Study of Smoke Control in High-rise Buildings and Safe Evacuation of the Occupants

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ABSTRACT

Study of Smoke Control in High-rise Buildings and Safe Evacuation of the Occupants

Shamim Mashayekh, Jr. Eng.

Fire protection systems in high-rise buildings play an essential role in the safety of human beings. These systems are in place to control the fire, to notify the occupants in case of emergency, and to provide the necessary time for a safe evacuation. Every year many fire incidents are reported in residential high-rise buildings. As reports show, many civilians' deaths, injuries, and property loss are caused by the smoke from the fire. When a fire starts in a high-rise building, the first goal is to control the fire and to evacuate the occupants safely. Smoke control in high-rise buildings has always been a big challenge, and as the technology advances and buildings are built higher, this challenge gets even more complicated.

In the event of a fire, staircases are the main and most unique way of evacuation. New construction buildings that are designed based on the new code requirements are mostly equipped with fire protection systems such as sprinkler and standpipe systems, which provide a safer environment for occupants and fire department employees during the evacuation process. On the other hand, there are many existing buildings that do not conform to the new codes. The purpose of this research is to study the smoke control in a staircase shaft of a forty-five-story building using a pressurized system and to provide a reasonable method that can be used for both existing and new construction buildings during the evacuation process.

Using Fire Dynamic Simulation (FDS), a model of the building is prepared, and the theoretical data from the fire department is compared with the results of the smoke movements from the software. By using Pathfinder and based on the results from the fire incidents reported in high-rise buildings, the evacuation time of the same building is analyzed. The advantage of the smoke control using the ventilation system and its effect on the evacuation process is studied to prove that keeping the HVAC system in service during an emergency is necessary. Due to high cost and safety concerns, a real experiment cannot be conducted to validate the theoretical and FDS model results. For future research and as a starting point for improving the emergency planning during an evacuation in the island of Montreal, a report of these analyses is gathered and presented to SFPE chapter St-Laurent located in Quebec and the fire department staffs at Service Incendies de Montreal (SIM).

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NOMENCLATURE

CFD	Computational Fluid Dynamics
FDS	Fire Dynamics Simulation
SFPE	Society of Fire Protection Engineers
NFPA	National Fire Protection Association
NBCC	National Building Code of Canada
CFAA	Canadian Fire Alarm Association
FM	Factory Mutual (FM Global)
AHJ	Authorities Having Jurisdiction - An organization, office, or individual responsible for enforcing the requirements of a code or standard, or for approving equipment, materials, an installation, or a procedure.
SIM	Service Incendie de Montréal
PIR	Polyisocyanurate
ACM	Aluminum Composite Material
Fr	Froude number
V	Average velocity of the liquid in a channel (ft/s or m/s)
g	Acceleration due to gravity (32.17 ft/sec^2 or 9.81 m/sec^2
D	Hydraulic depth
v_T	Eddy viscosity
K_{eff}	Effective loss of duct
V_{fan}	Volume-flow for supply fan with solid boundary

P	Friction resistance (bar/m of pipe)
Q	Flow (L/min)
C	Friction loss coefficient
d_m	Actual internal diameter (mm)
K_n	Equivalent K at a node
P	Pressure at the node
Z_s	Smoke layer height
ΔP	Pressure difference

1. INTRODUCTION

1.1 Background

In the field of fire protection, there are some key variables that shall be considered in reviewing statistics. These variables are the year of construction, property classification, construction material, source of ignition, and distance from the closest full-time or part-time fire department station.

Fire is one of the most common threats to humans and their surroundings. Accidental fires, which are the main topic of this thesis, are categorized into two groups. The first group is the accidental fires that are caused by human acts, such as a fire in a kitchen of an apartment building or a fire that is caused by the bad installation of an electrical cable during the construction. The second group is the fires that are due to natural phenomena such as lightning or natural fire such as wildfire. The cause of this type of fire cannot be controlled, but their impact on humans and the environment can be reduced by using engineered design procedures in the construction of buildings and by educating the society.

1.1.1 Fire protection engineers and home fire safety

According to Chris Jeleneicz, P.E. FSFPE, the origin of approximately 80% of all fire fatalities worldwide are from residential occupancies, which have the least fire protection [1]. Just looking at an average person, out of twenty-four hours of the day, about half of the day is spent outside of the house while at work, in the car or public transportation, shopping centers, restaurants, etc., and the rest of this time is spent at home. During these twelve hours at home, the person is sleeping more than half of it and is not aware of his/her surroundings. Therefore, we can assume that during the first half of the day, the person is either outside of the residential building or is at work in a public facility, which by the code requires a minimum fire protection system. As a common practice, most of the commercial buildings in Canada have the minimum fire protection system, such as alarm systems, which are required by the code and mostly requested by authorities having jurisdiction (AHJ). But looking at the other half of the day, the person is in a building that might or might not have the minimum fire protection system depending on the type of the building, year of the construction, requirements of the city and authorities having jurisdiction, insurance companies and building management company or owners.

Based on experience gained in the real work atmosphere while working in the field of fire protection for the last six years, mostly, the fire department is the most reliable source of data with regards to residential fires. These people are the ones that put their own lives in danger to save lives. Based on statistics existing buildings with older construction are considered a higher risk compared to the new construction buildings. Many existing buildings that are not up to codes avoid major renovation to maintain the current fire protection systems as is. The question to ask is how we can change the interest of the public and building owners to focus on saving more lives than saving more money? Why are some residential buildings fully equipped with fire protection systems, and some only respect the minimum requirements? How can the buildings with full-fire protection systems be affected by others conforming to the minimum requirements? Why is there a gap, and how can this be fixed? How can we design for a safer high-rise building?

Based on the SFPE survey between 2005 and 2014 in the United States of America, the majority of the Americans felt safer at home than other occupancies, but the people involved in the field of fire protection know that most of the studies and designs for fire protection systems are involved with public and commercial buildings. The concern about public and commercial buildings rises because there is always a bigger crowd involved, and building owners and insurance companies are more concerned about liability issues. However, in the residential buildings, mostly, the owners are the decision-makers, even though they might not always be aware of the great risk. Due to the high cost of fire protection systems, it is not reasonable to enforce a law that forces the owners of all the existing buildings that are not equipped with full-fire protection to conform to current codes. As a result, a minimum protection is accepted [1].

According to the fire protection engineering magazine of SFPE (02 2016/ISSUE #70), the fire experience of residential buildings in Canada is very similar to the U.S., and the leading causes are cooking, heating systems, and smoking. Based on the information provided among all sources, cooking and heating equipment caused most of the fire incidents and had the highest impact on civilians [2].

In Canada, the design of the fire protection system is based on the National Building Code of Canada, and this code refers to the National Fire Protection Association Standard for the design of different types of fire protection systems, but each province or territory is responsible for their code adoption. Some local jurisdictions have their programs to reduce residential fire deaths. For example, they have been directed primarily toward smoke alarms and public education programs and evacuation plans. Some authorities having jurisdiction required smoke alarms for existing buildings. In this case, in-unit smoke/heat alarm devices with batteries are acceptable, but new occupancies must have hard-wired detectors that are connected to the central alarm panel. The requirement of hard-wired smoke detectors connected to a central alarm panel is a positive step toward a safer environment. Many existing high-rise buildings with in-unit smoke/heat alarm device systems are not inspected regularly, and as a result, a lot of these devices passed their maximum lifetime.

1.1.2 Fire statistics in the USA

Fire is one of the most common threats to humans and their surroundings. All around the world, there are many deaths and injuries as a result of accidental fires. According to NFPA statistics in 2015 in the U.S., 1,345,500 fires were reported, which increased with 3.7% from 2014 [3].

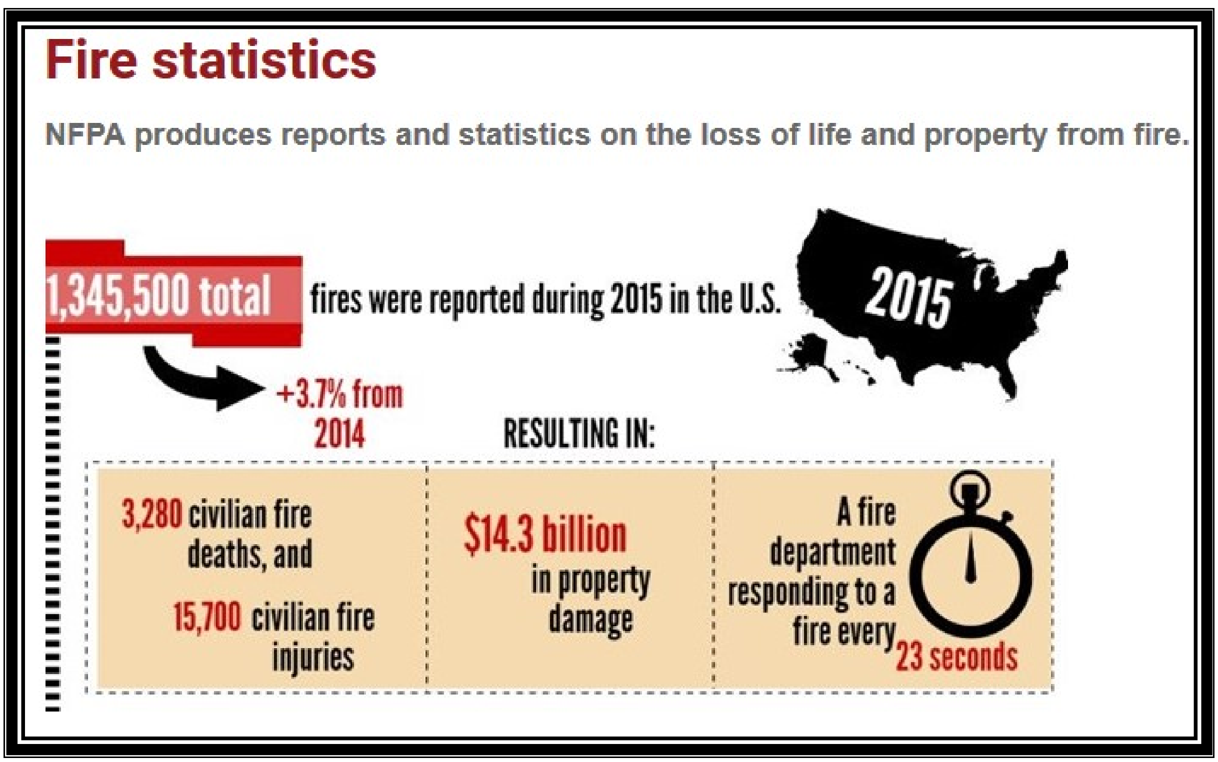

Figure 1 - NFPA Fire Statistics [3].

1.1.3 Fire statistics in Canada

In Canada, based on the summary of fire incidents, deaths, injuries, and financial losses from 1986 to 2000, there is an annual average of 6,622 fires [4]. The figure below shows how over the years, this number decreased. The addition of a sprinkler system to the residential buildings is one of the reasons why the number of fire deaths has a descending pattern between 1986 and 2000.

