooms is lower than the values in the bedrooms and bedrooms plus living rooms.

The percentage of floor coverage in bedrooms of motels and hotels is higher than that in office buildings, where the amount of floor space occupied by furniture and equipment is 25-30% [34].

3.4.5 Bed Size

Table 17 shows the regular bed or mattress size on the market. In the whole surveyed motels and hotels, no California king bed was found in any of the bedrooms of motels and hotels; only one twin bed was found with 2 double beds in a motel bedroom; and only two twin x-long beds were found in a bedroom of a suite, which had a second bedroom with one queen bed. The number of surveyed rooms and the representing rooms having the same bed size in different categories of motels and hotels is given in Table 18.

Table 17 Bed or mattress size on the market

Bed Size	Also Known as:	Bed or Mattress Dimension		Area (m ²)
		(in)	(m)	
Twin	Single	39" x 75"	0.99 x 1.91	1.89
Twin X-Long	Extra Long Single	39" x 80"	0.99 x 2.03	2.01
Double	Full	54" x 75"	1.37 x 1.91	2.61
Queen	Queen	60" x 80"	1.52 x 2.03	3.10
King	Eastern or Standard King	78" x 80"	1.98 x 2.06	4.03
California King	Western King	72" x 84"	1.83 x 2.13	3.90

Table 18 Distribution of bed size in the surveyed motels and hotels

Categories		Total Rooms	Number of Rooms with following Bed Size				
			Twin	Twin X-Long	Double	Queen	King
Bedrooms With 1 bed	Motels	12 (125) ^a	-	-	6 (75)	5 (49)	1 (1)
	Standard hotels	9 (433)	-	-	-	4 (140)	5 (293)
	Luxury hotels	6 (505)	-	-	-	2 (140)	4 (365)
	Hotel Suites	7 (225)		-	1 (9)	4 (208)	2 (8)
Bedrooms With 2 beds	Motels	13 (190)	1 (1) ^b	-	9 (141)	4 (49)	-
	Standard hotels	7 (416)	-	-	2 (256)	5 (160)	-
	Luxury hotels	5 (410)	-	-	5 (410)	-	-
	Hotel Suites	2 (52)	-	1 (29) ^c	1 (32)	1 (20)	-

^a The number in parentheses is the amount of representing rooms.

^b 1(1) not counted in the total number of rooms, because the twin bed was in a motel bedroom with another 2 double beds, and the number of room was counted in the motel bedrooms with 2 double beds.

^c 1(29) not counted in the total number of rooms, because the suite had 2 bedrooms--one having 2 twin x-long beds and one having one queen bed, and was counted in the hotel suite with one queen bed.

3.4.6 Fire Load Density

Moveable fire load density and total fire load density for motels, hotels and all surveyed guest rooms are summarized in Table 19. The three mean values of moveable fire load density are close to 387 MJ/m². The 80th percentile of moveable fire load density for motels and hotels, range from 436 to 453 MJ/m², which is close to the reported value of 420 MJ/m² [37]. The mean value of the total fire load density is 535 MJ/m² for motels, which is also close to the data provided by Yii [38]. The mean value of the total fire load density for hotels is 560 MJ/m², and that for all of the surveyed guest rooms is 550 MJ/m². Figure 41 provides 95th percentile and mean values of the total fire load density in different motel and hotel categories.

Table 19 Fire load density for guest rooms in motels and hotels

	Moveable Fire Load Density			Total Fire Load Density		
	Motels (MJ/m ²)	Hotels (MJ/m ²)	All Rooms (MJ/m ²)	Motels (MJ/m ²)	Hotels (MJ/m ²)	All Rooms (MJ/m ²)
Minimum	202	145	145	371	279	279
Maximum	569	571	571	736	848	848
Mean	383	391	388	535	560	550
80%	436	453	453	605	638	632
95%	501	544	539	712	776	753
Standard deviation	89	105	98	100	123	115

Figure 41 Total fire load density in different motel and hotel categories

[ML: motels; SH: standard hotels; LH: luxury hotels; Suite: hotel suites; LR: living rooms; BR & LR: hotel bedrooms plus living rooms without doors in between]

Figure 41 shows that the two types of bedrooms in standard hotels and hotel suites have the highest 95th percentile values of fire load density ranging from 757 to 795 MJ/m². The mean values of two types of bedrooms in hotel suites ranging from 664 to 691 MJ/m² are higher than all other mean values which range from 401 to 601 MJ/m². In motels, standard hotels and luxury hotels, the 95th percentile value and mean value for bedrooms with two beds are higher than the values for bedrooms with one bed. In hotel suites, the 95th percentile value for bedrooms with two beds is slightly lower than the value for bedrooms with one bed, but the mean value for bedrooms with two beds is also higher than the mean value for bedrooms with one bed. The mean values of fire load density in all the bedrooms of standard hotels and luxury hotels are close and range from 543 to 601 MJ/m². The living rooms have the lowest mean and 95th percentile fire load density values, and also the lowest values of the percentage of floor area covered by furnishings.

Table 20 and Table 21 provide the total fire load density and moveable fire load density of different combustible materials in different room types and hotel categories. Figure 42 to Figure 51 present the distribution of the total fire load density for different combustible materials in different room types and hotel categories.

Table 20 Total fire load density in different motel and hotel categories

Categories		Wood (MJ/m ²)	Plastic (MJ/m ²)	Textile (MJ/m ²)	Paper (MJ/m ²)	Mattress (MJ/m ²)	Sofa (MJ/m ²)	Total (MJ/m ²)
ML-1 bed	Mean	306.7	23.4	26.5	6.8	127.6	15.1	506.0
	95%	444.9	33.4	52.9	21.5	163.0	60.6	636.8
	% Contri. ^a	60.6	4.6	5.2	1.3	25.2	3.0	100.0
ML-2 beds	Mean	274.9	20.4	27.8	7.5	220.0	14.8	565.5
	95%	377.9	29.8	39.2	18.6	274.7	48.2	714.9
	% Contri.	48.6	3.6	4.9	1.3	38.9	2.6	100.0
SH-1 bed	Mean	341.5	17.3	39.2	15.7	137.2	39.5	590.3
	95%	538.1	25.6	53.3	22.4	161.1	66.0	758.2
	% Contri.	57.8	2.9	6.6	2.7	23.2	6.7	100.0
SH-2 beds	Mean	300.1	16.0	45.2	16.7	199.7	23.0	600.5
	95%	476.0	24.9	54.6	21.1	246.8	38.8	795.4
	% Contri.	50.0	2.7	7.5	2.8	33.2	3.8	100.0
LH-1 bed	Mean	315.1	13.0	43.5	17.4	120.1	33.5	542.6
	95%	347.8	16.2	56.1	19.4	130.0	41.9	593.8
	% Contri.	58.1	2.4	8.0	3.2	22.1	6.2	100.0
LH-2 beds	Mean	296.4	13.1	46.5	17.2	159.0	34.7	567.0
	95%	319.1	16.1	61.6	19.1	171.4	44.1	604.1
	% Contri.	52.3	2.3	8.2	3.0	28.0	6.1	100.0
Suite-1 bed	Mean	383.6	11.3	33.3	20.5	214.8	0.0	663.6
	95%	516.9	18.6	37.7	28.4	233.5	0.0	786.1
	% Contri.	57.8	1.7	5.0	3.1	32.4	0.0	100.0
Suite-2 beds	Mean	308.8	19.8	44.0	23.2	295.1	0.0	690.9
	95%	372.2	24.9	47.0	25.5	304.6	0.0	756.8
	% Contri.	44.7	2.9	6.4	3.4	42.7	0.0	100.0
LR	Mean	296.0	24.1	26.0	14.3	0.0	40.6	401.0
	95%	431.4	29.9	58.2	18.8	0.0	69.4	541.5
	% Contri.	73.8	6.0	6.5	3.6	0.0	10.1	100.0
BR & LR	Mean	316.4	14.0	31.6	12.6	71.6	35.5	481.7
	95%	419.2	21.9	41.8	16.1	77.0	39.8	596.0
	% Contri.	65.7	2.9	6.6	2.6	14.9	7.4	100.0

^a % contribution in the table: percentage of contribution to mean value of each category.

Table 21 Moveable fire load density in different motel and hotel categories

Categories		Wood (MJ/m ²)	Plastic (MJ/m ²)	Textile (MJ/m ²)	Paper (MJ/m ²)	Mattress (MJ/m ²)	Sofa (MJ/m ²)	Total (MJ/m ²)
ML-1 bed	Mean	81.1	11.5	7.4	1.0	63.8	7.5	172.3
	95%	224.2	31.7	29.5	3.3	156.6	51.1	427.1
	% Contri. ^a	47.1	6.7	4.3	0.6	37.0	4.4	100.0
ML-2 beds	Mean	79.4	10.0	8.2	0.9	110.0	7.4	215.8
	95%	189.2	26.9	20.9	2.9	266.9	47.1	501.3
	% Contri.	36.8	4.6	3.8	0.4	51.0	3.4	100.0
SH-1 bed	Mean	47.6	4.4	6.7	0.6	36.6	10.5	106.5
	95%	198.6	20.8	29.5	2.7	150.9	45.9	436.8
	% Contri.	44.7	4.2	6.3	0.6	34.4	9.9	100.0
SH-2 beds	Mean	43.9	3.9	7.3	0.5	49.9	5.7	111.2
	95%	191.0	16.8	32.0	2.7	219.0	35.4	475.9
	% Contri.	39.5	3.5	6.6	0.4	44.9	5.2	100.0
LH-1 bed	Mean	101.9	6.2	12.3	0.9	60.1	16.7	198.2
	95%	230.5	15.1	35.7	2.7	128.5	39.4	443.0
	% Contri.	51.4	3.1	6.2	0.5	30.3	8.4	100.0
LH-2 beds	Mean	104.8	7.0	15.4	1.0	88.3	19.3	235.8
	95%	195.9	15.0	40.7	2.1	170.7	44.0	458.6
	% Contri.	44.4	3.0	6.5	0.4	37.5	8.2	100.0
Suite-1 bed	Mean	23.2	1.2	2.1	0.2	23.9	0.0	50.6
	95%	207.1	7.1	18.5	1.2	223.4	0.0	440.0
	% Contri.	45.8	2.3	4.2	0.5	47.1	0.0	100.0
Suite-2 beds	Mean	16.7	1.5	2.0	0.3	23.3	0.0	43.8
	95%	199.8	15.5	20.7	3.1	288.3	0.0	545.9
	% Contri.	38.2	3.4	4.5	0.7	53.1	0.0	100.0
LR	Mean	18.5	3.8	1.9	0.1	0.0	6.6	31.0
	95%	115.2	27.1	4.4	0.6	0.0	34.9	188.3
	% Contri.	59.7	12.4	6.3	0.4	0.0	21.2	100.0
BR & LR	Mean	17.9	1.2	1.2	0.2	6.2	3.1	29.7
	95%	137.6	9.1	8.7	1.7	70.6	32.0	274.3
	% Contri.	60.2	4.0	3.9	0.5	21.0	10.4	100.0

^a % contribution in the table: percentage of contribution to mean value of each category.

Figure 42 Fire load density of different combustibles in motel bedrooms with one bed

[* Textile includes leather]

Figure 43 Fire load density of different combustibles in motel bedrooms with two beds

[* Textile includes leather]

Figure 44 Fire load density of different combustibles in standard hotel bedrooms with one bed [* Textile includes leather]

Figure 45 Fire load density of different combustibles in standard hotel bedrooms with two beds [* Textile includes leather]

Figure 46 Fire load density of different combustibles in luxury hotel bedrooms with one bed
 [* Textile includes leather]

Figure 47 Fire load density of different combustibles in luxury hotel bedrooms with two beds
 [* Textile includes leather]

Figure 48 Fire load density of different combustibles in hotel suite bedrooms with one bed
 [* Textile includes leather]

Figure 49 Fire load density of different combustibles in hotel suite bedrooms with two beds
 [* Textile includes leather]

Figure 50 Fire load density of different combustibles in hotel living rooms
 [* Textile includes leather]

Figure 51 Fire load density of different combustibles in hotel bedrooms plus living rooms without doors in between [* Textile includes leather]

From Figure 42 to Figure 51, and Table 20, wood has the highest contribution to the total fire load density in all types of motel and hotel guest rooms. Mattresses also provide a high contribution to total fire load density in all of the bedrooms. Textiles (including leather) and sofas each contribute less than 100 MJ/m^2 to the total fire load density. Plastic and paper provide less than 50 MJ/m^2 each to the total fire load density.

3.5 Summary and Recommendations

This chapter presented a description, methodology, and data analysis of a fire load survey, conducted in 10 motels and 12 hotels in Canada's National Capital Region (Ottawa and Gatineau area), from March 2007 to August 2007. The fire load density of different types of motel and hotel guest rooms in different hotel categories was computed. Typical values for floor area, area of openings and percentage of floor area covered by furnishings were reported for different types of guest rooms and hotel categories. The summary of fire load survey data for motels and hotels is given in Table 22. The results and analysis can be used to develop fuel packages and design fires representing hotels and motels.

The average total fire load density for all the surveyed motels and hotels is 550 MJ/m^2 , and the standard deviation is 115 MJ/m^2 . Both types of bedrooms in hotel suites have the highest average total fire load density ranging from 664 to 691 MJ/m^2 , and the living rooms have the lowest mean value of 401 MJ/m^2 . Wood provides the highest contribution to the fire load density in all the surveyed guest rooms.

Table 22 Summaries of Fire load survey data for motels and hotels

Categories		Floor Area (m ²)	Window Area (m ²)	Floor Coverage (%)	Total Fire Load Density (MJ/m ²)
ML-1 bed	Mean	20.4	2.5	33.1	506.0
	95%	29.4	3.3	40.2	636.8
ML-2 beds	Mean	22.9	2.5	40.3	565.5
	95%	29.8	3.4	48.2	714.9
SH-1 bed	Mean	22.8	4.0	34.5	590.3
	95%	28.3	6.4	40.0	758.2
SH-2 beds	Mean	26.0	2.9	38.1	600.5
	95%	31.9	5.2	43.3	795.4
LH-1 bed	Mean	26.2	5.9	35.3	542.6
	95%	32.1	9.2	40.8	593.8
LH-2 beds	Mean	28.4	5.3	34.5	567.0
	95%	32.2	9.3	36.0	604.1
Suites-1 bed	Mean	13.2	1.9	37.5	663.6
	95%	15.0	2.8	39.8	786.1
Suite-2 beds	Mean	14.6	2.0	47.1	690.9
	95%	17.0	2.6	49.7	756.8
Living Room	Mean	29.9	3.8	28.4	401.0
	95%	39.2	4.9	32.6	541.5
BR & LR	Mean	38.7	13.2	34.8	481.7
	95%	51.8	22.2	41.3	596.0

The surveyed bedrooms in motels, standard hotels, and luxury hotels have the 95th percentile of the floor areas ranging from 28 to 32 m² (excluding bathrooms), and the floor area covered by furnishings ranges from 35.9% to 48.2%. The bedrooms in hotel

suites have the lowest 95th percentile of floor areas ranging from 15 to 17 m² (excluding bathrooms). The 95 percent of hotel living rooms is less than the floor area of 39 m² (excluding bathrooms, and kitchens with doors), and less than 32% floor area covered by furnishings.

Most of the surveyed rooms were already cleaned and ready for rent. Guest luggage was not considered in this research. Guest clothes and belongings need to be added to the fuel package to get the total fire load density.

Chapter 4: Full-Scale Fire Tests

4.1 Introduction

Fire load surveys for motels and hotels have been conducted in Canada's National Capital Region---Ottawa and Gatineau, from March 2007 to August 2007. The surveyed motels included one-storey, two-storey, and three-storey buildings. The surveyed hotels covered hotel ratings from 2-star to 5-star, building ages from 6 years to over 100 years, and storeys from 3 to 24. All of the surveyed motels and hotels have two main types of bedrooms: bedrooms with one bed and bedrooms with two beds.

Two full-scale fire tests, one representing a bedroom with one bed and the other representing a bedroom with two beds, were conducted at the NRCC/Carleton (National Research Council of Canada/Carleton University) Fire Research Lab. The date of the first test was October 10th of 2008, and the second test was conducted on November 12th of 2008. The design of the tests was based on the survey of fire loads and their distribution. The dimensions of the test room for both tests were 3.77 m x 4.17 m x 2.37 m. The room had a smaller floor area than most of the mean values of those in the surveyed bedrooms. For both tests, the room had a window opening with dimensions of 1.5 m x 1.5 m.

A large hood with dimensions 6.0 m x 6.0 m was placed above the window soffit to collect the exhaust gases. The mass flow rate, gas temperature, and concentrations of oxygen, carbon dioxide, and carbon monoxide were measured in the exhaust duct for heat release rate calculation, based on the oxygen consumption method. In the test room, thermocouple trees, heat flux gauges, bidirectional probes, and gas analysers were used to measure temperature, heat flux, pressure, and gas concentration.

4.2 Test Room

The test room for the two full-scale fire tests was located in the northwest corner of a large burn-hall with dimensions of 52.0 m x 28.5 m x 12.2 m at the NRCC/Carleton Fire Research Fire Lab. The test room was originally designed for the “Characterization of Fires in Multi-Suite Residential Dwellings (CFMRD)” project, which was initiated by the National Research Council of Canada (NRCC or NRC-IRC) in 2006 for the study of fires in low-rise multi-suite residential dwellings of light-frame construction [63].

The test room was built on a concrete slab with a thickness of 15.2 cm. The walls and roof were constructed using lightweight steel frame. In the CFMRD project, the walls and floor were lined with a layer of cement board, and the ceiling with two layers of gypsum board. The interior dimensions of the test room were 3.8 m x 4.2 m x 2.37 m. Figure 52 shows the construction details of the roof, and Table 23 presents the framing and lining materials used in the CFMRD project [63].

Figure 52 Construction details of the roof in the CFMRD project [63]

Table 23 Framing and lining materials used in the CFMRD project [63]

	Framing	Interior lining	Exterior lining
Members			
Walls	152.4 mm 14 gauge steel studs @ 406.4 mm o.c.	12.7 mm cement board (one layer)	12.7 mm cement board (one layer)
Ceiling / Roof	152.4 mm steel joists* 14 gauge @ 406.4 mm o.c.	Gypsum board (two layers) ⁶	15.9 mm plywood (one layer)
Floor	none	12.7 mm cement board (one layer)	Concrete slab

* Two joists were fastened back-to-back to strengthen the ceiling and provide an extra flange for attaching the ceiling; ⁶Two layers of 15.9 mm Type-X gypsum boards

For the two full-scale fire tests in this project, the same test room was used with the same lightweight steel frame, and the same ceiling and floor lining materials as the one used in the CFMRD project. An additional layer of 15.7 mm Type-X gypsum board was used for the walls on the top of the layer of cement board, due to the severity concern of

the expected post-flashover fire. The final interior dimensions of the test room for the two full-scale fire tests were 3.77 m x 4.17 m x 2.37 m.

There was a 2.0 m x 0.9 m doorway in the middle of the north wall, which was closed by a removable door without hinges in both tests. A layer of 15.7 mm Type-X gypsum board was placed on the inside surface of the door. One window opening with a size of 1.5 m x 1.5 m was located on the south wall for the two full-scale fire tests.

4.3 Test Instrumentation and Set-up

The two full-scale fire tests were designed to simulate two fire scenarios, one in a bedroom with one bed, and another in a bedroom with two beds. The test measurements were categorized into three major parts: instrumentation for the measurement of the heat release rate, instrumentation in the test room, and instrumentation facing the window opening.

4.3.1 Heat Release Rate (HRR) Measurement

Heat release rate is one of the most important factors in the study of fire phenomena, and has been widely used to quantify the size of fires. The heat release rate calculation was based on the classical principle of oxygen consumption which states that the same amount of heat is produced per unit mass of oxygen consumed in the fires of many organic materials [43-47]. In this research, Janssen's [47] method was used in the heat release rate calculation for the two full-scale fire tests.

For heat release rate measurement and calculation, a hood with a dimension of 6.0 x 6.0 m was built above the window to collect exhaust gases, and a vertical exhaust duct with a diameter of 1.32 m (52") was connected to the hood. Figure 53 shows the hood and the exhaust duct. All of the parameters used for heat release rate calculation, such as the mass flow rate, gas temperature, pressure, and concentrations of oxygen, carbon dioxide, and carbon monoxide, were measured in the vertical exhaust duct at about 10 m height from the top of the window opening, as shown in Figure 54.

The exhaust gases were drawn by three fans, which were located at about 50 m away from the test room. Each exhaust fan had the capacity of 44 m³/s. In the two full-scale fire tests, all of the three exhaust fans were set at 75% of maximum speed.

Figure 53 Hood and exhaust duct for heat release rate measurement

Figure 54 Measurement locations for heat release rate

4.3.2 Instrumentation in the Test Room

In the two full-scale tests, a total of eight thermocouple trees, five single thermocouples, six heat flux gauges, four bidirectional probes, and two gas sampling probes were installed in the test room. Figure 55 presents the layout of instrumentation installed inside the room (including the ceiling), on the wall, at the window opening and outside the test room. For the 2nd test, two single beds with a separated distance of 0.67 m were used instead of one double bed in the 1st test. Figure 56 provides the section view of the instrumentation installed at the window opening.

Figure 55 Layout of instrumentation in the test room

Figure 56 Section view of instrumentation at window opening

4.3.2.1 Thermocouples

The temperature development in the test room during fire tests was measured by five thermocouple trees inside the room, three thermocouple trees at the window opening, one thermocouple in the middle of the room beneath the ceiling, and another four

thermocouples on the walls attached with heat flux gauges. The locations of the thermocouple trees and the single thermocouples are shown in Figure 55 and Figure 56.

The five thermocouple trees inside the room are labelled as SW (southwest), NW (northwest), NE (northeast), SE (southeast), and NW corner (northwest corner). All of them were suspended from the ceiling, and each thermocouple tree had five thermocouples with an elevation of 0.4 m, 0.9 m, 1.4 m, 1.9 m, and 2.35 m from the floor. The three thermocouple trees, NE, SE, and NW corner, had the same locations in the two tests, but the location of the other two thermocouple trees, SW and NW, were slightly changed in the north-south direction in the two tests, due to the conflict with the beds. In the first test, the room had one bed, and the thermocouple trees, SW and NW, were located at the two sides of the bed at the same distance from the south and the north wall. In the second test, the room had two beds, and the SW thermocouple tree was located between the window and one of the beds, and the NW thermocouple tree was located between the two beds and close to the middle line of the room.

One single thermocouple was located in the middle of the room and 0.02 m beneath the ceiling, and four other single thermocouples were located on the walls and mounted with heat flux gauges. Each of the three thermocouple trees at the window opening had three thermocouples, and the section view of their locations is given in Figure 56. All of them were kept at the same locations for the two tests.

Type-K thermocouples were used which have a measuring range of -200 to 1200°C. The temperature data was directly recorded by the data acquisition system.

4.3.2.2 Heat Flux Gauges

The rates of heat transfer can be measured by using heat flux gauges. On the ceiling of the test room, two heat flux gauges were installed at locations close to the SW and NE thermocouple trees.

A total of four heat flux gauges were mounted separately on the south, east, north, and west walls. Their locations and elevations are shown in Figure 55. The two heat flux gauges on the east wall and the west wall were placed at the same height of 1.2 m from the floor, and in the centre line of the wall. The heat flux gauge on the east wall was located above the headboard in the first test and between the two beds in the second test. The heat flux gauge on the west wall was above the TV sets in both tests. The heat flux gauges on the south and north walls were placed at the same height of 0.6 m from the floor, and 0.8 m from the west wall and the east wall.

In the first test, one heat flux gauge was placed on the floor to monitor the heat flux to the floor; however, due to the severity of the fire in the first test, the heat flux gauge was damaged, so it was not used in the second test. The damaged heat flux gauge in the first test is shown in Figure 57.

Gardon heat flux gauges were used which have a measuring range of 0 to 10 millivolts. The measured voltage data were converted to heat flux values using the certified calibration factor for each heat flux gauge that has been provided by the manufacturer.

Figure 57 Damaged heat flux gauge on the floor

4.3.2.3 Bidirectional Probes

Four bidirectional probes were installed in the middle line of the window opening, in order to monitor gas movement through the opening. Their locations and elevations are given in Figure 55 and Figure 56.

TT series Autozeroing Micromanometers were used to measure the differential pressures with a measuring range of 0 to 1 volts. The measured voltage data were converted to the pressure in Pascal by using the correlation factors derived from the operating manual for the TT series instruments.

4.3.2.4 Gas Analysers

Two gas analysis probes, at heights of 0.4 m, and 1.5 m from the floor, were installed on the north wall 0.9 m deep inside the room. The mole concentrations of oxygen, carbon

dioxide, and carbon monoxide were measured at these two locations, so that the changes of gas concentrations at the two different smoke layer heights can be compared.

The range of the gas analysers was set at 4 to 20 millivolts, and the different conversion factors were used to calculate the mole concentrations of oxygen, carbon dioxide, and carbon monoxide.

4.3.3 Instrumentation facing the Window Opening

Two heat flux gauges combined with two thermocouples were placed outside the test room at a distance of 3 m from the window. In addition, two infrared cameras and one digital video camera were set outside the test room at a distance of about 5 to 6 metres. The layout of instrumentation outside the test room is shown in Figure 55.

4.3.3.1 Heat Flux Gauges and Thermocouples

To measure the heat flux from the flame exiting the window opening, two heat flux gauges were installed on a moveable steel post at a height of 1.45 m and 2.08 m from the room floor level, and the steel post was placed outside the test room and opposite to the middle line of the window opening at a distance of 3 m.

Gardon heat flux gauges were also used with a measuring range of 0 to 10 millivolts. The measured voltage data were converted to the heat flux values by using the certified calibration factor for each heat flux gauge that has been provided by the manufacturer.

Each heat flux gauge was attached with a Type-K thermocouple to measure the temperature. The measuring range of the thermocouples was from -200 to 1200°C. The temperature data were directly recorded by the data acquisition system.

4.3.3.2 Infrared Camera

Two FLIR infrared cameras (model: P640 & SC640) were used to take thermo-pictures and monitor temperature developments of the flame and the south exterior wall. The infrared cameras can measure temperatures at a range of -40 to 2000°C.

4.3.3.3 Digital Video Camera and Still Camera

One Sony digital video (model: HDR-SR7) camera and two digital still cameras were used to take videos and pictures during the tests.

4.4 Furnishings Used in the Two Tests

Two full-scale fire tests were designed to simulate hotel room fires in a bedroom with one bed and a bedroom with two beds. The 3D views of the two tests from Smokeview software [64] are given in Figure 58 and Figure 59. The items used in the two tests include mattress, mattress boxes, headboards, footboards, dressers, desks, chairs, sofas, beddings, and TV etc, which are listed in Table 24 and Table 25. A total of 25 items with a total weight of 330.8 kg were used in the first test, and a total of 22 items with a total weight of 318.5 kg were used in the second test.

The fire loads for wood, textile, plastic, paper, and carpets were kept approximately the same for the two tests. The major difference of the two tests is that one double bed with a top surface area of 3.04 m^2 was used in the first test, and two single beds with a total top surface area of 3.57 m^2 and a separate distance of 0.65 m were used in the second test. Another difference is the weights of the two upholstered single sofas, which had similar polyurethane foam as the mattresses. The first test had a fire load density of 397.2 MJ/m^2 , and the second test had a fire load density of 366.1 MJ/m^2 , details of which are given in Table 26.

Figure 58 3D layout of the test room for the 1st test

Figure 59 3D layout of the test room for the 2nd test

Table 24 Items used in the first test

Items	Qty	Dimensions (m)	Mass (kg)
Furniture:			
Double Bed headboard	1	1.68 x 1.20 x 0.045	14.8
Double Bed footboard	1	1.64 x 0.6 x 0.055	10.0
Double Mattress	1	2.00 x 1.52 x 0.24	36.8
Double Mattress Box	1	2.01 x 1.52 x 0.25	37.5
Sofa Chairs	1	1.02 x 0.97 x 0.80	38.0
Nightstands	2	0.52 x 0.37 x 0.58	15.2
Desks	1	1.22 x 0.44 x 0.77	27.5
Chairs	1	0.55 x 0.59 x 0.81	11.3
Dressers	1	1.83 x 0.46 x 0.61	61.5
Beddings:			
Quilts	1		2.6
Pillows	3		2.0
Bed Covers & Sheets	1		4.2
Electronics:			
Televisions	1	0.65 x 0.50 x 0.58	30.8
Telephone--handset	1	0.16 x 0.05 x 0.03	0.1
Printer	1	0.45 x 0.24 x 0.18	6.2

Others:			
Telephone books	2		3.8
Rubbish Bins	1		0.3
Carpet-1	1	2.40 x 1.56 x 0.003	8.6
Carpet-2	1	2.45 x 1.53 x 0.003	6.3
Carpet-3	1	2.33 x 1.68 x 0.003	9.6
Carpet-4	1	1.66 x 1.14 x 0.003	3.7
Sum:	25		330.8

Table 25 Items used in the second test

Items	Qty	Dimensions (m)	Mass (kg)
Furniture:			
Single Bed headboard	1	1.02 x 0.86 x 0.055	6.1
Single Mattress-1	1	1.88 x 0.95 x 0.18	14.8
Single Mattress-2	1	1.88 x 0.95 x 0.18	17.0
Single Mattress Box-1	1	1.83 x 0.98 x 0.19	18.5
Single Mattress Box-2	1	1.83 x 0.98 x 0.19	18.2
Sofa Chairs	1	0.82 x 0.70 x 1.00	23.7
Nightstands	2	0.59 x 0.48 x 0.56	39.4
TV stand	1	0.80 x 0.45 x 0.60	27.9
Desks	1	1.07 x 0.60 x 0.74	29.3
Chairs	1	0.55 x 0.58 x 0.81	11.3
Dressers	1	1.39 x 0.48 x 0.41	28.3
Bedding:			
Pillows	2		1.5
Bed Covers & sheets	2		7.5
Blankets			
Electronics:			
Televisions	1	0.76 x 0.48 x 0.59	46.1
Others:			
Telephone books	2		3.8
Rubbish Bins	1		0.3
Carpet-1	1	3.15 x 1.22 x 0.003	13.1
Carpet-2	1	1.80 x 1.58 x 0.003	11.7
Sum:	22		318.5

Table 26 Fire load density for the two tests

	Wood	Plastic	Textile	Paper	Mattress	Sofa	Carpet	Sum
Test 1-FLD (MJ/m ²)	210.4	18.8	10.5	4.1	74.0	45.7	33.7	397.2
Test 2-FLD (MJ/m ²)	211.8	17.3	10.8	4.1	63.9	28.5	29.7	366.1

4.5 Test Results and Data Analysis

4.5.1 Test Observation and Record

Two full-scale fire tests were conducted in a test room with interior dimensions of 3.77 m x 4.17 m x 2.37 m at NRCC/Carleton (National Research Council of Canada/Carleton University) Fire Research Lab. The date of the first test was October 10, 2008, and the date of the second test was November 12, 2008.