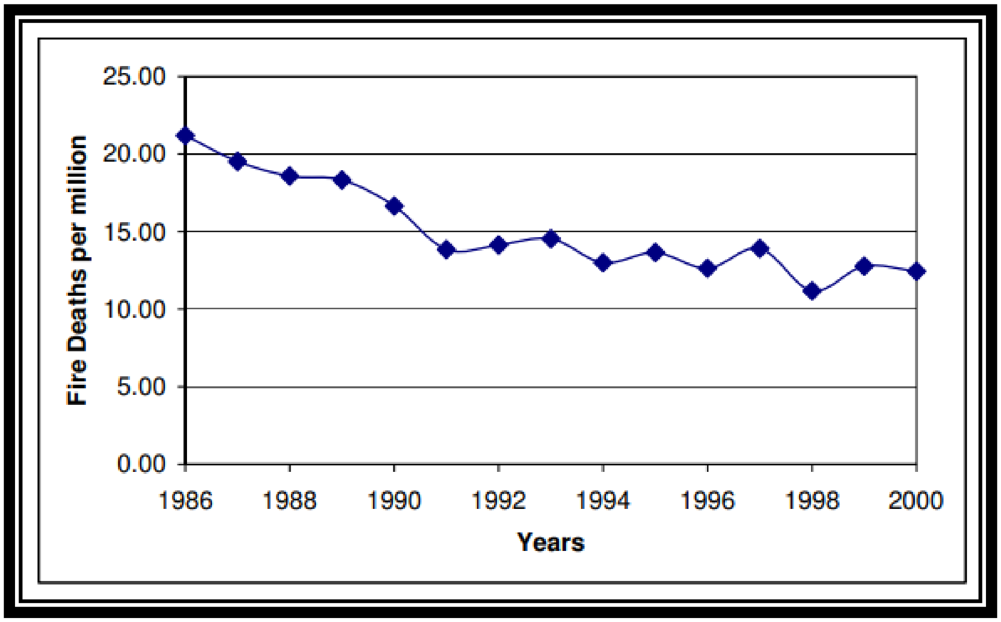

Figure 2 - Fire Deaths per Million for the Period 1986-2000 in Canada [4]

"Fire incident data for 2007 from BC, AB, MB, ON, NB, and NS provinces in Canada; for 2008 from SK; and for 2003 – 2007 from NT was analyzed separately. A total of 42,753 fires, resulted in 224 civilian deaths, two firefighter deaths, and $1,551,657,179 in direct property damage. On average, home fires accounted for 30% of all fires and 73% of all fire deaths in the jurisdictions that contributed data. Cooking is the leading cause of home fires and home fire injuries, while smoking materials are the leading cause of home fire deaths. One-third (33%) of all home fire deaths were caused by fires that started in the living room; 20% resulted from fires originating in the bedroom, and 11% were caused by fires starting in the kitchen. Fire causes in Canadian homes were very similar to those reported for homes in the United States. " [5].

Based on this document, the fires happening in residential buildings are divided into three categories—one to two-family dwellings, apartments, and condominiums, mobile homes. The first is one to two-family houses, which have a higher percentage with 74% fire mostly due to lack of central detection systems such as the alarm system, smoke detectors, sprinkler system. For these types of buildings, NBCC does not require central detection systems, even though that some authority of jurisdiction has their own rules and requirements for detection system in the new constructions. As a result, there is a longer delay in the fire department response as the fire spreads in this type of building. In Canada, most of the single-family dwellings have a wood structure and consequently, in case of a fire a greater loss is expected. The second type is apartment buildings and high-rise buildings that are the interest of this research. As can be seen in the table below, 24% of the fires happened in apartment buildings, and comparing this number to the single or multi-family dwelling, the percentage of the death is much lower due to the type of construction and detection systems. In these types of buildings, fire protection systems are mandatory for new constructions, and there is a minimum requirement of the detection systems for existing buildings. But surprisingly, although most of these buildings are equipped with fire protection systems, the percentage of injuries is very high which is believed due to the response time of the fire department and obstacles that exist during the evacuation in case of emergency [5]. This topic will be discussed more in details in chapter 4.

Table 1 - Percent Distribution of Home Fires by Type in Canada [5].

Percent Distribution of Home Fires by Type of Home

Type of Home	% Fires	% Deaths	% Injuries
One/Two Family Dwellings	74	78	62
Apartments, Tenements, Flats	24	17	36
Mobile Homes	2	5	2

This Table summarizes data for BC, AB, MB, ON, NB, NS (for 2007); SK (for 2008); and NT (for 2003-2007).

Table 2 shows the area of fire origin. As can be seen in Table 2, most of the fires in residential buildings started in the kitchen with the highest percent of injuries, but the highest deaths happened in the living room and bedroom. It is apparent that the reason for having more deaths and injuries in the living room and bedroom is because people are less aware of their surroundings when they are asleep or distracted.

Table 2 - Home Fire in Canada by Area of Fire Origin [5].

Home Fires in Canada by Area of Fire Origin

Area of Origin	Fires	%	Deaths	% Deaths	Injuries	% Injuries
Kitchen	2,955	22	20	12	334	29
Outside Area (inc porch, balcony, court, patio, terrace, lawn, other...)	1,201	9	5	3	47	4
Bedroom	1,136	9	35	20	242	21
Living Room	1,077	8	56	33	198	17
Chimney - masonry/factory built, metal; flue-pipe; gas-vent	690	5	2	1	6	1
Vehicle garage…	600	5	6	3	45	4
Exterior Wall	475	4	0	0	8	1
Laundry Area	421	3	2	1	24	2
Washroom	241	2	2	1	26	2
Heating equipment room	221	2	0	0	16	1
Other Areas (<=1%)	2,940	22	31	18	195	17
Undetermined/Unknown	1,299	10	14	8	27	2
Total	13,256	100	173	100	1,168	100

This Table contains data for BC, AB, MB, ON, NB, NS (for 2007); SK (for 2008); NT (for 2003-2007).

Table 3, on the next page, shows that 20% of the fires in the kitchen are caused by cooking. Also it can be seen that 12% of these fires are due to heating equipment in the kitchen, living room and bedroom, 7% from smoking inside, 3% from candles, and 8% of the fires are caused by electrical distribution equipment [5].

Table 3 - Causes of Fires in Canada [5].

Causes of Home Fires in Canada

Causes	Fires*	% Fires	Deaths	% Deaths	Injuries	% Injuries
Cooking∞	2,582	20	11	7	290	27
Heating Equipment Related	1,631	12	2	1	65	6
Arson/Set Fire	1,477	11	16	10	83	8
Electrical Distribution Equipment	1,092	8	11	7	60	6
Smoking	900	7	36	22	92	9
Candle	337	3	5	3	50	5
Appliance/Equipment Related	312	2	0	0	7	1
Exposure Fire	265	2	1	1	4	0
Clothes Dryer	231	2	0	0	8	1
Lighting Equipment	222	2	0	0	13	1
Cutting/Welding Equipment or Blow Torch	205	2	0	0	18	2
Child Fireplay	122	1	5	3	19	2
Flammable/Comb. Liquid Ignition	89	1	1	1	24	2
Flammable Gas Ignition	33	0	2	1	2	0
Other Causes/Unknown	3626	28	72	44	332	31
Total	13,124	100	162	100	1,067	100

* This Table contains data for one/two family dwellings, apartments and mobile homes in BC, AB, MB, ON, NB, NS (for 2007); SK (for 2008); NT (averaged for 2003-2007). Thus, the totals row reflects fire losses for these periods.

∞Cooking fires include cooking oil fires (30%) and all other cooking fires (without ignition of cooking oil) (70%). Injuries were equally distributed between these two types of cooking fires. Please refer to "*Cooking Oil: A Home Fire Hazard in Alberta, Canada*," by Mahendra S. Wijayasinghe and Thomas B. Makey. Fire Technology Second Quarter 1997.

Studying the above tables helps us to find the main cause of the fire in residential buildings. These data are the result of the study of each contributing jurisdiction, which represents 75% of the population of Canada in 2007 in the province of BC, AB, MB, ON, NB, NS, SK and NT. The result shows that most of the fires resulting in death started by smoking, Arson in the area, cooking, and candles. Although we might not be able to eliminate the cause, we can educate people to reduce the risk [5]. Also, safer designs can reduce risk. Based on the declaration of Sécurité Publique Québec, the total number of declared fires from 2010 to 2015 dropped 9.3 % [6], considering all the above information, modern building structures and materials, newer technologies, and prevention measures have a great influence on these statistics.

1.2 Codes and standards

Every building is designed based on codes and standards. These codes determine all the aspects from the design phase, choice of construction material, construction methods, installation, etc. These codes are reinforced by law and authorities having jurisdiction (AHJ) to be used by architects, engineers, and designers in different fields and followed by the property owners.

In Canada, the National Building Code of Canada (NBCC) is applicable to all existing and new buildings. The year of the NBCC used varies depending on each province. In Quebec, NBCC 2010 is the applicable code, and only for the existing buildings, and professionals can refer to the older versions that are applicable. The choice of the year depends on the year of construction of the building and the scope of the work to be done.

In Canada, the National Research Council (NRC) plays an important role in maintaining and revising the National Building Code of Canada every five years. Similarly, they do a lot of testing in the field of fire protection. Some of the data from these tests will be used for the purpose of this research. There are a lot of organizations such as the Canadian Fire Alarm Association (CFAA) and the National Fire Protection Association (NFPA) that have an essential role in the design of the fire protection system. In addition to the associations mentioned above, the Society of Fire Protection Engineers (SFPE) and FM Global (Factory Mutual) provide some guidelines and testing results that are useful during the design phase of fire protection systems. These data are often used to improve the codes and standards and likewise used by authorities having jurisdiction for building a safer environment.

NFPA standards referred by NBCC-2010 for the design of the fire protection system of this high-rise building are listed below. Some of these standards are out of the scope of this research but have been listed for general information. The two primary NFPA standards used for the design of the computer simulation model are NFPA 92 and NFPA 92A.

- NFPA13 - Standard for the Installation of Sprinkler Systems
- NFPA14 - Standpipes and Hose Systems
- NFPA 20 - Stationary Pumps for Fire Protection (applicable only if a fire pump is required) NFPA 25 - Inspection, Testing & Maintenance
- NFPA 72 - National Fire Alarm Code
- NFPA 80 - Fire doors
- NFPA 92 - Standard for Smoke Control Systems
- NFPA 92A - Standard for Smoke-Control Systems Utilizing Barriers and Pressure Differences
- NFPA 101 - Life Safety Code
- NFPA 220 - Types of Building Construction

1.2.1 NFPA Standards

NFPA13 is the standard that provides the minimum requirements for the design and installation of automatic fire sprinkler systems. This standard shall provide a reasonable degree of protection for life and property from the fire [7]. Also, NFPA14 covers the minimum requirements for the installation of standpipes and hose systems to be used by the fire department and sometimes occupants in case of fire [8].

Based on NFPA13, high-rise buildings shall be protected throughout by an approved, supervised automatic sprinkler system in accordance with NFPA101 [7]. The design of any residential building that does not land under the criteria of NFPA13R for Residential Occupancies up to 4 Stories shall be designed in accordance with NFPA13 guidelines. Except for some of the case studies discussed in Chapter 2, the literature review, it is assumed that all the fire cases mentioned in Chapter 4 are conforming to the requirements of NFPA13 and NFPA14.

NFPA20 is the standard for the design of fire pumps for private fire protection. Hydraulic calculation and fire pump selection are out of the scope of this research. However, fire pump location and its accessibility in case of emergency is an important topic for the safety of occupants and evacuation planning [9].

NFPA 80 regulates the installation of the assemblies, including doors to protect openings against the spread of fire and smoke within, into or out of the building [10]. Based on this standard, "fire doors and fire windows shall be classified by designing a required fire protection rating expressed in hours or fractions thereof" [11]. In the case of this study, we used the default setting for the building materials, which is applicable to the buildings in North America. Doing so does not reduce the importance of choosing the right material among the variety of available options. This choice is made to be able to start a base for future studies.

NFPA 92, the standard for the smoke control system, in article 4.1.1 and 4.1.2 explains the main design objective of the system. There are few parameters that have a direct effect on the design pressure differences such as the height of the ceiling, maximum and minimum pressure differentials, and if the smoke zone is sprinkled or not [12].

4.1 Design Objectives.

4.1.1* The methods for accomplishing smoke control shall include one or more of the following:

(1) The containment of smoke to the zone of origin by establishment and maintenance of pressure differences across smoke zone boundaries
(2) The management of smoke within a large-volume space and any unseparated spaces that communicate with the large-volume space

4.1.2* The specific objectives to be achieved over the design interval time shall include one or more of the following:

(1) Containing the smoke to the zone of fire origin
(2) Maintaining a tenable environment within exit stairwells for the time necessary to allow occupants to exit the building
(3) Maintaining a tenable environment within all exit access and smoke refuge area access paths for the time necessary to allow occupants to reach an exit or smoke refuge area
(4) Maintaining the smoke layer interface to a predetermined elevation in large volume spaces

Figure 3- NFPA 92 - Standard for Smoke Control Systems 2012 [12].

One of the most important elements when designing for smoke control systems is egress analysis. This analysis is done to confirm that there is enough time for the occupants to exit the space before being exposed to smoke or before tenability thresholds are reached. NFPA 92, also addresses the pressurization system in the stairwell and based on table 4.4.2.1.1 derived from Chapter 4 of this NFPA; the pressure difference between the smoke zone and the stairwell for a sprinkled building has to be 0.05 in. wg. The pressurization of stairwells can be done using a supply air fan [13].

Table 4.4.2.1.1 Minimum Design Pressure Differences Across Smoke Barriers

Building Type	Ceiling Height (ft)	Design Pressure Difference* (in. w.g.)
AS	Any	0.05
NS	9	0.10
NS	15	0.14
NS	21	0.18

For SI units, 1 ft = 0.305 m; 0.1 in. w.g. = 25 Pa.
AS: Sprinklered. NS: Nonsprinklered.
Notes:
(1) The table presents minimum design pressure differences developed for a gas temperature of 1700°F (927°C) next to the smoke barrier.
(2) For design purposes, a smoke control system must maintain these minimum pressure differences under specified design conditions of stack effect or wind.
*For zoned smoke control systems, the pressure difference is required to be measured between the smoke zone and adjacent spaces while the affected areas are in the smoke control mode.

Figure 4- NFPA 92 - Pressure differences - Standard for Smoke Control Systems 2012 [13].

1.2.2 National Building Code of Canada

The focus of this thesis is on fire protection systems, and as a result, section 3 of Division B of Code de construction du Québec [Chapitre I – Batiment, et code national du Batiment – Canada 2010 (modifié)], which is the applicable (French) version of NBCC in the province of Quebec is used [14]. In general, this document refers to National Fire Protection Association standards (NFPA) for the design of fire protection systems, the security of occupants, and accessibility.

The fireproofing of the building materials and structure, mechanical systems, and a safe emergency plan are considered at the early stage of a high-rise building design by architect and structural engineer. Mechanical and fire protection firms get involved when a layout of the building walls is ready. In any case, where the referred standard by the code does not provide enough guidelines, the engineer can ask for higher safety measures. Sometimes the way each specialist interprets the codes and standards leads to several options that need to be studied individually.

In this research, we will be looking at some decisions that require an engineer's judgment and fire department response method, which might lead to different conclusions. The interest of this research is to verify how these decisions might influence the design and how it affects public safety in case of an emergency.

1.3 Limitations

A human has the intention to adapt to his/her surroundings as technology advances, and new methods become available. In the last decade, more complex designs with newer technologies have been introduced in many fields. Building construction and fire protection systems are not excluded from that. As new technologies are introduced, guidelines and approvals are given, and accordingly, standards and codes get updated. But how these new methods or technologies can influence the concept in real life is always unknown until it has been studied and examined. In case of fire protection systems, sometimes real size testing is not possible due to the cost and safety concerns. As a result, this uncertainty might affect public safety in both positive and negative ways.

Moreover, as technology advances and new methods are introduced, the complexity of the work increases. This also affects the construction cost. Adapting to new technologies is a challenge, and in most cases, it increases the cost of the material while it reduces the labor cost. It is always the developer's decision to use the new techniques and approve the costs or stay with the existing approved methods. The use of newer technologies that are mostly safer and more environmentally friendly is always an alternative unless it is reinforced by law. As it has been observed over the decades, adjustments come over a certain period of time or only after an incident or tragedy that brings awareness to the topic.

In this study, due to the time limit, we are not able to present and study all existing and new construction materials using simulation software. In Chapter 2, some fire incidents in existing buildings will be reviewed, and the statistics from these fire incidents are used to model the simulation case. It is important to consider that it is not always possible to perform real scale testing due to the safety of humans and the environment, and the high cost. Therefore, sometimes scientists and engineers must make realistic assumptions or use other methods to prove that what they are introducing is valid and has no harm to humans and their surroundings. While simulation software is a great help, it has to be always considered that the data collected from simulations cannot be 100% accurate due to their limits. Simulation time and errors involved with data analysis done by humans have a direct influence on the conclusion, and this can definitely affect the result.

In this research, like many others, there are some limitations involved. The data collected from fire incidents in literature review and fire department employees' experiences on the island of Montreal might not be 100 percent complete due to the filling system or confidentiality of the data. This is simply because sometimes, fire does not leave enough evidence for professionals, and therefore, they cannot be sure if all conclusions are accurate. Many data from fire incidents cannot be shared for research purposes due to their confidentiality. Research on closed fire files can bring up some questions that might influence the parties to involve in that incident, and as a result, it is challenging to access the data. In the end, some assumptions are made alongside this data to model the residential high-rise building. Some assumptions are made based on field experience and based on one to one conversation with firefighters serving in Montreal.

Human behavior and their response in case of emergency have a direct influence on the result. Depending on how occupants correspond to the situation and how the firefighters handle the situation, the outcome will change. So, there is always a chance that someone reacts differently than what has been estimated, and to minimize this error, surveys can help, but still, it cannot be considered as a precise way of data collection.

Most of the severe fires in high-rise buildings are unique, and each is found in a different location around the world. As a result, the construction material, fire protection system, and fire department response time of each varies. Fortunately, no data show large fire incidents in residential high-rise buildings in Canada. As a result, the data gathered from other fire incidents are unique and cannot be compared with any real cases in Canada. This topic will be discussed more in detail in Chapter 2, but the reason behind the fire is not something that can be considered unexpected in Canada.

1.4 Objective and thesis outline

Following the limitations mentioned above, engineers are forced to make decisions based on the available information, which might not necessarily be enough. Sometimes, considering the costs, these decisions are in favor of the building owners while they are not entirely in favor of public safety, even though they conform to all applicable codes. The goal of this research is to find the elements that can reduce the chance of accidental fires in high-rise residential buildings and while considering all these elements, model a forty-five story building. Also, to find ways to control the smoke in the building in order to give enough time to the fire department to respond to the fire and enough time to the occupants to evacuate the fire zone and the building. This is only achieved by using the right method of fire protection and finding solutions to the gaps that exist in codes and standards and response methods. The main objective is to provide enough supporting results to recommend to the fire department to keep the ventilation system on active mode and use a pressurized supply system during a fire incident and the entire evacuation process. In this research, different fire scenarios in tall buildings, and some studies on smoke control and evacuation in a high-rise building will be reviewed. Based on simulation software (FDS and Pathfinder), human behavior and fire department response time and its effect will be studied and compared to the real fire incidents, and improvement methods will be provided.

Data from the fire incidents and survey reports prepared by professionals and individuals are used as a guide to complete the model for this research. The numerical model is first validated by comparing the predicted evacuation time and temperature that is expected based on the fire incident reports and information provided by the Fire department. This information is as listed below:

- In 3% of the fire incidents, the heat from fire and smoke delayed the evacuation on multiple floors above and below the floor of the fire origin.
- In 11% of the fire incidents, the heat from fire and smoke delayed the evacuation on the floor of the fire origin.
- In 86% of the fire incidents, the heat did not influence on evacuation time. But smoke percentage had a direct impact on human behavior and their ability to see.

Smoke layer height filled in each scenario helps to understand the smoke filling process better. As a result, the evacuation process and reasons to cause a delay in evacuation can also be studied. To perform a credible analysis, a real experiment must be conducted. However, with the limitations that exists in the field of fire protection, this is almost impossible. A lot of the information used in this analysis is based on daily experience working in the field of fire protection and also field observations and discussions with other professionals practicing in Quebec.

1.4.1 Research objectives

The research objectives of this thesis are listed below.

- Study real fire cases occurred in high-rise buildings in different places around the world and found the cause and the elements that made it more difficult to fight the fire.
- Study human behavior and fire department response time considering the location, construction material, available technologies including fire protection systems, social knowledge, and fire size. Canada is the home of people with different backgrounds and cultures, experiences, and languages. These differences make the job even more complicated. To be able to have a safer place to live, we need to invest in increasing public awareness and educating people. This is only possible if we learn about them and provide guidelines.
- Review studies were done on fire and smoke control in open spaces and high-rise buildings.
- Study the data gathered from the fire and smoke tests and simulation results.
- Develop a model using FDS to be able to visually see the pattern of the smoke and study numerical data to allow a comparison between the estimated evacuation time and survey time.
- Verify the developed model by adding the fire in different levels and locations of the high-rise building to be able to see the effects and validate the results.
- Recommend the use of automated pressurized staircases in both existing and new construction buildings using a simple air supply system on each floor in the stairwell.
- Develop a list of the results and potential solutions that can be presented to AHJ and organizations similar to SFPE for future studies and educational programs.