In both tests, the exhaust fans were set at 75% of the maximum speed. All of the doors in the burning-hall were closed, except the door at the south end, which is about 45 m from the test room. The gas analysers were calibrated on the test day by NRCC staff, and the other instruments, such as thermocouples, heat flux gauges, were checked with the data acquisition system one and two days before the test day.

For the two tests, the same propane burner was used as the ignition source at a flow rate of 6.6 L/min for 50 seconds. The burner was vertically placed beside the beds, at the side close to the window opening. The burner was located at a distance of 0.03 m from the side of the beds, and a distance of 0.85 m from the foot end of the beds. Figure 60 shows the start of the fire of the first test.

A test record sheet was prepared for the test day to record main observations during the tests. This information was also verified by reviewing digital videos and photos.

Table 27 provides the time frames of fire development in the two tests.

Figure 60 The start of the fire in the 1st test

Table 27 Records of the two tests

Test Record	Test 1	Test 2
	(sec.)	(sec.)
Burner ignites	00	000
Burner turn off	50	50
Flame reach ceiling	195	140
Smoke flow out of window	210	160
Flame issues out of window	240	180
Second item ignites	Could not see	Could not see
Flashover	240	180
TV explosion	310	260

Decay starts	780	900
Fire comes out of the door	~1500	No
Test terminated	1785	1325

4.5.2 Heat Release Rate

Heat release rate calculation was based on the oxygen consumption principle, using the equations developed by Janssen [47]. The input data include temperature, mass flow rate, and gas concentration that were measured in the exhaust system. The delay times of the gas analysers were estimated by comparing the two curves of gas temperature and oxygen concentration. The estimated delay time for both tests was 26 seconds. Figure 61, Figure 62, Figure 63 and Figure 64 present the curves of gas temperature and oxygen concentration before and after using delay time in the two tests.

The same pilot burner was ignited for 50 seconds in both tests. The following test description and plotted figures use the start time of pilot ignition as the start of the test. The calculated heat release rates for the two full-scale tests are presented in Figure 65.

Figure 61 Temperature and O₂ concentration before using the delay time for 1st test

Figure 62 Temperature and O₂ concentration after using the delay time for 1st test

Figure 63 Temperature and O₂ concentration before using the delay time for 2nd test

Figure 64 Temperature and O₂ concentration after using the delay time for 2nd test

Figure 65 Heat release rates for the two full-scale tests

The plot of the heat release rates of the two tests depicted in Figure 65 shows that the fire in the first test developed faster than the fire in the second test in the early stage. The time that the heat release rate reached 500 kW, 1000 kW, and 1500 kW in the first test was about 30 to 50 seconds earlier than that in the second test. The reason could be the different material layers of the ignited side of the mattresses.

For both tests, the maximum values of heat release rates occurred at the second peak. The maximum value of the heat release rate in the first test reached 4809 kW at 360 seconds (6 minutes), which is about 1 MW higher than the maximum value of the heat release rate in the second test that was 3735 kW at 338 seconds (5.6 minutes). In comparison with the two single beds in the second test, the one double bed in the first test

had a higher and more condensed fire load, which could contribute to the higher maximum value of the heat release rate. The third peak value of heat release rate in the first test is also higher than that in the second test by about 0.5 MW. This is reasonable as the fire load of the sofa chair in the first test was higher than that of the sofa used in the second test.

In the first test, there is a period of 400 seconds during which the heat release rate levels off during the decay stage. This phenomenon does not appear in the second test. This may be due to the type of furniture used in the first test, which had a dresser made of heavy solid timber. The characteristic heat release rate values for the two tests are listed in Table 28.

Table 28 Characteristic values of heat release rate in the two tests

	Time (s)		HRR (kW)	
	Test 1	Test 2	Test 1	Test 2
HRR at 500 kW	210	156	518	528
HRR at 1000 kW	236	194	1033	1007
HRR at 1500 kW	250	218	1511	1527
1st peak HRR	292	260	2965	3326
2nd peak HRR	360	338	4809	3735
3rd peak HRR	468	510	4006	3470
1st decay starts	550	772	3250	2714
2nd decay starts	1392	no	1612	no
Record ends	1792	1360	767	715

4.5.3 Temperature

Temperature changes during the two full-scale fire tests were measured by using thermocouples, and were also monitored by an infrared camera. The same thermocouples

were used in both tests with a total of 45 thermocouples in the first test, and a total of 44 in the second test. One thermocouple that was attached to the heat flux gauge on the floor was not used in the second test, because this heat flux gauge was not employed in the second test.

Table 29 and Table 30 provide the number and height of thermocouples attached to the five thermocouple trees in the room, and three thermocouple trees at the window opening. Temperature measurements obtained from these thermocouples are shown in the Figures 66 to 70, and 75 to 81.

Table 29 Thermocouple number and height for five thermocouple trees in the room

Height (m)	Southwest (SW)	Northwest (NW)	Northeast (NE)	Southeast (SE)	Northwest Corner (NW Corner)
2.35	TC5	TC10	TC15	TC20	TC25
1.90	TC4	TC9	TC14	TC19	TC24
1.40	TC3	TC8	TC13	TC18	TC23
0.90	TC2	TC7	TC12	TC17	TC22
0.40	TC1	TC6	TC11	TC16	TC21

Table 30 Thermocouple number and height for three thermocouple trees at the window

Height* (m)	West Line	Centre Line	East Line
1.14	WL T	CL T	EL T
0.76	WL M	CL M	EL M
0.38	WL B	CL B	EL B

* From bottom of the window opening

4.5.3.1 The First Test

The room temperatures were mainly measured by the five thermocouple trees, marked as SW (southwest), NW (northwest), NE (northeast), SE (southeast), and NW corner (northwest corner). There was also one thermocouple located in the centre of the room 0.02 m below the ceiling. Other single thermocouples were attached with heat flux gauges mounted on the wall, ceiling and floor.

The measured temperatures of the five thermocouples are presented in Figures 66 to 70. Almost all of the temperature curves reached the first peak value at about 300 seconds, when the heat release rate also reached the first peak value. Most of the thermocouples had their highest temperature at about 600 seconds, which corresponds to the start time of the decay phase from the heat release rate curve, but not the time that the maximum value of the heat release rate was reached. The measured temperature from the bottom thermocouple, 'TC11' of the NE thermocouple tree was unexpectedly higher after 608 seconds. The peak values of the room temperature from the SE thermocouple tree and NE thermocouple tree (except 'TC11') were 1060°C and 1091°C. These maximum temperatures have also been observed by the infra camera (Figure 73 and Figure 74).

Figure 66 Temperatures of TC tree at northwest in the 1st test

Figure 67 Temperatures of TC tree at southwest in the 1st test

Figure 68 Temperatures of TC tree at northeast in the 1st test

Figure 69 Temperatures of TC tree at southeast in the 1st test

Figure 70 Temperatures of TC tree at northwest corner in the 1st test

It was interesting to notice that the three thermocouple trees on the west, SW, NW, and NW corner, have very similar shape of the curves, which are different than another similar shape of the curves that the two thermocouple trees on the east, SE and NE have. It seems that the fire development in the room was divided into two zones, west zone (bed) and east zone (wood furniture and sofa chair), which can also be seen in the digital videos, photos (Figure 71 and Figure 72), and infrared pictures (Figure 73 and Figure 74).

Figure 71 Test picture at 300 seconds in the 1st test

Figure 72 Test picture at 600 seconds in the 1st test

Figure 73 Infrared picture in the 1st test

Figure 74 Infrared picture in the 1st test

Three thermocouple trees with a total of nine thermocouples were placed at the window opening. Figure 75 presents the temperature changes of the nine thermocouples in the first test. The three thermocouples on the top row, WL-T (West Line-Top), CL-T (Centre Line-Top), and EL-T (East Line-Top) have very similar temperature development. Also the three thermocouples of the bottom row (WL-B, CL-B, and EC-B) have similar results. The thermocouple in the middle of the west line had a lower temperature than the other two in the middle of the center line and east line during the decay stage.

Figure 75 Temperatures of TC trees at the window opening in the 1st test

4.5.3.2 The Second Test

The temperature development of the five thermocouple trees in the second test is presented in Figures 76 to 80. The figures also show the two different shapes of temperature curves that one group is the thermocouples at the west side of the room, and another group is the thermocouples at the east side of the room, which was noticed in the first test.

The temperatures measured by the five thermocouple trees during the second test increase faster than during the first test. This is consistent with the development of the heat release rates in both tests. Most of the thermocouples had the highest temperature at about 700 seconds, which correspond to the start time of the decay in the heat release rate curve that was also noticed during the first test.

The temperatures of the three thermocouple trees at the window opening are given in Figure 81. The three thermocouples at the middle height had temperatures closer to the temperatures of the thermocouples at the top than those at the bottom. Figure 81 also shows two thermocouple trees (WL and CL) fell at about 700 to 800 seconds when the decay started, which was also seen on the test site and the digital video.

Figure 76 Temperature of TC tree at northwest in the 2nd test

Figure 77 Temperature of TC tree at southwest in the 2nd test

Figure 78 Temperature of TC tree at northeast in the 2nd test

Figure 79 Temperature of TC tree at southeast in the 2nd test

Figure 80 Temperatures of TC tree at northwest corner in the 2nd test

Figure 81 Temperatures of TC trees at the window opening in the 2nd test

4.5.4 Heat Flux

A total of nine heat flux gauges were installed in the first test, and a total of eight heat flux gauges were used in the second test. The floor heat flux gauge was not used in the second test because it was damaged during the first test.

Figure 82 and Figure 83 present heat flux as measured on the north, south, west, and east walls of the test room during the tests. Figure 84 and Figure 85 present the heat flux measured at the northwest and southeast of the ceiling. In the first test, the damage of the cooling system for the heat flux gauges led to the damage of six heat flux gauges, and Table 31 provides the time when the data of “over range” appeared. The six damaged heat flux gauges were replaced in the second test, and the same installation locations were used in the second test.

Table 31 The time of "over range" appeared to HF gauges in the 1st test

Heat Flux Gauge location		"over range" at (sec.)
Walls	North	962
	South	no
	West	750
	East	884
Ceiling	Northeast	1206
	Southwest	674

Figure 82 Heat flux on the walls in the 1st test

Figure 83 Heat flux on the walls in the 2nd test

Figure 84 Heat flux on the ceiling in the 1st test

Figure 85 Heat flux on the ceiling in the 2nd test

From Figure 82 and Figure 83, the heat fluxes on the walls in both tests have two peak values. The first peak value for both tests was recorded by the heat flux gauge at the south wall 163 kW/m^2 (306 s) for the 1st test, and 236 kW/m^2 (278 s) for the 2nd test. The heat flux gauge at the south wall was the nearest to the pilot burner. The second peak value was recorded by the heat flux gauge at the west wall in the 1st test, which was located above the headboard of the double bed, at 258 kW/m^2 (552 s), and by the heat flux gauge at the east wall in the 2nd test, which was located above the TV, at 208 kW/m^2 (816 s). The time of the second peak corresponds to the time of the maximum heat release rates and maximum temperature in the room.

The heat fluxes measured at the ceiling have three peak values in the 2nd test, which is shown in Figure 85, but two peak values in the 1st test are shown in Figure 84. The first peak values were recorded by the heat flux gauge at the southwest of the ceiling in the two tests at about 160 kW/m^2 . The second peak values were recorded by the heat flux gauge at the northeast of the ceiling with values of 286 kW/m^2 (706 s) for the 1st test, and 207 kW/m^2 (626 s) for the 2nd test.

Figure 86 and Figure 87 present the heat flux measured 3 m outside the window opening with a highest value of about 13 kW/m^2 for both tests.

Figure 86 Heat flux measured 3 m outside the window opening in the 1st test

Figure 87 Heat flux measured 3 m outside the window opening in the 2nd test

4.5.5 Pressure Difference at the Window Opening

Figure 88 presents the pressure difference at the window opening measured in the 1st test. It shows positive pressure difference at the top of the window indicating that gases flow out of the room, and negative pressure difference at the bottom indicating that fresh air flow into the room. The curves of the top, H1.7 and H1.4, have more fluctuation than the curves of the bottom, H1.1 and H0.8, which might be due to the high turbulence of the hot gases. The bidirectional probes failed to give good measurements in the second test.

Figure 88 Pressure difference at the window opening in the 1st test

4.5.6 Gas Concentration in the Test Room

The gas concentrations in the test room were measured by two gas analysis probes, located at 0.5 m, and 1.5 m height from the floor, and at a distance of 0.9 m from the north wall for both probes. Figure 89 and Figure 91 present the mole concentrations of oxygen in the two tests, and Figure 90 and Figure 92 present the mole concentrations of carbon oxide, and carbon monoxide in the two tests.

In the two tests, the mole percentage of oxygen dropped to zero at about 300 seconds and stayed at zero for about 250 seconds for both tests. The reason could be the measuring locations of the gas probes, which were at the back corner of the room where fresh air could not easily flow.

The maximum values of CO₂ measured in the tests were 17.9% for the 1st test, and 18.3% for the second test. For both tests, the high value of CO₂ in the room started to drop at about 730 seconds, and they levelled off at about 7%.

The maximum values of CO could not be measured in the two tests, due to the higher values of CO over the maximum range of the instrument setting. The durations that the values are over range lasted 148 seconds for the 1st test, and 190 seconds for the 2nd test. The over range durations correspond to the periods where oxygen values dropped to zero.

Figure 89 Concentration of O₂ in the test room in the 1st test

Figure 90 Concentration of CO and CO₂ in the test room in the 1st test

[*T—op; B—Bottom]

Figure 91 Concentration of O₂ in the test room in the 2nd test

Figure 92 Concentration of CO and CO₂ in the test room in the 2nd test

[*T—Top; B—Bottom]

4.6 Data Derived for Design Fires

4.6.1 HRR vs. Time Curves

In enclosure fires, the maximum heat release rate is governed by the areas of all openings, and the equation [65] is given by:

$$\dot{Q} = 1.5A\sqrt{H} \quad (4.1)$$

Where, $\dot{Q}$ = heat release rate of the fire (MW)

A = total area of the openings (m²)

H = weighted height of the openings (m)

For this project, one window opening with the same dimensions of 1.5 m x 1.5 m was used in both tests, and the calculated maximum heat release rate was 4.13 MW. In the two experimental tests, the peak values of the heat release rate were 4.8 MW for the first test, and 3.7 MW for the second test, shown in Figure 65.

In design fires for enclosures, some parameters in the different fire development stages need to be quantified, such as the growth rate in the early stage, heat release rate of fully developed fire, duration of fully developed fire, and duration of decay phase. Figure 93 and Figure 94 provide the design fire curves for the two tests. The design curve 1 for both tests simply followed the heat release rate curve derived from experimental tests. The design curve 2 was conservative for fire protection design with a safety factor of 1.15 applied to the heat release rate of fully developed stage, and a longer duration of fully developed stage.

As shown in Figure 93, for the first test simulating a bedroom with one double bed, the growth rate of the fire matches a t^2 fire with a growth rate coefficient of 0.055, which is slightly higher than the value for fast fires (0.0466). In design curve 1, the heat release rate for the fully developed stage was assumed to be 3.14 MW, with a duration of 400 seconds, which is the average value of heat release rate between 290 to 690 seconds. The heat release rate for the second flat period is the average heat release rate between 982 to 1350 seconds. This value is 1.86 MW, with a duration of 368 seconds. The duration for the first decay slope is 292 seconds. The second decay slope was determined by extending the heat release rate curve to the horizontal axis, and drawing the line from the start of the second decay phase to that point. The point at which the curve meets the horizontal axis is 2000 seconds. In design curve 2, the same growth rate is used as in design curve 1. The heat release rate for the fully developed stage was assumed to be 3.61 MW, with a duration of 768 seconds. The value of 3.61 MW was obtained by multiplying the peak value of design curve 1 by 1.15. The duration of the fully developed phase was computed by adding the duration of the two horizontal portions of the design curve 1. The slope of design curve 2 was obtained by extending the curve from the end of the fully developed phase to the end of design curve 1. The slope of the decay is 3.897 with a duration of 926 seconds.

Figure 93 Heat release rate design curves for the 1st test

Figure 94 shows that for the second test, which simulates a bedroom with two single beds, the growth rate coefficient is 0.06. This value is used for both design curves, and is slightly higher than the characteristic value for fast fires. In design curve 1, the heat release rate for the fully developed stage is 2.86 MW, with a duration of 456 seconds, which is the average value of heat release rate between 268 to 724 seconds. The design curve 1 for the decay stage matches a t^2 curve with a coefficient of 0.00245, and the duration of the decay stage is approximately 1076 seconds. In design curve 2, the same growth rate is used as in the design curve 1. The heat release rate for the fully developed stage of 3.29 MW was determined by multiplying the peak value of design curve 1 by

1.15. The duration of the fully developed phase is 547 seconds, which is 1.2 times longer than that in design curve 1. The slope of design curve 2 was obtained by extending the curve from the end of the fully developed phase to the end of design curve 1.

Figure 94 Heat release rate design curves for the 2nd test

A possible design fire for hotel rooms with the same opening size could be the design curve 2 for the 1st test as it is more severe with higher heat release rate and longer duration.

4.6.2 Temperature beneath the Ceiling

In fire protection engineering, the design of many active systems, such as sprinklers and heat detection require knowledge of the temperature beneath the ceiling. In the test room,

five thermocouple trees, and one single thermocouple beneath the centre of the ceiling were used. A total of six thermocouples were located 0.02 m beneath the ceiling. Figure 95 presents the average temperature of the six thermocouples beneath the ceiling for the two tests. The temperature development of the two tests was very close in the growth stage with the first peak value of about 650°C at 286 seconds for the first test, and 262 seconds for the second test. The maximum average ceiling temperatures for the two tests were almost the same at about 990°C. For both tests, the average ceiling temperatures reached about 950°C after 600 seconds. In Test 1, temperature stayed at values over 600°C for close to 25 minutes.

Figure 95 Average ceiling temperature for the two tests

4.7 Summary of the Tests

Two full-scale fire tests have been conducted at the NRCC/Carleton (National Research Council of Canada/Carleton University) Fire Research Lab. The first test, designed to simulate a fire in a hotel bedroom with one bed, was conducted on October 10th of 2008, and the second test for simulating a fire in a bedroom with two beds, was conducted on November 12th of 2008. The interior dimensions of the test room for both tests were 3.77 m x 4.17 m x 2.37 m, and the window opening sizes for both tests were 1.5 m x 1.5 m.

At the early stage, the fire develops faster in the 2nd test than that in the 1st test. The 1st test had the higher maximum heat release rate of 4.8 MW, while the second test reached 3.7 MW. A delay time of 26 seconds was used in the heat release rate calculations for both tests.

In the test room, the highest temperature measured in the 1st test was close to 1200°C, and that measured in the 2nd test was about 1100°C, both of which were higher than the maximum average ceiling temperature for the two tests. The highest heat fluxes for both tests were measured at the northeast location of the ceiling, with a value of 286 kW/m² (706 s) for the 1st test, and 234 kW/m² (818 s) for the 2nd test.

Two distinguished vertical zones (west and east) of fire development were noticed in the two full-scale fire tests. This phenomenon might be applied to hotel guest rooms and other bedrooms with similar furnishing layout as that for the two tests. Further experimental tests and research on this phenomenon are needed.

Design fire curves of heat release rate were presented, which could be used as a prescribed fire in FDS input files to simulate smoke movement in the buildings. Average ceiling temperatures for the two tests were also provided, which could be helpful for the design of active and passive fire protection system.

Chapter 5: FDS Modelling

5.1 Introduction

In this project, the CFD model, FDS was used to simulate hotel fire tests. The Fire Dynamics Simulator (FDS), which is a CFD model developed in the fire community, solves numerically a form of the Navier-Stokes equations, which are appropriate for low-speed, thermally-driven flow that focuses on smoke and heat transport from fires. Most of the difficulties in simulating fires is to derive a suitable input data file.

5.2 Data Files Provided in FDS

In version 4 of FDS, a data file of commonly used materials with material properties and thermal properties was provided, which was quite convenient for fire researchers and engineers to use. However, the new version 5 of FDS does not provide the data file. The reason is that the model developers do not want to (also should not) take the responsibility of people using and quoting the data provided in FDS. Currently, a project was undertaken by WPI (Worcester Polytechnic Institute), the Southwest Research Institute, and the SFPE (Society of Fire Protection Engineers) to develop a standard guide for fire model input parameters, including documentation of the standard test methods used to obtain material properties [66].

Actually, in FDS version 5, some examples are also given, which have some data, but most of them are labelled as 'Properties completely fabricated'. The normally used materials for room fire, such as PMMA, upholstery, and spruce, can be found in both the data files of FDS version 4, and the examples of FDS version 5.

In FDS, two burning phases are considered. One is a solid phase pyrolysis, and the other is gas phase combustion. Different materials can have different solid phase pyrolysis, but for the gas phase combustion, only one gaseous fuel can be defined in FDS, due to the cost of solving the transport equations or multiple gaseous fuels [52].

5.3 Virtual Fuels Developed for FDS Modelling

Based on the assumption that all of the fuels in compartment are uniformly distributed, a virtual fuel package was used to model the fuels in different commercial stores, such as computer stores, book stores, shoe stores, and toy stores [60]. Virtual fuel packages were developed for the seven types of stores with PMMA as the base material. The material properties of virtual fuel packages for different commercial stores are summarized in Table 32. Properties common to all seven packages were the conductivity 'KS', specific heat 'C_P', maximum burning rate 'BURNING_RATE_MAX', and density 'DENSITY', with the values of 0.19 W/m/K, 1.42 kJ/kg/K, 0.028 s⁻¹, and 536 kg/m³, respectively. Properties, which were different for each fuel package, were the heat of vaporization 'HEAT_OF_VAPORIZATION', heat of combustion 'HEAT_OF_COMBUSTION', and the ignition temperature 'TEMPIGN'. Two values for 'HEAT_OF_VAPORIZATION' were used, 1620 kJ/kg for five stores, and 1134 kJ/kg for two stores. For

'HEAT_OF_COMBUSTION', three values were used, 18270 kJ/kg for five stores, 20097 kJ/kg and 22000 kJ/kg for two stores. For ignition temperature, four values were used. They were 285, 304, 380 and 383°C.

Table 32 Virtual fuel packages for different commercial stores (summarized from [60])

Material properties in solid phase	'CMP'	'SA-II'	'CLC-II'	'TOY-II'	'SHO-II'	'BK-II'	'FF-II'
HEAT_OF_VAPORIZATION	1134	1620	1134	1620	1620	1620	1620
HEAT_OF_COMBUSTION	20097	18270	18270	18270	18270	18270	22000
BURNING_RATE_MAX	0.028	0.028	0.028	0.028	0.028	0.028	0.028
DELTA	0.012	0.02	0.01	0.02	0.0216	0.0216	0.015
KS	0.19	0.19	0.19	0.19	0.19	0.19	0.19
C_P	1.42	1.42	1.42	1.42	1.42	1.42	1.42
DENSITY	536	536	536	536	536	536	536
BACKING			INSULATED				
TMPIGN	380	285	380	285	304	304	383

[*'CMP'—Computer Store; 'SA-II'—Storage Area; 'CLC-II'—Clothing Store; 'TOY-II'—Toy Store; 'SHO-II'—Shoe Store; 'BK-II'—Bookstore; 'FF-II'—Fast Food Outlet]

In the hotel room scenario, the fuels are not uniformly distributed. One important feature for these room fires is that there are two distinguished groups of materials or fuels involved in fire. One group is the foam and fabric of the bed and sofa with lower density and higher heat of combustion, which usually is involved during the early stages of the fire. The other group includes all other materials, such as wood, plastic, paper, foam and fabric, which become involved after flashover. The materials of wood and plastic have higher density and lower heat of combustion than the foam and fabric.

Two virtual fuels were developed for simulating hotel room fires. One virtual fuel that mainly includes foam and fabric is named 'FF'. The other virtual fuel includes the

materials of wood, plastic, paper, foam and fabric is named 'WPFF'. The material and thermal properties for the two virtual fuels are given in Table 33.

For gas phase combustion, only one gaseous fuel can be defined in the reaction ID for each FDS modelling. POLYURETHANE was used in the room fire example of FDS version 4 and 5. The data have a source that is from 'C_{6.3} H_{7.1} N O_{2.1}, NFPA Handbook, Babrauskas' [52]. PROPANE is one of the widely used gaseous fuels in FDS, which is known as 'C₃ H₈'. In order to check the sensitivity of different gaseous fuel used in the FDS modelling, both POLYURETHANE and PROPANE were tried in the same simulation setup.

Table 33 Material and thermal properties for two virtual fuels

&MATL ID	'FF'	'WPFF'
CONDUCTIVITY	0.1	0.1
SPECIFIC_HEAT	1.0	1.5
DENSITY	25	450
HEAT_OF_REACTION	1500	1500
HEAT_OF_COMBUSTION	35000	18000
REFERENCE_TEMPERATURE	280	320
REFERENCE_RATE	0.05	0.005
N-REACTIONS	1	1
NU_FUEL	1	1
&SURF ID	'VF-1'	'VF-2'
THICKNESS	0.1	0.02
BURN_AWAY	.TRUE.	.TRUE.
PART_ID	'smoke'	'smoke'
MATL_ID	'FF'	'WPFF'

5.4 FDS Simulation for the Fire Test 1

For the virtual fuel 'FF', a form of slab was constructed with dimensions of 2.1 m x 1.5 m x 0.3 m. For the virtual combined fuel 'WPFF', a form of bar was used with a cross

section of 0.1 x 0.1 m, and three lengths of the bars (1.5 m, 2.0 m, and 2.1 m). Two types of fuel layouts were considered. The layout 1 was to put the two virtual fuels in the middle of the room with FF slab on the top and WPFF bar beneath the slab. Layout 2 was to locate the FF slab and one layer of WPFF bar at the place where the bed was located in the test, and place all other WPFF bars at the place close to the middle of the east wall, where the furniture was located in the test. Layout 2 was based on the observation of two vertical zones (west and east) of fire development noticed in the experimental tests. The same total volumes of 'FF' and 'WPFF' were used in the two different fuel layouts. Figure 96 and Figure 97 show the two floor layouts of the two virtual fuels.

In each simulation, one pilot burner was placed beside the FF slab at the side close to window opening. Both burners had the same dimensions of 0.2 m x 0.3 m, the same heat release rate of 60 kW. A grid size of 0.1 m x 0.1 m was used for all simulations.

Figure 96 Layout 1 of virtual fuels

Figure 97 Layout 2 of virtual fuels

5.4.1 Heat Release Rate Prediction

Figure 98 and Figure 99 present the simulation results by using different gaseous fuels (PROPANE and POLYURETHANE) for different solid fuel layouts. For the simulations with PROPANE gaseous fuel, the two solid fuel layouts gave good predictions at the early stage of fire development. Both simulations even predicted the first peak value, the maximum values, and their time close to the experimental data. The predicted heat release rates for the fully developed stage were higher than the experimental data. In the decay stage, both simulations had poor prediction with the sharp slope of the decay, and Layout 2 had a slightly better prediction than Layout 1, probably because the two locations of the fuels in the layout 2 prolonged the time of flame spread.

For the simulations with POLYURETHANE gaseous fuel, both solid fuel layouts did not give good predictions. The simulation of Layout 2 predicted the first peak value of heat release rate at about 90 seconds, which was about 145 seconds earlier than the

simulation result of Layout 1, and about 200 seconds earlier than the experimental data. In the fully developed stage, the heat release rates for both simulations continued to rise until they reach the maximum values, and then dropped sharply. Almost no decay stages appeared.

Among the four simulation setups, the simulation using propane gaseous fuel and solid fuel layout 2 had a better prediction. The problem of predicting for decay stage, which appeared in all simulations, can be improved in fire protection design by adjusting the slope of the decay curve within a reasonable range.

Figure 98 Heat release rate prediction by using PROPANE with two virtual fuel layouts

Figure 99 Heat release rate prediction by using PU with two virtual fuel layouts

5.4.2 Temperature Prediction

In the two fire tests, five thermocouple trees, SW (southwest), NW (northwest), NE (northeast), SE (southeast), and NW Corner (northwest corner), were used to measure the room temperature. For the FDS simulation using the two different virtual fuel layouts, the temperature measurement of the thermocouple tree at the NW Corner was chosen for comparison with the experimental data.

Figure 100 and Figure 101 present the temperature predictions using PROPANE gaseous fuel with two virtual fuel layouts. Both simulations predicted two peak values, which compared well with experimental data, especially in the early stage of the fire. In the simulation with Layout 2, the two bottom thermocouples of the NW Corner tree measured the second peak value (also maximum value) of 1070°C at about 660 s, which was very close to the experimental data. The two simulations had poor predictions in the decay stage, which is similar to heat release rate prediction. Figure 102 and Figure 103 present the temperature predictions by using POLYURETHANE gaseous fuels with two virtual fuel layouts, but both simulations had poor predictions.

Figure 104 and Figure 105 present the temperature in the centre of the room beneath the ceiling measured in the experiments and the simulations with the two different gaseous fuels and two different virtual fuel layouts. The simulation with PROPANE and Layout 2 also had a relatively better prediction than the other three simulations.

Figure 100 TC tree temperature prediction by using PROPANE and virtual fuel layout 1

Figure 101 TC tree temperature prediction by using PROPANE and virtual fuel layout 2

Figure 102 TC tree temperature prediction by using PU and virtual fuel layout 1

Figure 103 TC tree temperature prediction by using PU and virtual fuel layout 2

Figure 104 Ceiling center temperature prediction by using PA with two virtual fuel layouts

Figure 105 Ceiling center temperature prediction by using PU with two virtual fuel layouts

5.4.3 Gas Concentration Prediction

In the four simulations with two different gaseous fuels and two different virtual fuel layouts, gas concentrations were also measured at the same locations as that in the experiment, which were at heights of 0.4 m, and 1.5 m from the floor and at the northwest corner of the room. Figures 106 to 109 present the simulation results of CO and CO₂ concentration using two different gaseous fuels (PROPANE and POLYURETHANE) and two different virtual fuel layouts. All of the four simulations did not predict CO concentration. Except for the simulation with POLYURETHANE and virtual fuel layout 1, the other three simulations had good predictions of CO₂ concentrations. The two simulations using PROPANE gaseous fuel had similar CO₂ concentration plateau values at about 10%, and the other two simulations with POLYURETHANE had similar CO₂ concentration plateau values at about 13.5%, both of which were lower than the experimental data at the maximum value of 17.9%.