1.4.2 Thesis outline

Chapter 2 presents a literature review of fire incidents and smoke damage in high-rise buildings, an understanding of the cause of fire in different high-rise buildings around the world, and a review of CFD cases conducted in open spaces and high-rise buildings.

Chapter 3 presents the theoretical models of three fire scenarios in a forty-five-story residential high-rise building using FDS; First case, fire starting on the top floor (45^{th} floor), second case fire starting on the 10th floor and the third beginning in the basement. A theoretical model of emergency evacuation is also simulated using Pathfinder.

Chapter 4 validates the FDS and Pathfinder models for all three scenarios with the information available from the fire incidents and information provided by the fire department.

Chapter 5 analyzes the results from chapter 4, presents the evacuation strategies that can be employed to evacuate a high-rise building, and finally explains the future research work and the conclusions from this research.

2. LITERATURE REVIEW

In this section, some of the fire incidents in high-rise buildings around the world are studied. Each case is individually analyzed considering the effect of the response time of the fire protection system, emergency planning and human behavior, and fire department employees' response time. Correspondingly, many publications related to smoke control, evacuation, and emergency planning are studied to achieve a wide perspective on the concern associated with this topic.

The focus of this research is more on improving the safety of occupants by understanding the reason behind each fire in similar buildings, human behavior and understanding the cause of the failures, even though most of the buildings are conforming to the codes and standards, and finally looking at the importance of smoke control in high-rise buildings which have an effect on the human behavior and fire department's operation. More precisely, the effect of pressurized staircases and their impact on smoke control and safe evacuation.

2.1 Grenfell Tower

The fire in the twenty-four story Grenfell Tower located in London (United Kingdom) caused 72 deaths and over 70 injuries. After the investigations, it is reported that the fire started accidentally in a fridge-freezer on the fourth floor. The hot smoke and fire reached the building's exterior cladding. Due to the presence of a gap between the insulation material and aluminum composite material cladding (ACM), the fire and hot smoke found its way to the upper floors on the façade. The polyethylene cores of the cladding acted as a fuel, and as they melted downward, the fire started to spread to the lower floors. The presence of polyisocyanurate (PIR) and phenolic foam insulation accelerated the speed. As the fire reached different units, the hot smoke found its way to other floors through the extractor fan units in the kitchens [15].

Figure 5 - Grenfell Tower located in London (United Kingdom) [15].

The following key events from the backbone of the narrative of the incident occurred on 14 June 2017 is given below [15]:

00.54 Behailu Kebede Calls 999 to report a fire in flat 16, floor 4 Grenfell Tower.

00.59 First firefighters reach the tower.

01.09 Fire breaks out of Flat 16 into the exterior cladding and starts to climb the east façade rapidly.

01.14 Firefighters enter the kitchen of Flat 16 for the first time.

01.21 First 999 call to the control room from an occupant in the lower (Naomi Li, Floor 22).

01.25 First 999 call to report smoke coming into the flat from the lobby (Denis Murphy, Floor 14).

01.26 MPS declares a major incident.

01.27 Fire reaches the roof and starts to spread horizontally.

01.29 WM Michael Dowden, the LFB incident commander, makes pumps 20 (having made up for 4 to 6, to 8, to 10 and 15 between 01.13 and 01.28).

01.30 First 999 call reporting fire penetrating a flat (Mariem Elgwahry, floor 22).

01.31 WM Dowden makes pumps 25. By this time, 110 out of 297 occupants have escaped; the fire starts to spread to the north elevation of the tower.

01.42 The LAS declares a significant incident.

01.45 First NPAS (police) helicopter arrives at the scene.

01.50 WM Dowden hands over incident command to SM Andrew Walton. By this time, 168 of 297 occupants had escaped.

01.58 SM Walton hands over incident command to DAC Andrew O'Loughlin.

02.00 Flames travel across the north and east elevations of the tower and start to spread around the crown and diagonally across the face of the building, affecting flats in the south-east and north-west corners.

02.04 GM Richard Welch declares himself incident commander, not knowing that DAC O'Loughlin has already assumed command.

02.06 GM Welch declares a major incident.

02.11 DAC O'Loughlin takes handover from GM Welch.

02.15 SOM Joanne Smith arrives at the control room.

02.17 Bridgehead moves from floor 2 up to floor 3.

02.20 Flames start to spread to south elevation.

02.26 The LAS declares a major incident.

02.35 Control room decides to revoke the "stay put" advice and tell all occupants calling 999 to leave the tower.

02.44 AC Andrew Roe takes over incident command from DAC O'Loughlin.

02.47 AC Roe revokes the “stay put” advice.

02.50 Fire spreads horizontally across the south elevation at the crown. Commissioner Dany Cotton arrives at Grenfell tower.

03.00 Fire starts to spread across the west elevation of the tower, from north to south.

03.08 Bridgehead relocates to ground-floor lobby.

03.20 First Tactical Coordination Group (TCG) meeting.

03.30 Flame continuous to spread across the south and west elevation of the tower.

04.02 Fires on the south and west elevation start to converge at the top of the southern.

08.07 Elpidio Bonifacio, the last survivor to leave the tower, is evacuated.

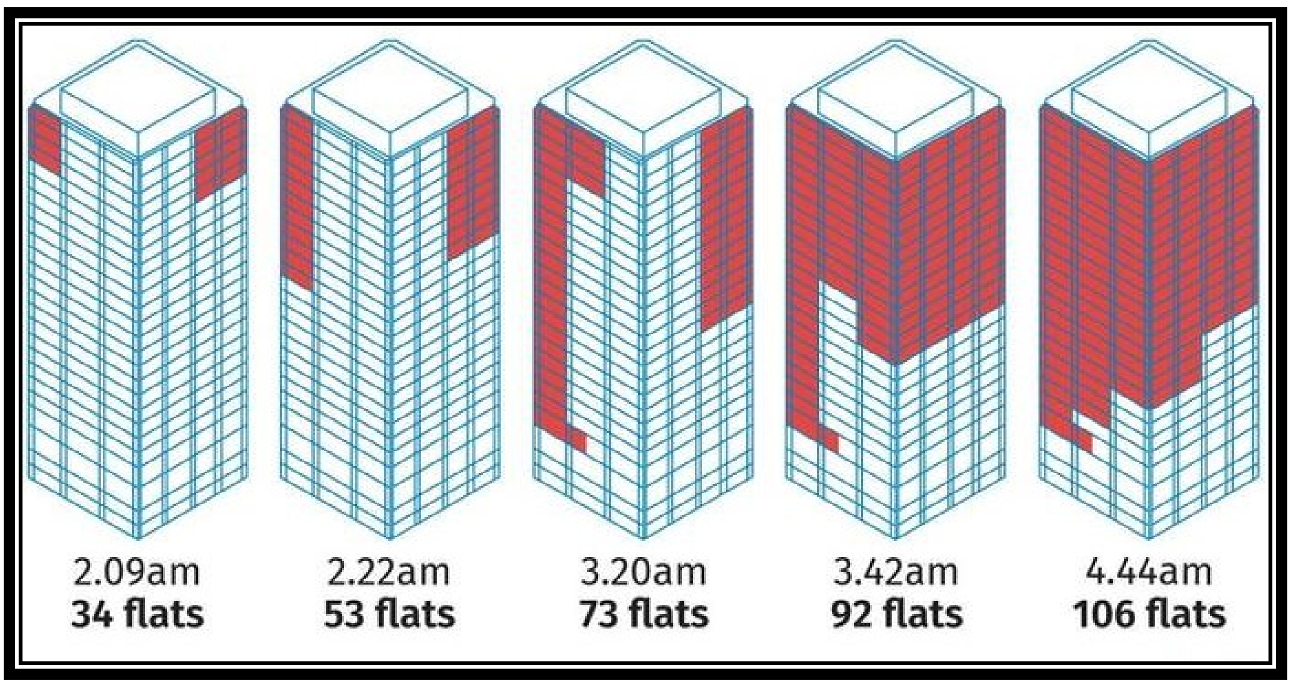

Figure 6 - Grenfell Tower – west/south face of the tower [15].

As described in the reports, the main lobbies started to be filled with smoke in the first hour after the authorities were notified of the incident. 168 of occupants were able to evacuate before smoke found its way to the staircases. It must be considered that on some floors, the smoke was very thick, and the temperature was higher than what humans can tolerate [16]. As a result, the evacuation progress was much harder as many occupants could not find their way outside without the help of the firefighters.

The exterior building walls failed, and there is some evidence after investigations that explain these walls were not probably designed based on the building regulations 2010. As a result, they did not have the required minimum fire resistance and fire spread faster and did not leave enough time for evacuation [16].

The building burned about 60 hours, and more than two hundred and fifty fire brigade firefighters and seventy fire engines were involved in controlling and extinguishing the fire. This building was constructed in the early 1970s, and since then, it underwent few renovations and a major renovation between 2012 and 2016. During this final renovation, the new cladding was added to improve the appearance of the building. One of the discussions that are always a concern for AHJ is whether the fire department and commanders are aware of the risks involved with different buildings [17]. In the case of this fire, according to legal documents, "the LFB's policy for fighting fires in high-rise buildings, PN633, envisages that evacuation of a high-rise residential building may be necessary and suggests that during familiarization visits officers consider evacuation arrangements." [15]. Some specialist believes that the lack of fire safety, fire department's delayed response and lack of supervision by experts during the renovation were the three main reasons that turned this fire into a tragedy [17]. The evacuation report and available data from this worldwide tragedy will be used as a source to validate the result of the Pathfinder software.

2.3 Edificio Wilton Paes de Almeida

Edificio Wilton Paes de Almeida was a 24-story building built in 1968 in Sao Paulo, Brazil. In May 2018, due to a short circuit in a power extension in one of the units on the 5th floor, a fire started. The fire began to grow and spread through the vertical shafts and left seven deaths behind. After 90 hours of the fire, this building collapsed, which raised a lot of questions with regards to its concrete structure and reinforcement used [18]. Buildings with reinforced concrete structures have always been known as the most solid and rigid structures. It is expected that these buildings last longer in case of fire. Studies showed that this building might have had a structural problem. After extinguishing the fire, the rebars in the columns were studied. The study result included some evidence of missing proper reinforcement. However, due to collapse, the collected material from the site was not 100% complete. Therefore, this idea was only considered as a theory [18].

There are a lot of concrete buildings designed all around the world. Besides the main structure design of these types of buildings, it is very important to make sure the fire separation of different zones is respected. One of the requirements in any type of building is to make sure to avoid having openings in the walls and in between floors that allow the fire or smoke to spread to other zones. In the case of Edificio Wilton Paes de Almeida, not only the structure could not hold, but also the fire spread throughout the building faster due to lack of fire resistance and fire separation between floors. The vertical openings like staircase and elevator shafts are the interest of this research, and as a result, a detailed discussion will be presented in Chapter 4.