Figures 110 to 113 present the predictions of O₂ concentration using two different gaseous fuels and two different virtual fuel layouts. Similar to CO₂ prediction, the three simulations, except for the simulation with POLYURETHANE and virtual fuel layout 1, predicted well O₂ concentration. The two simulations using PROPANE gaseous fuel had similar O₂ concentration plateau values at about 1.9%, and the other two simulations with POLYURETHANE had similar O₂ concentration plateau values at about 2.6%.

Figure 106 CO and CO₂ prediction by using PROPANE and virtual fuel layout 1

Figure 107 CO and CO₂ prediction by using PROPANE and virtual fuel layout 2

Figure 108 CO and CO₂ prediction by using PU and virtual fuel layout 1

Figure 109 CO and CO₂ prediction by using PU and virtual fuel layout 2

Figure 110 O₂ prediction by using PROPANE and virtual fuel layout 1

Figure 111 O₂ prediction by using PROPANE and virtual fuel layout 2

Figure 112 O₂ prediction by using PU and virtual fuel layout 1

Figure 113 O₂ prediction by using PU and virtual fuel layout 2

5.4.4 Sensitivity of Reference Rate

The default value of `REFERENCE_RATE` (reaction rate) in FDS version 5 is 0.1 s^{-1} . In the FDS user's guide [52], "it is suggested that unless you have information to the contrary, `REFERENCE_RATE` at its default value and just specify the `REFERENCE_TEMPERATURE`." In this FDS simulation, different reference rates were tried for both virtual fuels in different fuel layouts. Figure 114 shows the simulation results using the same propane gaseous fuel and the same solid fuel layout 2 with different reference rates. Simulation 'PAL2-RR1' used the FDS default reference rate for both virtual fuels. 'PAL2-RR2' and 'PAL2-RR3' used the same value of 0.05 s^{-1} for the 'FF' virtual fuel, and different values of 0.002 and 0.005 s^{-1} for the 'WPFF' virtual fuel. 'PAL2-RR3' resulted in a better prediction.

Figure 114 Sensitivity of the Reference Rate

5.5 FDS Simulation for the Fire Test 2

The same material and thermal properties of virtual fuels, 'FF' and 'WPF'F', were used to simulate fire test 2. Based on Layout 2 for fire test 1, a Layout 3 was developed to simulate fire test 2. Layout 3 used the same amount and same locations of WPF'F' virtual fuels that were placed close to the middle of the east wall in Layout 2. The difference of Layout 3 and Layout 2 is that two small FF slabs with one layer of WPF'F' bars beneath each FF slab was used in Layout 3 instead of one big FF slab and one layer of WPF'F' bars as used in Layout 2. Figure 115 provides the 3D view of Layout 3.

Figure 115 Layout 3 of virtual fuels

Two gaseous fuels, PROPANE and POLYURETHANE, were also used to simulate fire test 2. Figure 116 presents the simulation results using two gaseous fuels in Layout 3. The simulation with PROPANE gaseous fuel had a better prediction than that with POLYURETHANE in the early stage of fire development. For the simulation with

PROPANE, the predicted time to reach the first peak heat release rate value was close to that in the experiment, but the predicted first peak heat release value was higher than the experimental data by about 13.8%. For the simulation with POLYURETHANE, the fire developed earlier than in the experiment. This is similar to the simulation results using POLYURETHANE and virtual fuel Layout 2 for fire test 1. The two simulations with Layout 3 also had poor predictions in the decay stage as the four simulations for fire test 1.

Figure 116 Heat release rate prediction by using two gaseous fuels in layout 3

5.6 Summary of the Modelling

Two groups of materials or fuels with different density and heat of combustion were noticed in different stages of fire development. Based on this, these two virtual fuels were used for the two groups of materials. One virtual fuel, 'FF', mainly included foam and fabric, and the other virtual fuel, 'WPFF', included the materials of wood, plastic, paper, foam, and fabric. The material and thermal properties of the two virtual fuels were given.

Two virtual fuel layouts were used to simulate fire test 1. In one layout, the two virtual fuels were placed in the middle of the room, and in the other layout, the virtual fuels were located separately in two places. A third virtual fuel layout was used to simulate fire test 2.

In order to check the effect of the burning gaseous fuel on the results, two gaseous fuels, POLYURETHANE and PROPANE were used. For the simulation for fire test 1, the predicted heat release rates, temperature, and gas concentration were compared with experimental data. Different reference rates for the two virtual fuels were also checked. For the simulation for fire test 2, the predicted heat release rates were compared with experimental data.

For the simulation for fire test 1, both simulations with PROPANE gaseous fuel had good predictions of heat release rate at the early stage of fire development. The predicted first peak value and the maximum value of heat release rate, and their time were close to the experimental data. The two simulations with POLYURETHANE gaseous fuel did not

show good results. The poor prediction for the decay stage could be improved in fire protection design by adjusting the slope of the decay curve.

The temperature prediction of fire test 1, shown in Figure 101, with PROPANE and virtual fuel layout 2 had a relatively better result than the other three simulations with different gaseous fuels and different virtual fuel layouts. The two simulations using PROPANE gaseous fuel had similar CO₂ and O₂ concentration plateau values at about 10% and 1.9%, respectively, and the other two simulations with POLYURETHANE had similar CO₂ and O₂ concentration plateau values at about 13.5% and 2.6%, respectively. The model was not set to predict CO concentrations.

With the third virtual fuel layout for fire test 2, the simulation with PROPANE gaseous fuel had a better prediction than that with POLYURETHANE in the early stage of fire development.

The virtual fuels provide a simplified way to predict a fire in FDS when many materials are involved with many unknown parameters. It is much easier to set up the input files using representative virtual fuels than using the real materials. The material and thermal properties of the virtual fuels, such as density, ignition temperature, and reference rate, affect the simulation results; hence it is recommended to check the predicted heat release rate with experimental data from literature.

Chapter 6: Conclusions and Recommendations

6.1 Conclusions

This project included fire load surveys, experimental tests, and fire modelling. The fire load surveys have been conducted in 10 motels and 12 hotels in Canada's National Capital Region---Ottawa and Gatineau, from March 2007 to August 2007. Two full-scale fire tests have been conducted at NRCC/Carleton (National Research Council of Canada/Carleton University) Fire Research Lab. Test 1 was conducted on October 10th of 2008, and Test 2 was conducted on November 12th of 2008. A field model, Fire Dynamics Simulator (FDS), was used to simulate the fire tests. The major findings and contributions of this project are listed below:

Fire Load Survey:

1. The fire load survey included a wide range of motels and hotels from one storey to 24 storeys, and from hotel rating of 2-star to 5-star.
2. Three categories were used to report the survey results for hotels: standard hotels, luxury hotels and hotel suites.

3. Total fire load density and moveable fire load density were analysed for the different types of guest rooms and hotel categories. The average total fire load density for all the surveyed motels and hotels was 550 MJ/m².
4. Typical values for floor area, area of openings and percentage of floor area covered by furnishings were also provided in terms of different types of guest rooms and hotel categories.

Full-scale Fire Tests:

5. Two full-scale tests were conducted. One was designed to simulate a fire in a hotel bedroom with one bed, and the other was to simulate a fire in a bedroom with two beds.
6. The heat release rates of the two tests were calculated by using oxygen consumption principle. A delay time of 26 seconds was chosen by comparing the curves of temperature and oxygen concentration. The 1st test had a maximum heat release rate of 4.8 MW, and the 2nd test had a maximum value of 3.7 MW.
7. Temperature, heat flux and gas concentration in the test room during the tests were also measured and provided.
8. Two distinguished vertical zones (west and east) of fire development were noticed in the two full-scale fire tests, which could be applied to most hotel guest rooms and other bedrooms with the similar furnishing layouts.

9. Design fire curves of heat release rate were developed from the tests, which could be used as a prescribed fire in FDS input files to simulate smoke movement in the buildings. The average ceiling temperatures for the two tests are provided, which could be helpful for the design of active or passive fire protection system.

FDS Modelling:

10. Two virtual fuels were designed and used to define two groups of materials or fuels, which had different density and heat of combustion. Their material and thermal properties were provided.
11. The sensitivity of different gaseous fuels was checked by using PROPANE and POLYURETHANE. Two different fuel layouts were used to simulate the 1st fire test, and the simulation results of heat release rate, temperature, and gas concentration were used to compare with experimental data. The simulation using PROPANE gaseous fuel and solid fuel layout 2 had a better prediction in the early stage of the fire development. Different values of REFERENCE_RATE were used to check the sensitivity.
12. A third fuel layout was used to simulate the 2nd fire test. The simulation with PROPANE had a better heat release rate prediction than that with POLYURETHANE in the early stage of the fire development.

This study provides the data obtained from field survey and full-scale fire tests, which will be useful for fire protection engineers to conduct performance-based design. A

simplified approach of using two virtual fuels in FDS simulation had a good prediction in the early stages of the fires. The predicted heat release rate curves can be checked and verified using the data from literature. The modified heat release rate curve can be prescribed in FDS input files to model the smoke movement in the buildings.

6.2 Recommendations for future work

Fire load survey is a tedious and time-consuming work. The survey has been conducted in a wide range of motels and hotels, but some of the categories may not have enough samples due to the difficulty to get the permission to access. The surveyed values of fire load density may change by regions and countries. A round-robin exercise to conduct fire load survey in different countries would be valuable.

For experimental tests, a larger size test room with two double beds is recommended to be used for further research. It will be interesting to see if the two vertical zones still appear in the fire development, when similar furniture layouts are used.

To predict a fire in a room with ordinary furniture is one of the most challenging applications for FDS, due to many unknown parameters, and the sensitivity of the parameters. Using two virtual fuels to predict the room fires provides a simplified approach in FDS application. For different room use and different building categories, the material and thermal properties of the two virtual fuels need to be identified by comparing with the experimental data.

Tests can be conducted with different ventilation openings to cover the range of openings obtained by the survey.

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Appendices:

Appendix A: Big Hotel Fires

Table A-1 Big hotel fires in history (modified from [67])

Year	Hotel	Country	Life Loss	Injured	Damage
2006	Hotel Fire in Downtown Reno	USA	12	31	
2006	Five victims in NE China	China	5		
2006	Hotel Fire in Atlanta	USA	1	12	
2005	Disneyland hotel	USA			
2005	Hilton New York hotel	USA		33	
2005	Paris Hotel Fire	France	20	50	
2005	Grandview Inn	USA,Ohio			
2005	Williamsburg hotel	USA			
2005	Fredericktown hotel	USA			
2005	Schloss Elmau -Bavaria	Germany			
2005	Richmond hotel	Canada	1	14	
2005	Lakeview Hotel	CBC	5		
2005	Riverside Tower Hotel	USA	6		
2005	Park Hotel, Broxton	USA			
2004	Sheraton Hotel Fire	USA			
2004	Jinja Hotel Fire	Uganda			\$15
2004	Westin Hotel Fire	USA			
2004	San Diego Hotel fire	USA	1	17	\$1 M
2004	Houston Hotel Fire	USA			
2004	Maui Hotel Fire. Hawaii	USA			\$1 M
2004	Osceola County Hotel .Florida	USA			
2004	Parco dei Principi Hotel ,Rome	Italy	3		
2004	Provincial Hotel Fire .Gananoque	Canada		1	\$ 0.5 M
2004	Luoyang hotel fire	China	7	17	
2004	Greenville Hotel	USA	6		
2003	Canadian Hotel Fire	Canada			

2003	Rand Inn International Hotel	South Africa	6	67	
2003	Tiantan Hotel	Beijing,China	33	16	
2002	Çiragan Palace Hotel Kempinski,Ist	Turkey			
2002	Marriott's Grand Hotel,Alabama	USA			\$40 million.
2002	Oklahoma City Hotel	USA			\$1 million
2002	Redding Hotel,San Francisco	USA			\$3.5 million
2002	Sunset Hotel ,San Bernardino	USA,Ca	4	18	\$150,000
2002	Pretoria	South Africa	2	20	
2002	Days Inn Hotel ,Wisconsin	USA			\$1 million
2001	Holiday Inn,Kansas City International	USA	4		\$35,000
2001	Palomar Hotel	USA,La	2	6	
2001	Louvre,Paris	France	4	18	
2001	Kazakhstan Hotel in Alma Ata	Kazakhstan	4	14	
2001	Greater Manchester,Bolton	GB	2	6	
2001	Gold Strike Hotel-Casino,Las Vegas	USA			\$30 million
2001	Manor Hotel	Philippine	70	50	
2001	South Valley Hotel	USA			\$300,000
2001	Kashmir	India	14		
2000	Childers	Australia	15		
2000	Marriott Vail Mountain Resort	USA			\$20 million
1999	West Side Transient Hotel	USA		15	
1999	Crown Plaza Hotel,Madison	USA			\$20,000
1999	Mars Hotel ,Seattle	USA			\$3 million
1999	Beijing Hotel	China	9	14	
1998	Days Inn,Oregon	USA			\$500,000
1998	Hotel Vintage Plaza,Oregon	USA			\$400,000
1997	Delta Hotel.San Fransisco	USA	6		
1997	Yanshan Hotel i,Changsha	China	30	24	
1997	Shenzen Hotel	China	29	13	
1997	Pattaya Royal Resort	Thailand	91	51	\$40 million.
1996	Tozbey Hotel,Istanbul	Turkey	18	41	
1995	St. George Hotel Fire	USA			
1994	Antwerp Switel hotel	Belgium	15	160	
1994	Hotel Wakagi	Japan	5		
1993	Paxton Hotel,Chicago	USA	19		
1990	Sheraton,Cairo	Egypt	18	70	

1990	Miami Beach Hotel	USA	9	24	
1989	Sydney	Australia	6		
1987	Ramada Inn Fire	USA	10	11	
1987	La Posada Hotel Fire Texas	USA		1	\$150,000
1986	Hotel Caledonian	Norway	14		£3.8 million
1986	Dupont Plaza Hotel	Puerto Rico	96	140	
1986	New Delhi	India	38		
1986	Daitokan Hotel	Japan	24		
1985	Regent Hotel, Manila	Philippine	17		
1984	Pusan	Japan	36		
1983	Washington Hotel, Istanbul	Turkey	38	56	
1982	Houston Hilton, Westchase	USA	12	5	
1982	Zao Kanko hotel	Japan	11		
1982	Hotel New Japan , Akasaka	Japan	33	29	3 billion yen
1981	Hilton, Las Vegas	USA	8	252	
1980	Stouffer's Inn	USA	26		
1980	Prince Hotel	Japan	44		
1980	MGM Grand Hotel, Las Vegas	USA	84	679	\$300 million
1979	Zaragoza	Spain	76		
1978	Coates House Hotel, Kansas	USA	16		
1977	Duc Del brabant Hotel, Bruxelles	Belgium	302		
1977	Beverly Hills Supper Club	USA	165	116	
1977	Hotel Polen, Amsterdam	Holland	33	21	
1974	Duluth, Minnesota	USA	4	4	
1974	Seoul	South Korea	88		
1973	Copenhagen	Danemark	35		
1972	Vendome Hotel, Boston	USA			
1971	New Orleans, Louisiana	USA	6		
1971	Taeyokale Hotel in Seoul	South Korea	166		
1970	Chicago, Illinois	USA			
1970	Pioneer Internatioanal, Tucson	USA	49	69	
1970	Ozark Hotel , Seattle	USA	19	10	
1966	The Paramount Hotel Fire	USA	11	57	
1963	Hotel Roosevelt fire	USA	22		
1960	Long Beach Hotel	USA			\$5,5 million
1946	Winecoff Hotel	USA	119		
1943	Gulf Hotel Fire	USA	55	36	
1934	Kern Hotel Fire	USA	34	44	
1909	Windsor (Williams) Hotel	USA			

Appendix B: Fire Load Survey Form

Fire Load Survey Form

Hotel/Motel: _____ Address: _____
Number of Rooms: _____ Building Age: _____
Number of Floors: _____ Survey Date: _____
Survey Room: _____ Surveyor: _____

1. Room Dimensions:

Rooms	L1 (m)	W 1(m)	L2 (m)	W2 (m)	H (m)	Area (m ²)
Bedroom-1						
Bedroom-2						
Living room						
Bathroom						
Kitchen						

2. Opening Dimensions:

Openings	W (m)	H (m)	H ₀ (m)	Area (m ²)
Window-1				
Window-2				
Door-1				
Door-2				

H₀: height from floor to the bottom of windows, doors.