Figure 7- Edificio Wilton Paes de Almeida (Sao Paulo, Brazil) [18].

2.4 Address Downtown

Address Downtown is a 63-story building constructed in 2008 in Dubai, UAE. This building caught fire in December 2015, where the fire started on the 14th floor. Falling debris and aluminum pieces used as construction material led fire eruption in other places while the fire spread upward via external cladding. The fire was controlled in less than 9 hours. The factors that helped was the availability of the team members and equipment at a neighbor building, Burj Khalifa, which is the tallest building in the world at the time, pre-coordination for emergency plan, public awareness about evacuation procedure and fire protection systems to prevent spreading fire [19]. Based on the UAE National, a fire started due to an electrical fault. A short circuit from cables connected to the light on the exterior wall between the 14th and 15th floor started the fire. According to the occupants, since the fire started on an outside wall, the alarm did not sound immediately, but due to the fast response of the fire department, the occupant evacuated the building. There is one death reported caused by a heart attack, which is believed that could be the result of the shock from the incident. According to the data, the death was not due to smoke inhalation [19].

Figure 8- Address Downtown (Dubai, UAE) [19].

2.5 Torch Tower

The Marina Torch tower located in Dubai (United Arab Emirates) is an 86-story residential skyscraper that got damaged by fire twice. Once in February 2015 and a second time while it was undergoing restorative work in August 2017. The first fire in 2015 started with a grill located on one of the building balconies. Based on the available data, wind and falling flaming debris caused the flame to flare up from almost the 50th floor to the top of the tower. Based on the reports, 64 exterior floors of the tower were damaged. Seven people were treated at the scene for smoke inhalation, but since the building was fully sprinkled, no injuries due to burning were reported. The second fire happened in 2017, which was easily controlled since it was at the street level, and the building was fully sprinkled. No injuries reported, and most residents were able to return within days [19].

New construction, adequate fire protection systems, location of the fire, especially in the second fire in 2017, and the response of the fire department are the main reasons why fighting these two fires was successful. This is an excellent example of the further discussion in Chapter 5, where the effect of the wind on exterior fires and also the response time of the fire department will be discussed.

Figure 9- Torch Tower (Dubai, UAE) [19].

2.6 Marco Polo Condo

Marco Polo apartments in Honolulu, Hawaii, was a 36-story reinforced concrete building built in 1971. The fire started on the 26th floor in July 2017, and although the building did not have sprinklers, due to the presence of noncombustible construction, the fire didn't spread to many floors. Four deaths were reported, and the victims were between 54 and 87 years old. It has been reported that the sound of the alarm was not heard on some floors, and that had a major impact on the evacuation progress [20]. According to Christopher J. Wieczorek," the Marco Polo apartment fire showed what can happen when no sprinklers are present in a building made of non-combustible exterior construction." [20]. Even though the fire did not spread on the facade as it found its way to outside, the combustible material inside and lack of sprinklers increased the speed of fire spreading inside the building. As a result, the hot smoke percentage increased, and a tragedy happened. The victims of this incident were above the age of 50 and considerably more at risk due to their physical conditions that make the evacuation harder. The adequate time for evacuation versus the speed of smoke spreading in the building will be discussed in more detail for the purpose of this research.

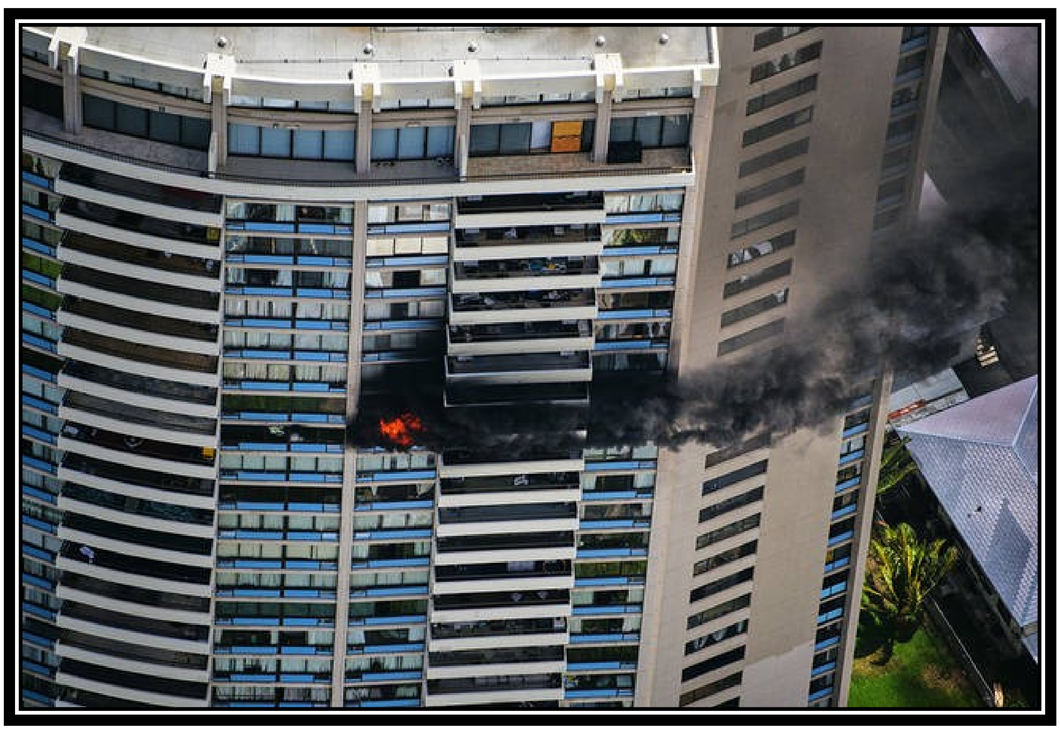

Figure 10 - Marco Polo (Honolulu, Hawaii) [20].

2.7 Plasco Buildinng

Plasco tower, a 17-story high-rise landmark building in Tehran, Iran got destroyed during a fire in January 2017. This building was the tallest building at the time of its construction in the 1960s. The building was used as a residential and commercial building with a major shopping center and several clothing workshops. The fire started around 8 am on the nineteenth floor. Ten fire brigades arrived to fight the fire for a few hours, but due to the old structure and combustible materials and lack of a sprinkler system, part of the building collapsed. Following smaller collapses, which it is believed that it happened due to the presence of the heating propane tanks inside the units, few major explosions happened, which in the end caused the building to collapse. Twenty firefighters have been reported killed, about ninety got injured [21]. In April 2017, it was reported that this building failed 22 national building regulations. Based on the data provided by the fire department to the VOA news, the fire department requested to evacuate the building a few years before the accident. Still, the occupants ignored the notice since they didn’t want to lose business [21].

The importance of the government's support and educating the public can minimize the chance of having a tragedy. In this scenario, a sprinkler system could have helped the fire department to control the fire and cool down the structure to minimize the collapse. Also, based on the visual judgment from the pictures and videos of the day of the event, it can be seen that the fire department trucks were not high enough to reach the highest floors. Having propane tanks as a fuel source for heating system shows the lack of inspections. This building was located in one of the old neighborhoods with lots of traffic and many buildings surrounding it, which limited the firefighters to take action and, as a result, increased the risk. The importance of emergency planning for existing buildings that are considered as a higher risk for the city will be discussed in detail in Chapter 5.

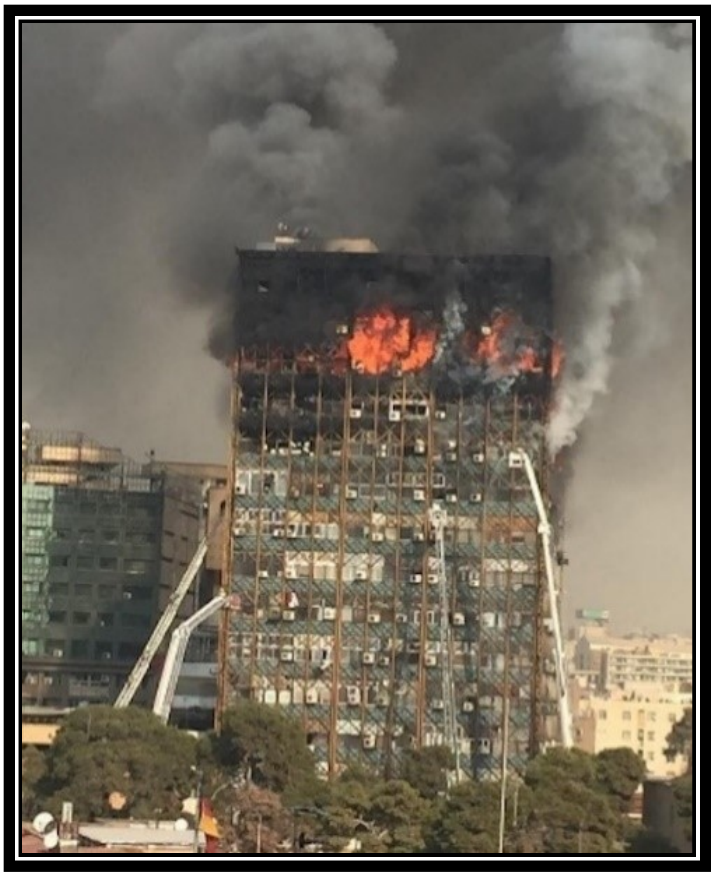

Figure 11 - Plasco Building (Tehran, Iran).

2.8 The perfect formula for tragedy

"The perfect formula for tragedy," written by Christopher J. Wieczorek from FM Global, describes the failure of safe evacuation and saving lives as a lack of automatic fire sprinklers and/or used of highly combustible exterior construction [24]. FM Global plays an essential role in providing guidelines for the fire protection industry where NFPA standards have no guidelines to help experts. Datasheets supplied by FM Global are used all around the world by professionals, and it is their responsibility to make sure to use these recommendations and design guidelines properly.

In general, many different factors can affect the response time of the fire department and fire service people. Some of these factors could vary for different cities, and it must be studied and addressed for each case separately. The average response time for less than 50 percent of the fire incidents in Dubai is less than four minutes, which this number compared to the UK for non-residential fires is more than double [23, 25]. New developing cities with modern construction are considered challenging as the fire service needs to adapt to new methods and higher buildings. As a result, code requires to add sprinklers throughout the building to control the fire and to have pressurized staircases and/or to have positive/negative zones to control the smoke. The figure below explains the importance of the automatic sprinkler system and the use of non-combustible construction materials.

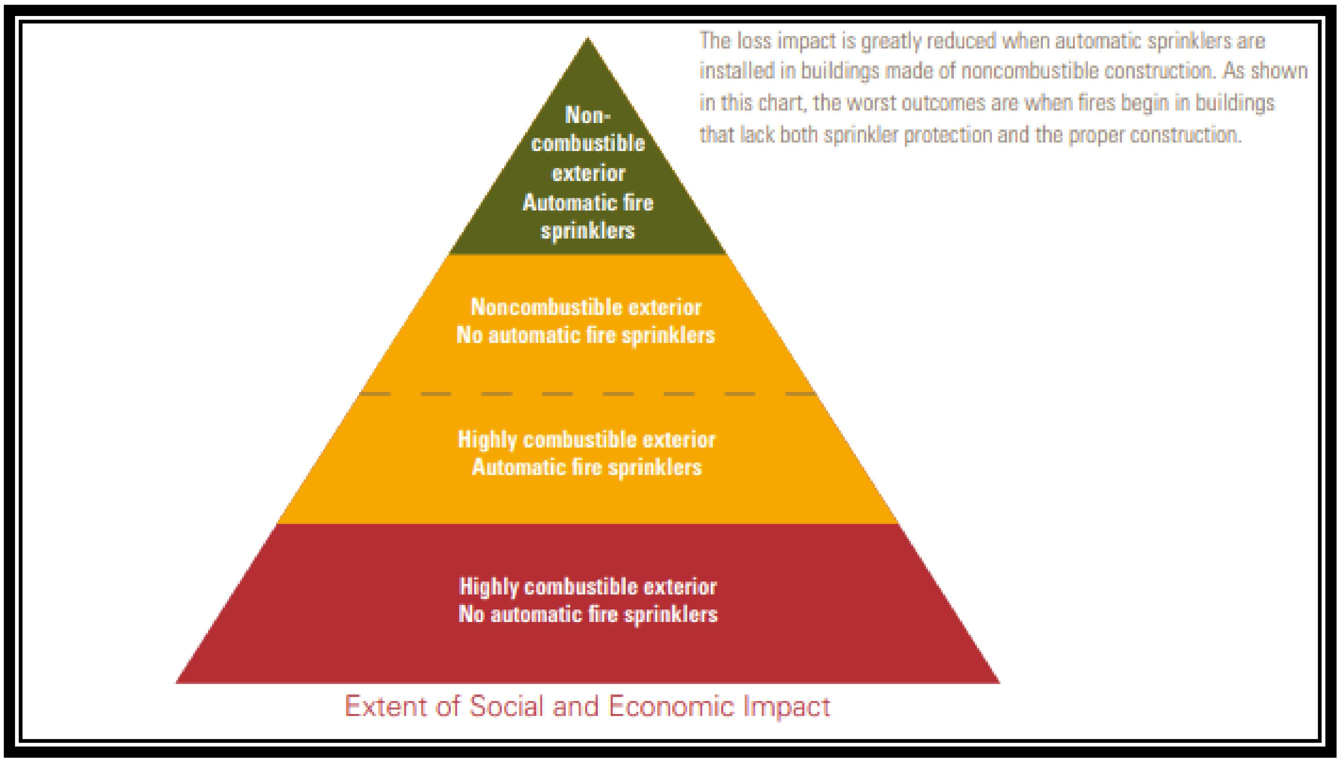

Figure 12-Extent of the social and economic impact of the sprinkler system and non-combustible construction [24].

FM Global is a mutual insurance company, whose capital and scientific research capability are a great help to industry and safety of public and environment. The company has done a lot of research on the recent fire incidents. Table 4 shows a summary of the buildings studied. Most of these buildings have combustible exterior construction, and many did not have fire protection systems in place due to the year of construction. The information provided in this table, which includes some of the fire incidents covered in this chapter as well, helps us to understand what are the major points that need to be studied more in detail for this study.

Table 4- FM Global -summary of recent fires [24].

A Glimpse of Recent Tower and Hotel Fire Losses

As figures show, a combination of automatic sprinklers and noncombustible construction is the most effective solution to minimize both property and casualty losses in high-rise buildings.

Date	Name	Location	Exterior Construction	Automatic Fire Sprinklers	Fatalities	Ref.
August 3, 2017	The Torch	Dubai, UAE	Combustible	Yes	0	
July 14, 2017	Marco Polo Apartments	Hawaii, USA	Noncombustible	No	3	
June 13, 2017	Grenfell Tower	London, UK	Combustible	No	80	
December 31, 2015	The Address	Dubai, UAE	Combustible	Yes	0*	
October 1, 2015	Nasser Tower	Sharjah, UAE	Combustible	No	0	
May 19, 2015		Baku, Azerbaijan	Combustible	No	17	15
February 21, 2015	Torch Tower	Dubai, UAE	Combustible	Yes	0	
November 25, 2014	Lacrosse building	Melbourne, Australia	Combustible	Yes	0	16
May 14, 2012	Mermoz Tower	Roubaix, France	Combustible	No	1	
October 1, 2010	Wooshin Golden Suites	Busan, South Korea	Combustible	Yes	0	17

**It is reported that one person suffered a heart attack while exiting the building.*

Based on this table, most of the fire cases studied had a combustible exterior construction, and the presence of the sprinkler system had a very positive impact on reducing the number of fatalities. The only building with noncombustible exterior construction that was studied is the Marco Polo Apartments that was not protected with the sprinkler system. The lack of a sprinkler system and combustible interior construction allowed the fire to spread inside the building.

2.9 Smoke control in large spaces and vertical shafts

One of the key elements to smoke control is the size of the compartment. Based on a study by H.P. Morgan and G.O. Hansell, in large spaces, the control of smoke by the ventilation system is very difficult. The reason for doubting a successful design besides the exceptional circumstances is the height [26]. Reduced-scale experiments to develop formulas and numerical simulations are the most common practice for validating the data. To be able to up-scale the data, the Froude number can be used along with a series of CFD simulations [27]. This concept is suggested since, in many circumstances, a real model of the fire cannot be built. The Froude number is a dimensionless number proportional to the square root of the ratio of the inertial forces over the weight or, in other words, the flow inertia to the external field. Figure 14 shows the CFD model of the atrium and the results for heat and smoke control in reduced-scale and full-scale atrium. The effect of the ventilation on the smoke and heat is almost negligible for both cases [28].

$F_r = V/(gD)^{1/2}$

F_r = Froude number

V = Average velocity of the liquid in a channel (feet/second or meters/second)

g = Acceleration due to gravity (32.17 ft/sec^2 or 9.81 m/sec^2)

D = Hydraulic depth = cross-sectional area of flow/top width

Equation 1- Froude number [28].

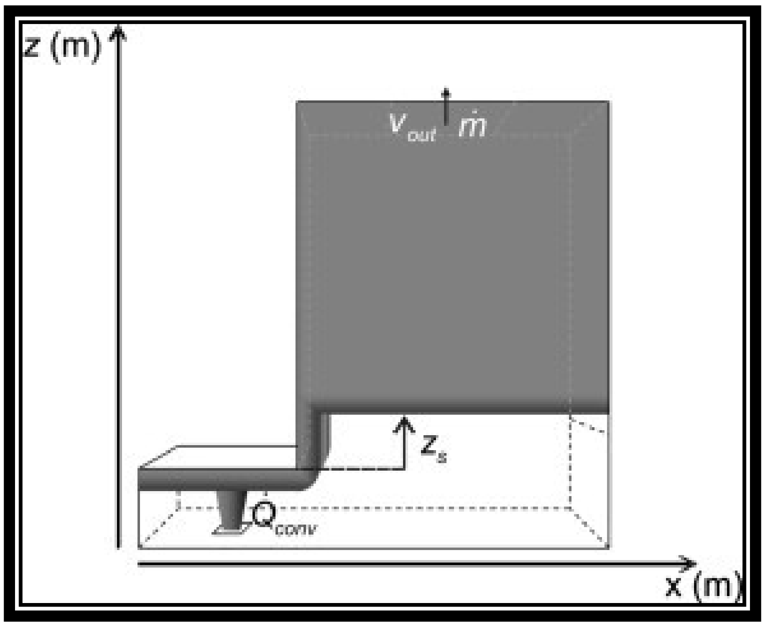

Figure 13- CFD model of an atrium [27].

Figure 14 shows the distribution of temperature difference of both reduced-scale atrium model and full-scale atrium model. It is important to consider the time of the simulation for each model when comparing the results of the left column (reduced-scale) with the right column (full-scale).

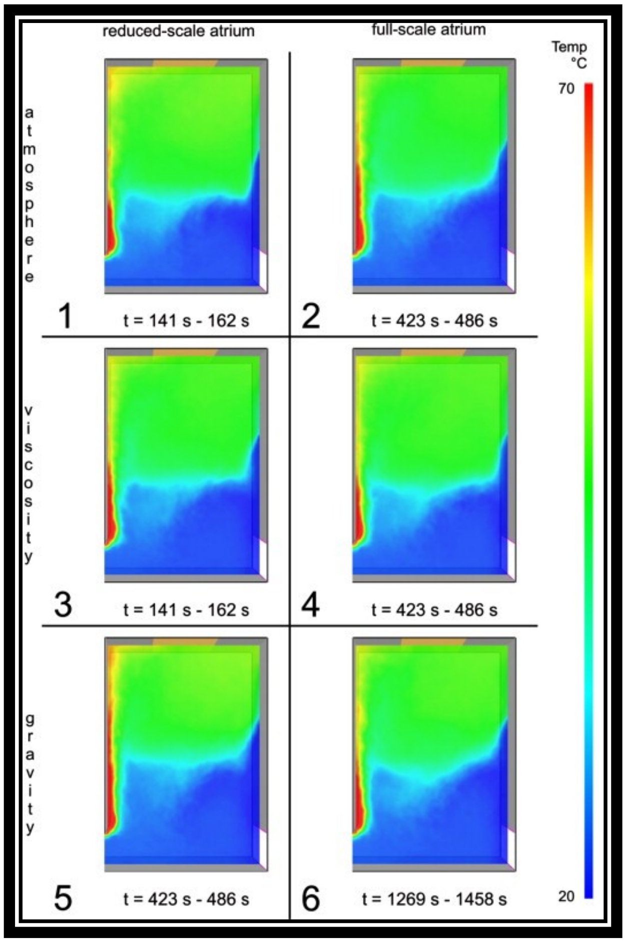

Figure 14- Smoke and heat control for the full-scale and reduced-scale models in the atrium [27].