3. Floor Plan:

4. Fixed fire load: (all combustibles in or on the walls, floor and ceiling)

Combustibles	No	Yes, Qty	L (m)	W (m)	H (m)	Material	Mass(kg)
Extension Cords							
Window Frames							
Door Frames							
Doors							
Wall Lining							
Wall Decoration							
Cupboards							
Bookshelves							
Floor Covering							
Telephones							

5. Moveable Fire Load: (all items that are brought into the compartment)

Furniture:	No	Yes, Qty	L (m)	W (m)	H (m)	Material	Mass(kg)
Double Beds							
Single Beds							
Double Bed Frame							
Single Bed Frame							
Mattresses--1							
Mattresses--2							
Mattresses Boxes							
Nightstands							
Sofas							
Tables							
Desks--1							
Desks--2							
Chairs--1							
Chairs--2							
Chairs--3							
Chests							

Dressers							
Cabinets--1							
Cabinets--2							

Bedding:	No	Yes, Qty	L (m)	W (m)	H (m)	Material	Mass(kg)
Quilts							
Pillows							
Sheets							
Bed Covers							
Blankets							

Electronics:	No	Yes, Qty	L (m)	W (m)	H (m)	Material	Mass(kg)
Televisions							
Computers							
CD/DVD							
Refrigerators							
Coffee Makers							
Microwaves							

Others:	No	Yes, Qty	L (m)	W (m)	H (m)	Material	Mass(kg)
Papers/Books							
Curtains							
Cover of Lamps							
Frame of Pictures							
Rubbish Bins							

Appendix C: Assumptions for fire load calculation

Table C-1 Calorific value of different materials

Items	H _c	Unit	Reference
Wood	18.6	MJ/Kg	[35]
Plastic	22.1	MJ/Kg	[35]
Textile	18.8	MJ/Kg	[60]
Paper	17	MJ/Kg	[35], [60]
Leather	19	MJ/Kg	[35], [60]
Mattress	35.9	MJ/Kg	Calculated from [38]
Sofa	18.9	MJ/Kg	[60]
Carpet (wool)	23	MJ/Kg	[60]
Carpet (PU))	36	MJ/Kg	Calculated from [38]

Table C-2 Electronics or items containing plastics

Items	Value	Unit	Reference
Extension Cords	0.03	Kg/m	Lab results 2007
Television	10.2	Kg/piece	[60]
Data projector	1	Kg/piece	estimated
DVD player	1	Kg/piece	estimated
Computer	3	Kg/piece	[60]
Keyboard	0.5	Kg/piece	estimated
Air Conditioner	1	Kg/piece	estimated
Fridge---1 door	10	Kg/piece	[60]
Fridge---2 door	15	Kg/piece	estimated
Coffee Makers	1	Kg/piece	[60]
Microwaves	1	Kg/piece	[60]
Dish Washers	5	Kg/piece	[60]
Hairdryers---small	0.4	Kg/piece	weighted
Hairdryers---large	1.5	Kg/piece	[60]
Alarm Clock	0.5	Kg/piece	estimated

Telephone	0.5	Kg/piece	estimated
Lamp shade	0.3	Kg/piece	estimated
Cloth hangers (plastic)	0.05	Kg/piece	weighted
Wastebasket	0.7	Kg/piece	weighted
Ice container	0.5	Kg/piece	estimated

Table C-3 Density of wood and mass of furniture or other items

Items	Value	Unit	Reference
wood density	550	Kg/m ³	estimated
Thickness of hardwood floor	0.02	m	estimated
Sofa Stud	15	Kg/piece	estimated
Sofa--1 seat	25	Kg/piece	[60]
Sofa--2 seat	35	Kg/piece	estimated ^a
Sofa--3 seat	50	Kg/piece	estimated ^a
Frame of Pictures (small)	2	Kg/piece	estimated
Frame of Pictures (large)	4	Kg/piece	[38]
Frame of Mirrors	3	Kg/piece	estimated
Trees (small)	2	Kg/piece	estimated
Trees (medium)	4	Kg/piece	estimated
Christmas Trees (regular)	7	Kg/piece	[60]
cloth hangers (wood)	0.16	Kg/piece	weighted

^a estimated by reference of item weights obtained from Internet

Table C-4 Mass of textile and leather

Items	Value	Unit	Reference
Carpet	1	Kg/m ²	[38], [60]
Quilts (small)	2	Kg/piece	weighted
Quilts (medium)	4	Kg/piece	estimated
Quilts (large)	6.4	Kg/piece	weighted
Pillows	0.8	Kg/piece	weighted
Sheets	1	Kg/piece	weighted
Bed Covers	3	Kg/piece	weighted
Blankets	1.5	Kg/piece	weighted
Mattress Cover	1.2	Kg/piece	weighted
Mattress box Cover	1	Kg/piece	weighted
Curtains	0.5	Kg/m ²	estimated
Curtain--Silk	0.1	Kg/m ²	estimated
Towel (small)	0.2	Kg/piece	weighted
Towel (large)	0.5	Kg/piece	weighted
Bath gown	1	Kg/piece	estimated
Chair (leather)	18	Kg/piece	estimated ^a
Brochures (Leather)	0.5	Kg/piece	weighted

^a estimated by reference of item weights obtained from Internet

Table C-5 Mass of paper

Items	Value	Unit	Reference
Wall Paper	0.5	Kg/m ²	estimated
Telephone books	1.5	Kg/piece	weighted
Brochures (paper)	0.3	Kg/piece	weighted
Newspaper	0.2	Kg/piece	estimated

Appendix D: Calibration of the ultrasonic measuring device

Table D Calibration test on the ultrasonic measuring device

Tape Rule (m)	Ultrasonic Measuring Tool (m)				Difference (m)	Accuracy (%)
	Wall 1	Wall 2	Wall 3	Average		
0.6	0.6	0.61	0.6	0.603	0.003	0.556
1.0	1.00	1.01	1.01	1.007	0.007	0.667
1.5	1.52	1.5	1.51	1.510	0.010	0.667
2.0	2.02	2.01	2.02	2.017	0.017	0.833
2.5	2.52	2.52	2.52	2.520	0.020	0.800
3.0	3.02	3.01	3.02	3.017	0.017	0.556
3.5	3.53	3.51	3.53	3.523	0.023	0.667
4.0	4.04	4.03	4.03	4.033	0.033	0.833
4.5	4.53	4.51	4.52	4.520	0.020	0.444
5.0	5.03	5.03	5.02	5.027	0.027	0.533
5.5	5.55	5.53		5.540	0.040	0.727
6.0	6.04	6.02		6.030	0.030	0.500
6.5	6.55	6.52		6.535	0.035	0.538
7.0	7.04	7.02		7.030	0.030	0.429
7.5	7.54	7.52		7.530	0.030	0.400
8.0	8.05	8.03		8.040	0.040	0.500
8.5	8.53	8.54		8.535	0.035	0.412
9.0	9.02	9.05		9.035	0.035	0.389

Appendix E: FDS (Version 5.2.0) Input Files

E-1: Propane gaseous fuel and virtual fuel layout 1

```
&HEAD CHID='2VF-PA-Layout1', TITLE='Hotel Room Fire Test, Test 1, FDS version 5' /

&MESH IJK=38,44,24, XB=0.0,3.8,0.0,4.4,0.0,2.4 /

&TIME T_END=1800 /

&MISC SURF_DEFAULT='WALL', /

&REAC ID      = 'PROPANE'
  FYI         = 'C_3_H_8'
  SOOT_YIELD   = 0.01
  C           = 3
  H           = 8 /

&SURF ID='BURNER', HRRPUA=1000., RAMP_Q='fireramp', PART_ID='smoke',
COLOR='RASPBERRY' /

&RAMP ID='fireramp', T=0.0, F=0.0/
&RAMP ID='fireramp', T=1.0, F=1/
&RAMP ID='fireramp', T=310.0, F=1/
&RAMP ID='fireramp', T=311.0, F=0.0/

&MATL ID      = 'VF_1'
  FYI          = 'Carleton U.'
  SPECIFIC_HEAT = 1.0
  CONDUCTIVITY  = 0.1
  DENSITY       = 25.0
  N_REACTIONS   = 1
  NU_FUEL       = 1.
  REFERENCE_TEMPERATURE = 280.
  REFERENCE_RATE   = 0.05
  HEAT_OF_REACTION  = 1500.
  HEAT_OF_COMBUSTION = 35000. /

&MATL ID      = 'VF_2'
  FYI          = 'Carleton U.'
  SPECIFIC_HEAT = 1.5
  CONDUCTIVITY  = 0.1
  DENSITY       = 450.0
  N_REACTIONS   = 1
  NU_FUEL       = 1.
  REFERENCE_TEMPERATURE = 320.
```



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REFERENCE_RATE      = 0.005
HEAT_OF_REACTION    = 1500.
HEAT_OF_COMBUSTION   = 18000. /

&MATL ID            = 'GYPSUM PLASTER'
FYI                 = 'Quintiere, Fire Behavior'
CONDUCTIVITY        = 0.48
SPECIFIC_HEAT       = 0.84
DENSITY             = 1440. /

&MATL ID            = 'CARPET PILE'
FYI                 = 'FDS5 example data & FDS4 Ohlemiller cone data'
CONDUCTIVITY        = 0.16
SPECIFIC_HEAT       = 2.0
DENSITY             = 750.
N_REACTIONS         = 1
NU_FUEL             = 1.
REFERENCE_TEMPERATURE = 290.
HEAT_OF_COMBUSTION   = 22300.
HEAT_OF_REACTION    = 2000. /

&SURF ID            = 'FF'
COLOR               = 'CADET BLUE'
BURN_AWAY           = .TRUE.
MATL_ID             = 'VF_1'
THICKNESS           = 0.1
PART_ID             = 'smoke' /

&SURF ID            = 'WPFF'
COLOR               = 'CHOCOLATE'
BURN_AWAY           = .TRUE.
MATL_ID             = 'VF_2'
THICKNESS           = 0.02
PART_ID             = 'smoke' /

&SURF ID            = 'WALL'
RGB                 = 200,200,200
MATL_ID             = 'GYPSUM PLASTER'
THICKNESS           = 0.012 /

&SURF ID            = 'CARPET'
MATL_ID             = 'CARPET PILE'
COLOR               = 'KHAKI 3'
BACKING             = 'INSULATED'
THICKNESS           = 0.006
BURN_AWAY           = .TRUE. /

&PART ID='smoke', MASSLESS=.TRUE., SAMPLING_FACTOR=1 /

&VENT XB= 1.30, 1.50, 1.50, 1.50, 0.40, 0.70, SURF_ID='BURNER' / Ignition source

&OBST XB= 0.90, 3.00, 1.50, 3.00, 0.40, 0.70 SURF_ID='FF' /

```

&OBST XB= 0.90, 3.00, 1.50, 1.60, 0.30, 0.40 SURF_ID='WPFF' /
 &OBST XB= 0.90, 3.00, 1.70, 1.80, 0.30, 0.40 SURF_ID='WPFF' /
 &OBST XB= 0.90, 3.00, 1.90, 2.00, 0.30, 0.40 SURF_ID='WPFF' /
 &OBST XB= 0.90, 3.00, 2.10, 2.20, 0.30, 0.40 SURF_ID='WPFF' /
 &OBST XB= 0.90, 3.00, 2.30, 2.40, 0.30, 0.40 SURF_ID='WPFF' /
 &OBST XB= 0.90, 3.00, 2.50, 2.60, 0.30, 0.40 SURF_ID='WPFF' /
 &OBST XB= 0.90, 3.00, 2.70, 2.80, 0.30, 0.40 SURF_ID='WPFF' /
 &OBST XB= 0.90, 3.00, 2.90, 3.00, 0.30, 0.40 SURF_ID='WPFF' /

 &OBST XB= 0.90, 1.00, 1.50, 3.00, 0.20, 0.30 SURF_ID='WPFF' /
 &OBST XB= 1.10, 1.20, 1.50, 3.00, 0.20, 0.30 SURF_ID='WPFF' /
 &OBST XB= 1.30, 1.40, 1.50, 3.00, 0.20, 0.30 SURF_ID='WPFF' /
 &OBST XB= 1.50, 1.60, 1.50, 3.00, 0.20, 0.30 SURF_ID='WPFF' /
 &OBST XB= 1.70, 1.80, 1.50, 3.00, 0.20, 0.30 SURF_ID='WPFF' /
 &OBST XB= 1.90, 2.00, 1.50, 3.00, 0.20, 0.30 SURF_ID='WPFF' /
 &OBST XB= 2.10, 2.20, 1.50, 3.00, 0.20, 0.30 SURF_ID='WPFF' /
 &OBST XB= 2.30, 2.40, 1.50, 3.00, 0.20, 0.30 SURF_ID='WPFF' /
 &OBST XB= 2.50, 2.60, 1.50, 3.00, 0.20, 0.30 SURF_ID='WPFF' /
 &OBST XB= 2.70, 2.80, 1.50, 3.00, 0.20, 0.30 SURF_ID='WPFF' /
 &OBST XB= 2.90, 3.00, 1.50, 3.00, 0.20, 0.30 SURF_ID='WPFF' /

 &OBST XB= 0.90, 3.00, 1.50, 1.60, 0.10, 0.20 SURF_ID='WPFF' /
 &OBST XB= 0.90, 3.00, 1.70, 1.80, 0.10, 0.20 SURF_ID='WPFF' /
 &OBST XB= 0.90, 3.00, 1.90, 2.00, 0.10, 0.20 SURF_ID='WPFF' /
 &OBST XB= 0.90, 3.00, 2.10, 2.20, 0.10, 0.20 SURF_ID='WPFF' /
 &OBST XB= 0.90, 3.00, 2.30, 2.40, 0.10, 0.20 SURF_ID='WPFF' /
 &OBST XB= 0.90, 3.00, 2.50, 2.60, 0.10, 0.20 SURF_ID='WPFF' /
 &OBST XB= 0.90, 3.00, 2.70, 2.80, 0.10, 0.20 SURF_ID='WPFF' /
 &OBST XB= 0.90, 3.00, 2.90, 3.00, 0.10, 0.20 SURF_ID='WPFF' /

 &OBST XB= 0.90, 1.00, 1.50, 3.00, 0.00, 0.10 SURF_ID='WPFF' /
 &OBST XB= 1.50, 1.60, 1.50, 3.00, 0.00, 0.10 SURF_ID='WPFF' /
 &OBST XB= 2.30, 2.40, 1.50, 3.00, 0.00, 0.10 SURF_ID='WPFF' /
 &OBST XB= 2.90, 3.00, 1.50, 3.00, 0.00, 0.10 SURF_ID='WPFF' /

 &OBST XB= 0.00, 3.80, 0.10, 0.20, 0.00, 2.40 / Front wall
 &HOLE XB= 1.15, 2.65, 0.11, 0.21, 0.50, 2.00 / Window

 &VENT MB='YMIN',SURF_ID='OPEN' /
 &VENT XB=0.00,3.80,0.20,4.40,0.00,0.00, SURF_ID='CARPET' /

 &DEVC XYZ=1.0,3.4,1.5, QUANTITY='carbon dioxide' ID='CO2-Top'/
 &DEVC XYZ=1.0,3.4,0.4, QUANTITY='carbon dioxide' ID='CO2-Bottom'/

 &DEVC XYZ=1.0,3.4,1.5, QUANTITY='carbon monoxide' ID='CO-Top'/
 &DEVC XYZ=1.0,3.4,0.4, QUANTITY='carbon monoxide' ID='CO-Bottom'/

 &DEVC XYZ=1.0,3.4,1.5, QUANTITY='oxygen' ID='O2-Top'/
 &DEVC XYZ=1.0,3.4,0.4, QUANTITY='oxygen' ID='O2-Bottom'/

 &DEVC XYZ=0.3,3.9,2.3, QUANTITY='TEMPERATURE' ID='TC-NW Corner'/