Large-eddy simulation of smoke movement is another method of simulating fire scenarios using computational grids. Constant eddy viscosity is used to represent the sub-grid scale motion of the large or full-scale eddies. As can be seen in the output, the vertical velocity of the smoke compares to height fluctuate a lot, but as it is expected, the temperature decreases over time as we reach a higher elevation. The decrease in temperature is obvious in both graphs in Figures 15 and 16 [29]. All figures show that as the height increases, the velocity and temperature decrease. The eddy viscosity is defined as a coefficient relating average shear stress within a turbulent flow of air to the vertical gradient of velocity [30].

$$\boxed{\nu_T = (C\,\Delta)^2\overline{\omega}}$$

Equation 2- Eddy viscosity [30]

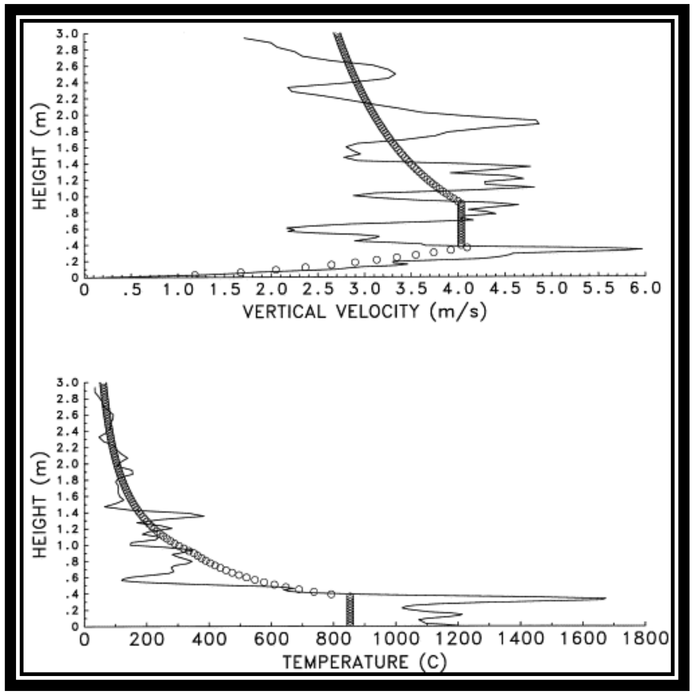

Figure 15 - Large eddy simulation results of smoke movement in the example [30].

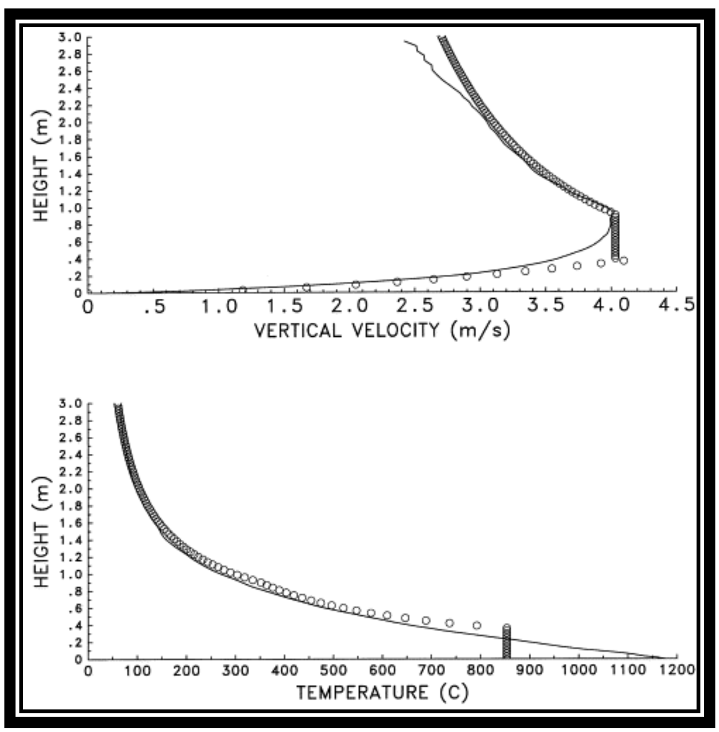

Figure 16- Large eddy simulation of smoke movement [30].

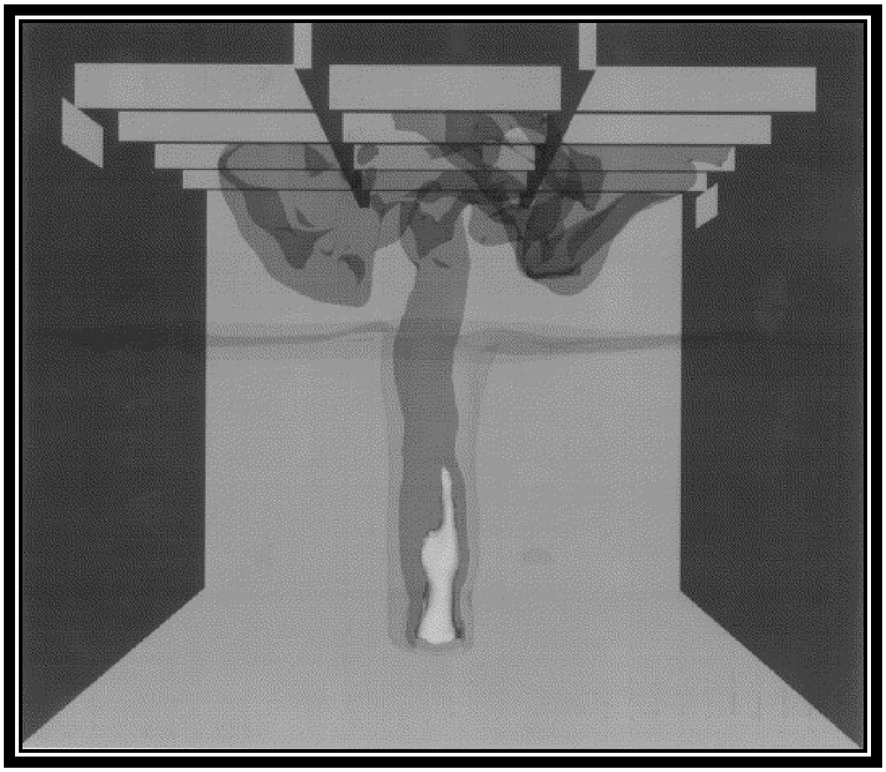

Figure 17 - Model of the pool fire and the smoke movement concerning height [30].

The same concept can be used when it comes to testing the smoke control in vertical shafts similar to a staircase shaft or elevator shaft. As buildings are getting taller, the understanding of the smoke pattern and fire spreading in the building is becoming more important. It is necessary to have an adequate fire protection system in order to be able to keep the space safe for the occupants. Smoke travels to remote locations, even if the fire stops at the start zone of the fire. That is the reason why smoke is considered the major killer in building fires [31]. Failure in fire protection systems is the most common reason behind fatalities when looking at different fire cases. Not having proper protection systems and planning could cause a tragedy, but the failure of the designs done by professionals is the most common reason behind the new construction building fires [32]. World Trade Center tragedy is an example of a big failure of engineered design due to the uniqueness of the event. Based on the information that was published, after the tragedy of the World Trade Center evacuation, there were three scenarios on how occupants evacuated the building. A great percentage of the occupants used the stairs, few people used elevators, and few people used both stairs and elevators. The percentage corresponding is shown in the table below [33, 34].

	WTC 1, n=202	WTC 2, n=158
Stairs	198 people (98%)	114 people (72%)
Elevator	1 person (0.5%)	18 people (11%)
Stairs and elevators	3 people (1.5%)	26 people (16%)

Figure 18- World Trade Center means of egress used within the towers [33].

Based on the data from the fire incident, occupants who were able to evacuate the building noticed the event by the sound of the explosion, by seeing the fire and smoke, by the movement of the building and the smell of the smoke [34]. The presence of smoke was one of the reasons that many people felt the need to leave the building before it was too late, but at the same time, smoke filling the space caused a lot of delay during the evacuation. The two other variables that added to this delay were the age of the occupants as well as their behavior at the time of emergency.

Fire cues	WTC 1, n=212	WTC 2, n=145
Audio cues: heard explosion, crash, rumble	107 (50%)	69 (48%)
Visual cues: saw fire, debris, smoke	87 (41%)	96 (66%)
Building movement: felt building sway, jolt, tremble	146 (69%)	30 (21%)
Contents movement: furniture movement, ceiling falling	66 (31%)	11 (8%)
Warning from others	14 (7%)	34 (23%)
Impact	29 (14%)	1 (1%)
Smelled fumes or felt heat	12 (6%)	16 (11%)

Figure 19 -World Trade Center first cues of the event within the towers [34].

	21-35 yr old (n=74)	36-50 yr old (n=58)	51-65 yr old (n=21)
Calm	39 (53%)	31 (53%)	9 (43%)
Panicked	25 (34%)	14 (24%)	6 (29%)
Upset	31 (42%)	22 (38%)	4 (19%)
Helpful	16 (22%)	17 (29%)	8 (38%)

Figure 20- World Trade Center distribution of age and perception of others [34].

In general, for a safe evacuation, it is required to control smoke movement to keep the smoke concentration thinner. As a result, the pressurization system is used in shafts and staircases in order to keep the evacuation paths safer and isolate the area from the fire and smoke zone. To do so, the movement of smoke in a tall vertical shaft needs to be examined. The movement of the smoke can be disturbed by the type of construction material, HVAC equipment, location of the fire, and also the size of the fire. In high-rise buildings, the movement of the smoke is mostly upward and through vertical openings such as elevator shafts and staircases. Based on the study of smoke movement in elevator shafts during a high-rise structural fire, the interaction of building construction material was studied. The information from these studies shows how the smoke pattern can vary in the same building with different construction materials. Figure 21 shows a typical model of the pressurization system for a typical multistory building and its effect on the smoke movement. Based on this figure, by pushing air into the other floors, the smoke is moved toward outside using the shaft. There are many factors that might affect the smoke layer. Based on the studies done by W.Z. Black, for the same fire scenario, the temperature has a great effect on it. As the temperature goes higher, the smoke layer will increase too [35]. The temperature effect on the pattern and the height of the smoke layer is the interest of this research due to the major temperature difference and existing weather conditions in Montreal. Considering the above information, we believe that any fire happening in a high-rise building in Montreal during a hot and humid summer day will have a higher percentage of smoke compared to a cold winter day.

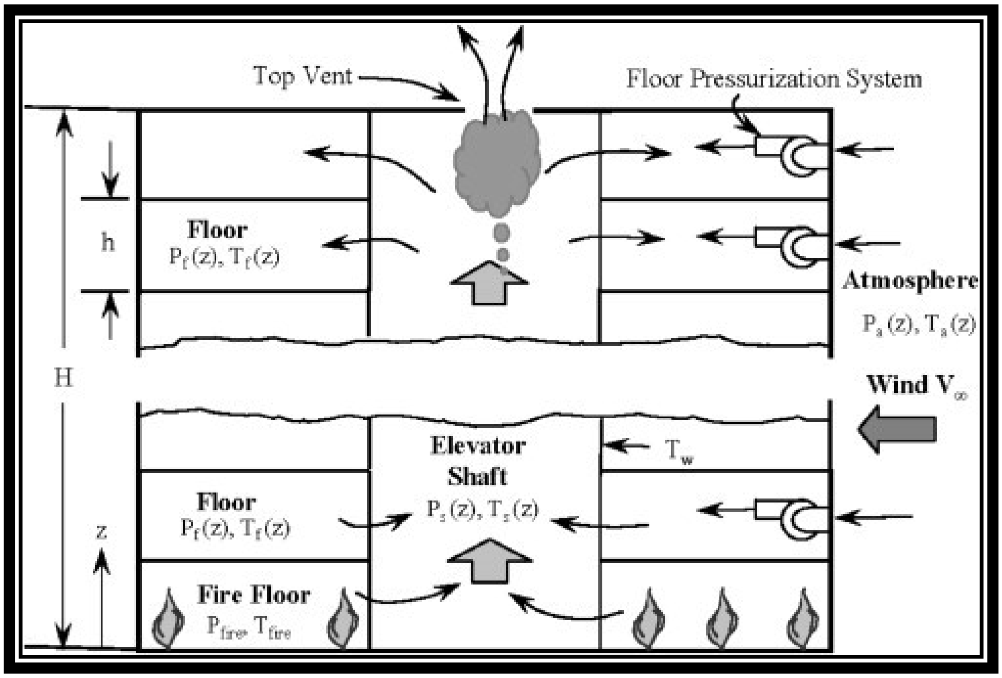

Figure 21 - Smoke movement in shaft [35].