```

&DEVC XYZ=0.3,3.9,1.9, QUANTITY='TEMPERATURE' ID='TC-NW Corner'/
&DEVC XYZ=0.3,3.9,1.4, QUANTITY='TEMPERATURE' ID='TC-NW Corner'/
&DEVC XYZ=0.3,3.9,0.9, QUANTITY='TEMPERATURE' ID='TC-NW Corner'/
&DEVC XYZ=0.3,3.9,0.4, QUANTITY='TEMPERATURE' ID='TC-NW Corner'/

&DEVC XYZ=1.9,2.3,2.3, QUANTITY='TEMPERATURE' ID='TC-CC'/middle of room

&TAIL /

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E-2: Propane gaseous fuel and virtual fuel layout 2

```

&HEAD CHID='2VF-PA-Layout2', TITLE='Hotel Room Fire Test, Test 1, FDS version 5' /

&MESH IJK=38,44,24, XB=0.0,3.8,0.0,4.4,0.0,2.4 /

&TIME T_END=1800 /

&MISC SURF_DEFAULT='WALL', /

&REAC ID      = 'PROPANE'
  FYI         = 'C_3 H_8'
  SOOT_YIELD   = 0.01
  C           = 3
  H           = 8 /

&SURF ID='BURNER',   HRRPUA=1000.,   RAMP_Q='fireramp',   PART_ID='smoke',
COLOR='RASPBERRY' /

&RAMP ID='fireramp', T=0.0, F=0.0/
&RAMP ID='fireramp', T=1.0, F=1/
&RAMP ID='fireramp', T=310.0, F=1/
&RAMP ID='fireramp', T=311.0, F=0.0/

&MATL ID      = 'VF_1'
  FYI          = 'Carleton U.'
  SPECIFIC_HEAT = 1.0
  CONDUCTIVITY  = 0.1
  DENSITY       = 25.0
  N_REACTIONS   = 1
  NU_FUEL       = 1.
  REFERENCE_TEMPERATURE = 280.
  REFERENCE_RATE   = 0.05
  HEAT_OF_REACTION  = 1500.
  HEAT_OF_COMBUSTION = 35000. /

&MATL ID      = 'VF_2'
  FYI          = 'Carleton U.'
  SPECIFIC_HEAT = 1.5
  CONDUCTIVITY  = 0.1
  DENSITY       = 450.0

```

```

N_REACTIONS      = 1
NU_FUEL          = 1.
REFERENCE_TEMPERATURE = 320.
REFERENCE_RATE    = 0.005
HEAT_OF_REACTION  = 1500.
HEAT_OF_COMBUSTION = 18000. /

&MATL ID          = 'GYPSUM PLASTER'
FYI               = 'Quintiere, Fire Behavior'
CONDUCTIVITY      = 0.48
SPECIFIC_HEAT     = 0.84
DENSITY           = 1440. /

&MATL ID          = 'CARPET PILE'
FYI               = 'FDS5 example data & FDS4 Ohlemiller cone data'
CONDUCTIVITY      = 0.16
SPECIFIC_HEAT     = 2.0
DENSITY           = 750.
N_REACTIONS      = 1
NU_FUEL          = 1.
REFERENCE_TEMPERATURE = 290.
HEAT_OF_COMBUSTION = 22300.
HEAT_OF_REACTION  = 2000. /

&SURF ID          = 'FF'
COLOR             = 'CADET BLUE'
BURN_AWAY         = .TRUE.
MATL_ID           = 'VF_1'
THICKNESS         = 0.1
PART_ID           = 'smoke' /

&SURF ID          = 'WPFF'
COLOR             = 'CHOCOLATE'
BURN_AWAY         = .TRUE.
MATL_ID           = 'VF_2'
THICKNESS         = 0.02
PART_ID           = 'smoke' /

&SURF ID          = 'WALL'
RGB               = 200,200,200
MATL_ID           = 'GYPSUM PLASTER'
THICKNESS         = 0.012 /

&SURF ID          = 'CARPET'
MATL_ID           = 'CARPET PILE'
COLOR             = 'KHAKI 3'
BACKING           = 'INSULATED'
THICKNESS         = 0.006
BURN_AWAY         = .TRUE. /

&PART ID='smoke', MASSLESS=.TRUE., SAMPLING_FACTOR=1 /

```

&VENT XB= 1.30, 1.50, 1.50, 1.50, 0.40, 0.70, SURF_ID='BURNER' / Ignition source

&OBST XB= 0.10, 2.20, 1.50, 3.00, 0.40, 0.70 SURF_ID='FF' /

&OBST XB= 0.10, 2.20, 1.50, 1.60, 0.30, 0.40 SURF_ID='WPFF' /

&OBST XB= 0.10, 2.20, 1.70, 1.80, 0.30, 0.40 SURF_ID='WPFF' /

&OBST XB= 0.10, 2.20, 1.90, 2.00, 0.30, 0.40 SURF_ID='WPFF' /

&OBST XB= 0.10, 2.20, 2.10, 2.20, 0.30, 0.40 SURF_ID='WPFF' /

&OBST XB= 0.10, 2.20, 2.30, 2.40, 0.30, 0.40 SURF_ID='WPFF' /

&OBST XB= 0.10, 2.20, 2.50, 2.60, 0.30, 0.40 SURF_ID='WPFF' /

&OBST XB= 0.10, 2.20, 2.70, 2.80, 0.30, 0.40 SURF_ID='WPFF' /

&OBST XB= 0.10, 2.20, 2.90, 3.00, 0.30, 0.40 SURF_ID='WPFF' /

&OBST XB= 2.90, 3.00, 1.30, 3.30, 0.00, 0.10 SURF_ID='WPFF' /

&OBST XB= 3.70, 3.80, 1.30, 3.30, 0.00, 0.10 SURF_ID='WPFF' /

&OBST XB= 3.00, 3.10, 1.30, 3.30, 0.10, 0.20 SURF_ID='WPFF' /

&OBST XB= 3.20, 3.30, 1.30, 3.30, 0.10, 0.20 SURF_ID='WPFF' /

&OBST XB= 3.40, 3.50, 1.30, 3.30, 0.10, 0.20 SURF_ID='WPFF' /

&OBST XB= 3.60, 3.70, 1.30, 3.30, 0.10, 0.20 SURF_ID='WPFF' /

&OBST XB= 2.90, 3.00, 1.30, 3.30, 0.20, 0.30 SURF_ID='WPFF' /

&OBST XB= 3.10, 3.20, 1.30, 3.30, 0.20, 0.30 SURF_ID='WPFF' /

&OBST XB= 3.30, 3.40, 1.30, 3.30, 0.20, 0.30 SURF_ID='WPFF' /

&OBST XB= 3.50, 3.60, 1.30, 3.30, 0.20, 0.30 SURF_ID='WPFF' /

&OBST XB= 3.70, 3.80, 1.30, 3.30, 0.20, 0.30 SURF_ID='WPFF' /

&OBST XB= 3.00, 3.10, 1.30, 3.30, 0.30, 0.40 SURF_ID='WPFF' /

&OBST XB= 3.20, 3.30, 1.30, 3.30, 0.30, 0.40 SURF_ID='WPFF' /

&OBST XB= 3.40, 3.50, 1.30, 3.30, 0.30, 0.40 SURF_ID='WPFF' /

&OBST XB= 3.60, 3.70, 1.30, 3.30, 0.30, 0.40 SURF_ID='WPFF' /

&OBST XB= 2.90, 3.00, 1.30, 3.30, 0.40, 0.50 SURF_ID='WPFF' /

&OBST XB= 3.10, 3.20, 1.30, 3.30, 0.40, 0.50 SURF_ID='WPFF' /

&OBST XB= 3.30, 3.40, 1.30, 3.30, 0.40, 0.50 SURF_ID='WPFF' /

&OBST XB= 3.50, 3.60, 1.30, 3.30, 0.40, 0.50 SURF_ID='WPFF' /

&OBST XB= 3.70, 3.80, 1.30, 3.30, 0.40, 0.50 SURF_ID='WPFF' /

&OBST XB= 0.00, 3.80, 0.10, 0.20, 0.00, 2.40 / Front wall

&HOLE XB= 1.15, 2.65, 0.11, 0.21, 0.50, 2.00 / Window

&VENT MB='YMIN',SURF_ID='OPEN' /

&VENT XB=0.00,3.80,0.20,4.40,0.00,0.00, SURF_ID='CARPET' /

&DEVC XYZ=1.0,3.4,1.5, QUANTITY='carbon dioxide' ID='CO2-Top' /

&DEVC XYZ=1.0,3.4,0.4, QUANTITY='carbon dioxide' ID='CO2-Bottom' /

&DEVC XYZ=1.0,3.4,1.5, QUANTITY='carbon monoxide' ID='CO-Top' /

&DEVC XYZ=1.0,3.4,0.4, QUANTITY='carbon monoxide' ID='CO-Bottom' /

&DEVC XYZ=1.0,3.4,1.5, QUANTITY='oxygen' ID='O2-Top' /

&DEVC XYZ=1.0,3.4,0.4, QUANTITY='oxygen' ID='O2-Bottom' /

```

&DEVC XYZ=0.3,3.9,2.3, QUANTITY='TEMPERATURE' ID='TC-NW Corner'/
&DEVC XYZ=0.3,3.9,1.9, QUANTITY='TEMPERATURE' ID='TC-NW Corner'/
&DEVC XYZ=0.3,3.9,1.4, QUANTITY='TEMPERATURE' ID='TC-NW Corner'/
&DEVC XYZ=0.3,3.9,0.9, QUANTITY='TEMPERATURE' ID='TC-NW Corner'/
&DEVC XYZ=0.3,3.9,0.4, QUANTITY='TEMPERATURE' ID='TC-NW Corner'/

&DEVC XYZ=1.9,2.3,2.3, QUANTITY='TEMPERATURE' ID='TC-CC'/middle of room

&TAIL /

```

E-3: Polyurethane gaseous fuel and virtual fuel layout 1

```

&HEAD CHID='2VF-PU-Layout1', TITLE='Hotel Room Fire Test, Test 1, FDS version 5' /

&MESH IJK=38,44,24, XB=0.0,3.8,0.0,4.4,0.0,2.4 /

&TIME T_END=1800 /

&MISC SURF_DEFAULT='WALL', /

&REAC ID      = 'POLYURETHANE'
  FYI         = 'C_6.3 H_7.1 N_O_2.1, NFPA Handbook, Babrauskas'
  SOOT_YIELD   = 0.10
  N            = 1.0
  C            = 6.3
  H            = 7.1
  O            = 2.1 /

  &SURF ID='BURNER',   HRRPUA=1000.,   RAMP_Q='fireramp',   PART_ID='smoke',
  COLOR='RASPBERRY' /

  &RAMP ID='fireramp', T=0.0, F=0.0/
  &RAMP ID='fireramp', T=1.0, F=1/
  &RAMP ID='fireramp', T=310.0, F=1/
  &RAMP ID='fireramp', T=311.0, F=0.0/

&MATL ID      = 'VF_1'
  FYI          = 'Carleton U.'
  SPECIFIC_HEAT = 1.0
  CONDUCTIVITY  = 0.1
  DENSITY       = 25.0
  N_REACTIONS   = 1
  NU_FUEL       = 1.
  REFERENCE_TEMPERATURE = 280.
  REFERENCE_RATE   = 0.05
  HEAT_OF_REACTION  = 1500.
  HEAT_OF_COMBUSTION = 35000. /

```

```

&MATL ID      = 'VF_2'
  FYI          = 'Carleton U.'
  SPECIFIC_HEAT = 1.5
  CONDUCTIVITY  = 0.1
  DENSITY       = 450.0
  N_REACTIONS   = 1
  NU_FUEL       = 1.
  REFERENCE_TEMPERATURE = 320.
  REFERENCE_RATE  = 0.005
  HEAT_OF_REACTION = 1500.
  HEAT_OF_COMBUSTION = 18000. /

&MATL ID      = 'GYPSUM PLASTER'
  FYI          = 'Quintiere, Fire Behavior'
  CONDUCTIVITY = 0.48
  SPECIFIC_HEAT = 0.84
  DENSITY      = 1440. /

&MATL ID      = 'CARPET PILE'
  FYI          = 'FDS5 example data & FDS4 Ohlemiller cone data'
  CONDUCTIVITY = 0.16
  SPECIFIC_HEAT = 2.0
  DENSITY       = 750.
  N_REACTIONS   = 1
  NU_FUEL       = 1.
  REFERENCE_TEMPERATURE = 290.
  HEAT_OF_COMBUSTION = 22300.
  HEAT_OF_REACTION = 2000. /

&SURF ID      = 'FF'
  COLOR        = 'CADET BLUE'
  BURN_AWAY    = .TRUE.
  MATL_ID      = 'VF_1'
  THICKNESS    = 0.1
  PART_ID      = 'smoke' /

&SURF ID      = 'WPFF'
  COLOR        = 'CHOCOLATE'
  BURN_AWAY    = .TRUE.
  MATL_ID      = 'VF_2'
  THICKNESS    = 0.02
  PART_ID      = 'smoke' /

&SURF ID      = 'WALL'
  RGB          = 200,200,200
  MATL_ID      = 'GYPSUM PLASTER'
  THICKNESS    = 0.012 /

&SURF ID      = 'CARPET'
  MATL_ID      = 'CARPET PILE'

```

COLOR = 'KHAKI 3'
 BACKING = 'INSULATED'
 THICKNESS = 0.006
 BURN_AWAY=.TRUE. /

&PART ID='smoke', MASSLESS=.TRUE., SAMPLING_FACTOR=1 /

&VENT XB= 1.30, 1.50, 1.50, 1.50, 0.40, 0.70, SURF_ID='BURNER' / Ignition source

&OBST XB= 0.90, 3.00, 1.50, 3.00, 0.40, 0.70 SURF_ID='FF' /

&OBST XB= 0.90, 3.00, 1.50, 1.60, 0.30, 0.40 SURF_ID='WPFF' /
 &OBST XB= 0.90, 3.00, 1.70, 1.80, 0.30, 0.40 SURF_ID='WPFF' /
 &OBST XB= 0.90, 3.00, 1.90, 2.00, 0.30, 0.40 SURF_ID='WPFF' /
 &OBST XB= 0.90, 3.00, 2.10, 2.20, 0.30, 0.40 SURF_ID='WPFF' /
 &OBST XB= 0.90, 3.00, 2.30, 2.40, 0.30, 0.40 SURF_ID='WPFF' /
 &OBST XB= 0.90, 3.00, 2.50, 2.60, 0.30, 0.40 SURF_ID='WPFF' /
 &OBST XB= 0.90, 3.00, 2.70, 2.80, 0.30, 0.40 SURF_ID='WPFF' /
 &OBST XB= 0.90, 3.00, 2.90, 3.00, 0.30, 0.40 SURF_ID='WPFF' /

&OBST XB= 0.90, 1.00, 1.50, 3.00, 0.20, 0.30 SURF_ID='WPFF' /
 &OBST XB= 1.10, 1.20, 1.50, 3.00, 0.20, 0.30 SURF_ID='WPFF' /
 &OBST XB= 1.30, 1.40, 1.50, 3.00, 0.20, 0.30 SURF_ID='WPFF' /
 &OBST XB= 1.50, 1.60, 1.50, 3.00, 0.20, 0.30 SURF_ID='WPFF' /
 &OBST XB= 1.70, 1.80, 1.50, 3.00, 0.20, 0.30 SURF_ID='WPFF' /
 &OBST XB= 1.90, 2.00, 1.50, 3.00, 0.20, 0.30 SURF_ID='WPFF' /
 &OBST XB= 2.10, 2.20, 1.50, 3.00, 0.20, 0.30 SURF_ID='WPFF' /
 &OBST XB= 2.30, 2.40, 1.50, 3.00, 0.20, 0.30 SURF_ID='WPFF' /
 &OBST XB= 2.50, 2.60, 1.50, 3.00, 0.20, 0.30 SURF_ID='WPFF' /
 &OBST XB= 2.70, 2.80, 1.50, 3.00, 0.20, 0.30 SURF_ID='WPFF' /
 &OBST XB= 2.90, 3.00, 1.50, 3.00, 0.20, 0.30 SURF_ID='WPFF' /

&OBST XB= 0.90, 3.00, 1.50, 1.60, 0.10, 0.20 SURF_ID='WPFF' /
 &OBST XB= 0.90, 3.00, 1.70, 1.80, 0.10, 0.20 SURF_ID='WPFF' /
 &OBST XB= 0.90, 3.00, 1.90, 2.00, 0.10, 0.20 SURF_ID='WPFF' /
 &OBST XB= 0.90, 3.00, 2.10, 2.20, 0.10, 0.20 SURF_ID='WPFF' /
 &OBST XB= 0.90, 3.00, 2.30, 2.40, 0.10, 0.20 SURF_ID='WPFF' /
 &OBST XB= 0.90, 3.00, 2.50, 2.60, 0.10, 0.20 SURF_ID='WPFF' /
 &OBST XB= 0.90, 3.00, 2.70, 2.80, 0.10, 0.20 SURF_ID='WPFF' /
 &OBST XB= 0.90, 3.00, 2.90, 3.00, 0.10, 0.20 SURF_ID='WPFF' /

&OBST XB= 0.90, 1.00, 1.50, 3.00, 0.00, 0.10 SURF_ID='WPFF' /
 &OBST XB= 1.50, 1.60, 1.50, 3.00, 0.00, 0.10 SURF_ID='WPFF' /
 &OBST XB= 2.30, 2.40, 1.50, 3.00, 0.00, 0.10 SURF_ID='WPFF' /
 &OBST XB= 2.90, 3.00, 1.50, 3.00, 0.00, 0.10 SURF_ID='WPFF' /

&OBST XB= 0.00, 3.80, 0.10, 0.20, 0.00, 2.40 / Front wall
 &HOLE XB= 1.15, 2.65, 0.11, 0.21, 0.50, 2.00 / Window

&VENT MB='YMIN',SURF_ID='OPEN' /
 &VENT XB=0.00,3.80,0.20,4.40,0.00,0.00, SURF_ID='CARPET' /


```

&DEVC XYZ=1.0,3.4,1.5, QUANTITY='carbon dioxide' ID='CO2-Top'/
&DEVC XYZ=1.0,3.4,0.4, QUANTITY='carbon dioxide' ID='CO2-Bottom'/

&DEVC XYZ=1.0,3.4,1.5, QUANTITY='carbon monoxide' ID='CO-Top'/
&DEVC XYZ=1.0,3.4,0.4, QUANTITY='carbon monoxide' ID='CO-Bottom'/

&DEVC XYZ=1.0,3.4,1.5, QUANTITY='oxygen' ID='O2-Top'/
&DEVC XYZ=1.0,3.4,0.4, QUANTITY='oxygen' ID='O2-Bottom'/

&DEVC XYZ=0.3,3.9,2.3, QUANTITY='TEMPERATURE' ID='TC-NW Corner'/
&DEVC XYZ=0.3,3.9,1.9, QUANTITY='TEMPERATURE' ID='TC-NW Corner'/
&DEVC XYZ=0.3,3.9,1.4, QUANTITY='TEMPERATURE' ID='TC-NW Corner'/
&DEVC XYZ=0.3,3.9,0.9, QUANTITY='TEMPERATURE' ID='TC-NW Corner'/
&DEVC XYZ=0.3,3.9,0.4, QUANTITY='TEMPERATURE' ID='TC-NW Corner'/

&DEVC XYZ=1.9,2.3,2.3, QUANTITY='TEMPERATURE' ID='TC-CC'/middle of room

&TAIL /

```

E-4: Polyurethane gaseous fuel and virtual fuel layout 2

```

&HEAD CHID='2VF-PU-Layout2', TITLE='Hotel Room Fire Test, Test 1, FDS version 5' /

&MESH IJK=38,44,24, XB=0.0,3.8,0.0,4.4,0.0,2.4 /

&TIME T_END=1800 /

&MISC SURF_DEFAULT='WALL', /

&REAC ID      = 'POLYURETHANE'
  FYI      = 'C_6.3 H_7.1 N_O_2.1, NFPA Handbook, Babrauskas'
  SOOT_YIELD = 0.10
  N        = 1.0
  C        = 6.3
  H        = 7.1
  O        = 2.1 /

&SURF ID='BURNER', HRRPUA=1000., RAMP_Q='fireramp', PART_ID='smoke',
COLOR='RASPBERRY' /

&RAMP ID='fireramp', T=0.0, F=0.0/
&RAMP ID='fireramp', T=1.0, F=1/
&RAMP ID='fireramp', T=310.0, F=1/
&RAMP ID='fireramp', T=311.0, F=0.0/

&MATL ID      = 'VF_1'
  FYI          = 'Carleton U.'
  SPECIFIC_HEAT = 1.0

```

```

CONDUCTIVITY      = 0.1
DENSITY           = 25.0
N_REACTIONS       = 1
NU_FUEL           = 1.
REFERENCE_TEMPERATURE = 280.
REFERENCE_RATE     = 0.05
HEAT_OF_REACTION  = 1500.
HEAT_OF_COMBUSTION = 35000. /

```

```

&MATL ID          = 'VF_2'
FYI               = 'Carleton U.'
SPECIFIC_HEAT     = 1.5
CONDUCTIVITY      = 0.1
DENSITY           = 450.0
N_REACTIONS       = 1
NU_FUEL           = 1.
REFERENCE_TEMPERATURE = 320.
REFERENCE_RATE     = 0.005
HEAT_OF_REACTION  = 1500.
HEAT_OF_COMBUSTION = 18000. /

```

```

&MATL ID          = 'GYPSUM PLASTER'
FYI               = 'Quintiere, Fire Behavior'
CONDUCTIVITY      = 0.48
SPECIFIC_HEAT     = 0.84
DENSITY           = 1440. /

```

```

&MATL ID          = 'CARPET PILE'
FYI               = 'FDS5 example data & FDS4 Ohlemiller cone data'
CONDUCTIVITY      = 0.16
SPECIFIC_HEAT     = 2.0
DENSITY           = 750.
N_REACTIONS       = 1
NU_FUEL           = 1.
REFERENCE_TEMPERATURE = 290.
HEAT_OF_COMBUSTION = 22300.
HEAT_OF_REACTION  = 2000. /

```

```

&SURF ID          = 'FF'
COLOR             = 'CADET BLUE'
BURN_AWAY         = .TRUE.
MATL_ID           = 'VF_1'
THICKNESS         = 0.1
PART_ID           = 'smoke' /

```

```

&SURF ID          = 'WPFF'
COLOR             = 'CHOCOLATE'
BURN_AWAY         = .TRUE.
MATL_ID           = 'VF_2'
THICKNESS         = 0.02
PART_ID           = 'smoke' /

```

```

&SURF ID      = 'WALL'
  RGB          = 200,200,200
  MATL_ID      = 'GYPSUM PLASTER'
  THICKNESS    = 0.012 /

```

```

&SURF ID      = 'CARPET'
  MATL_ID      = 'CARPET PILE'
  COLOR        = 'KHAKI 3'
  BACKING      = 'INSULATED'
  THICKNESS    = 0.006
  BURN_AWAY    = .TRUE. /

```

```

&PART ID='smoke', MASSLESS=.TRUE., SAMPLING_FACTOR=1 /

```

```

&VENT XB= 1.30, 1.50, 1.50, 1.50, 0.40, 0.70, SURF_ID='BURNER' / Ignition source

```

```

&OBST XB= 0.10, 2.20, 1.50, 3.00, 0.40, 0.70 SURF_ID='FF' /

```

```

&OBST XB= 0.10, 2.20, 1.50, 1.60, 0.30, 0.40 SURF_ID='WPFF' /
&OBST XB= 0.10, 2.20, 1.70, 1.80, 0.30, 0.40 SURF_ID='WPFF' /
&OBST XB= 0.10, 2.20, 1.90, 2.00, 0.30, 0.40 SURF_ID='WPFF' /
&OBST XB= 0.10, 2.20, 2.10, 2.20, 0.30, 0.40 SURF_ID='WPFF' /
&OBST XB= 0.10, 2.20, 2.30, 2.40, 0.30, 0.40 SURF_ID='WPFF' /
&OBST XB= 0.10, 2.20, 2.50, 2.60, 0.30, 0.40 SURF_ID='WPFF' /
&OBST XB= 0.10, 2.20, 2.70, 2.80, 0.30, 0.40 SURF_ID='WPFF' /
&OBST XB= 0.10, 2.20, 2.90, 3.00, 0.30, 0.40 SURF_ID='WPFF' /

```

```

&OBST XB= 2.90, 3.00, 1.30, 3.30, 0.00, 0.10 SURF_ID='WPFF' /
&OBST XB= 3.70, 3.80, 1.30, 3.30, 0.00, 0.10 SURF_ID='WPFF' /

```

```

&OBST XB= 3.00, 3.10, 1.30, 3.30, 0.10, 0.20 SURF_ID='WPFF' /
&OBST XB= 3.20, 3.30, 1.30, 3.30, 0.10, 0.20 SURF_ID='WPFF' /
&OBST XB= 3.40, 3.50, 1.30, 3.30, 0.10, 0.20 SURF_ID='WPFF' /
&OBST XB= 3.60, 3.70, 1.30, 3.30, 0.10, 0.20 SURF_ID='WPFF' /

```

```

&OBST XB= 2.90, 3.00, 1.30, 3.30, 0.20, 0.30 SURF_ID='WPFF' /
&OBST XB= 3.10, 3.20, 1.30, 3.30, 0.20, 0.30 SURF_ID='WPFF' /
&OBST XB= 3.30, 3.40, 1.30, 3.30, 0.20, 0.30 SURF_ID='WPFF' /
&OBST XB= 3.50, 3.60, 1.30, 3.30, 0.20, 0.30 SURF_ID='WPFF' /
&OBST XB= 3.70, 3.80, 1.30, 3.30, 0.20, 0.30 SURF_ID='WPFF' /

```

```

&OBST XB= 3.00, 3.10, 1.30, 3.30, 0.30, 0.40 SURF_ID='WPFF' /
&OBST XB= 3.20, 3.30, 1.30, 3.30, 0.30, 0.40 SURF_ID='WPFF' /
&OBST XB= 3.40, 3.50, 1.30, 3.30, 0.30, 0.40 SURF_ID='WPFF' /
&OBST XB= 3.60, 3.70, 1.30, 3.30, 0.30, 0.40 SURF_ID='WPFF' /

```

```

&OBST XB= 2.90, 3.00, 1.30, 3.30, 0.40, 0.50 SURF_ID='WPFF' /
&OBST XB= 3.10, 3.20, 1.30, 3.30, 0.40, 0.50 SURF_ID='WPFF' /
&OBST XB= 3.30, 3.40, 1.30, 3.30, 0.40, 0.50 SURF_ID='WPFF' /
&OBST XB= 3.50, 3.60, 1.30, 3.30, 0.40, 0.50 SURF_ID='WPFF' /
&OBST XB= 3.70, 3.80, 1.30, 3.30, 0.40, 0.50 SURF_ID='WPFF' /

```

&OBST XB= 0.00, 3.80, 0.10, 0.20, 0.00, 2.40 / Front wall
 &HOLE XB= 1.15, 2.65, 0.11, 0.21, 0.50, 2.00 / Window

 &VENT MB='YMIN',SURF_ID='OPEN' /
 &VENT XB=0.00,3.80,0.20,4.40,0.00,0.00, SURF_ID='CARPET' /

 &DEVC XYZ=1.0,3.4,1.5, QUANTITY='carbon dioxide' ID='CO2-Top'/
 &DEVC XYZ=1.0,3.4,0.4, QUANTITY='carbon dioxide' ID='CO2-Bottom'/

 &DEVC XYZ=1.0,3.4,1.5, QUANTITY='carbon monoxide' ID='CO-Top'/
 &DEVC XYZ=1.0,3.4,0.4, QUANTITY='carbon monoxide' ID='CO-Bottom'/

 &DEVC XYZ=1.0,3.4,1.5, QUANTITY='oxygen' ID='O2-Top'/
 &DEVC XYZ=1.0,3.4,0.4, QUANTITY='oxygen' ID='O2-Bottom'/

 &DEVC XYZ=0.3,3.9,2.3, QUANTITY='TEMPERATURE' ID='TC-NW Corner'/
 &DEVC XYZ=0.3,3.9,1.9, QUANTITY='TEMPERATURE' ID='TC-NW Corner'/
 &DEVC XYZ=0.3,3.9,1.4, QUANTITY='TEMPERATURE' ID='TC-NW Corner'/
 &DEVC XYZ=0.3,3.9,0.9, QUANTITY='TEMPERATURE' ID='TC-NW Corner'/
 &DEVC XYZ=0.3,3.9,0.4, QUANTITY='TEMPERATURE' ID='TC-NW Corner'/

 &DEVC XYZ=1.9,2.3,2.3, QUANTITY='TEMPERATURE' ID='TC-CC'/middle of room

 &TAIL /