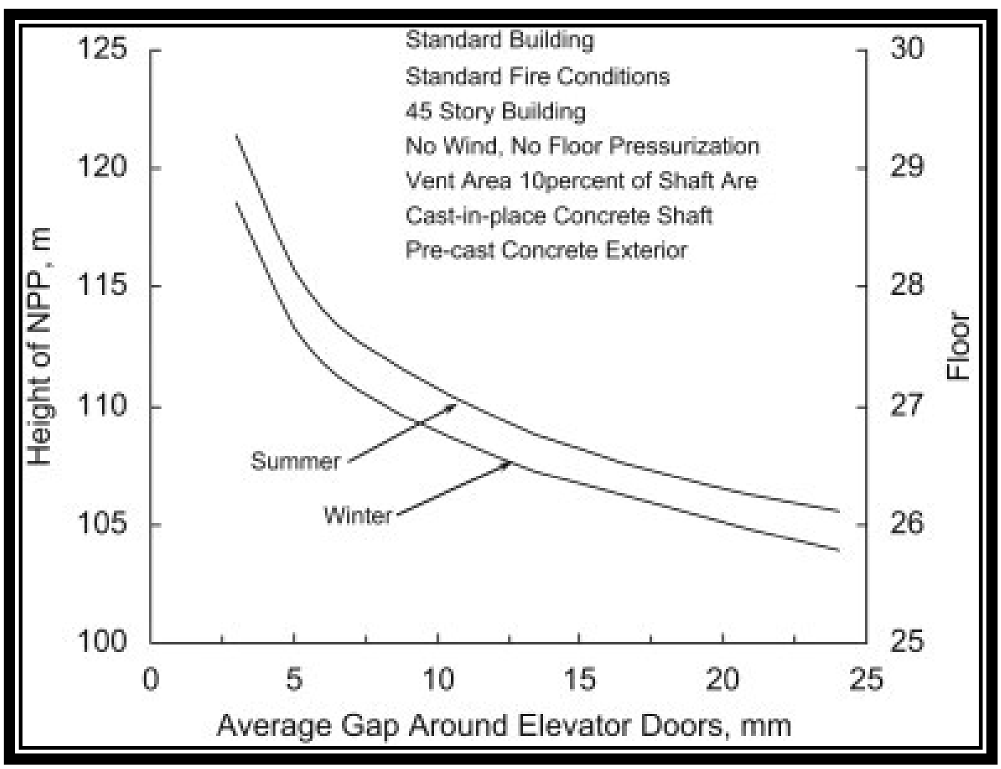

Figure 22- Height of NPP in summer vs winter [35].

Another similar study for pressurized shaft with more complex details was done by Richard S. Miller and Don Beasley. In this study, multiple shafts are considered in the same analysis. Having large pressure differences can spread the smoke and fire. As a result, they suggest that minimum pressure differences must be maintained at both open and closed doors. This helps not to let the smoke spread throughout the building by a fan system as there might be some big openings like doors. One of the other variables that affect the smoke pattern and the speed of the smoke spreading in the building is the fan speed. Fans are sensitive to the ambient temperature, and therefore the location of the supply fan, louvers, vents, and elevation with respect to the floor and the height of the building is very important. The smoke behavior traveling through an opening on a cold day versus a hot day when there is no fan is very different. To minimize this gap, especially during summertime, the fan can be added. A comparison between graph a and b of Figure 23 shows that adding a fan has a positive effect on the pressure and the smoke layer. By adding a fan, pressure increases, and as a result, the smoke cannot travel from the smoke zone into the staircase shaft. The same conclusion can be drawn for case c and d of Figure 23 [36].

Using the information above and also the result of all of the four cases shown in the next page a single fan per each floor is introduced to the FDS model for this research to validate the effect of the supply fan in a constant temperature of 22 degree Celsius during summertime and -12 degree Celsius in the wintertime. A detailed discussion on this topic is given in Chapters 4 and 5 of this thesis.

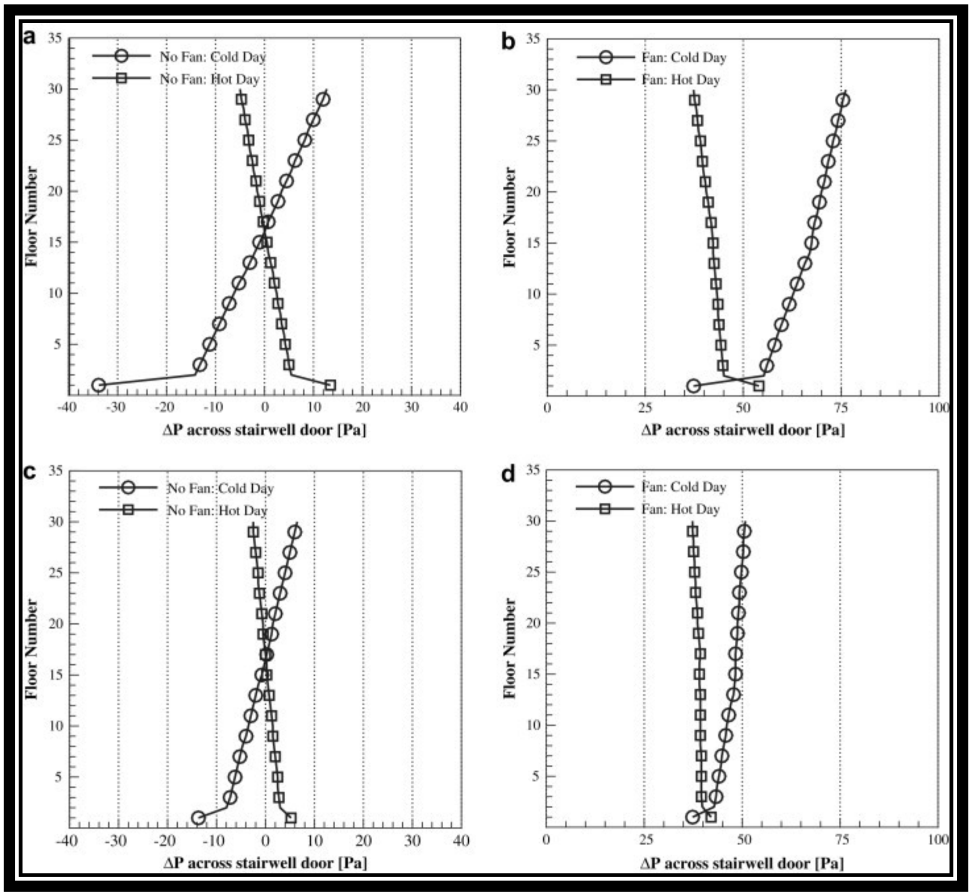

Figure 23- Pressure difference of stairwell door [36].

2.10 Fire safety and evacuation in high-rise buildings

High-rise buildings are not inherently dangerous structures but require additional attention when it comes to the design of these types of buildings. Every year there are terrible tragedies caused by a fire in high-rise buildings, which affects the lives of thousands of people. Awareness and training are important for both occupants and service personnel to be able to reduce the risk. There are buildings that are labeled as the world's tallest buildings, which require more complex designs and systems. Often there are special methods used to protect these buildings. The security of these types of buildings is more complex due to the existence of multiple occupied floors, especially in residential buildings, which means a higher concentration of the occupants. Depending on the location of the building, reaching the area for assistance during an emergency might be difficult. Due to the vertical nature of these buildings, the probability of a large uncontrolled fire moving skyward is very high. Based on a study conducted by Hall Jr JR., in modern buildings, special fire protection requirements are reflected in strict laws, codes and standards. These requirements are designed to provide life safety. However, they might not completely consider people's behavior, readiness and reaction at the time of emergency. Therefore, the management programs to provide sound fire life safety program has an important role as well [37, 38].

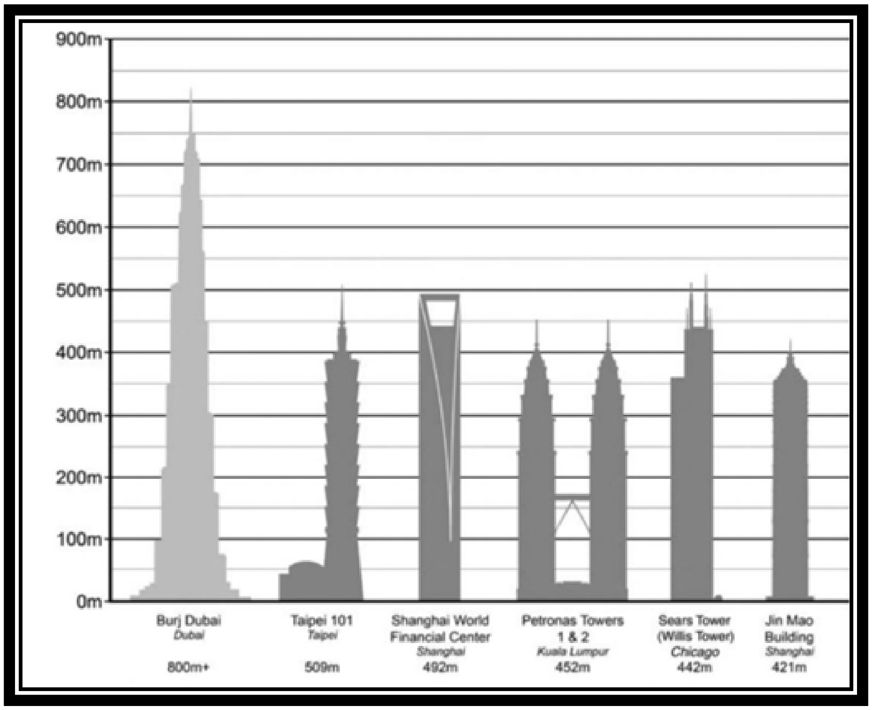

Figure 24- World's tallest buildings [37].

Based on the information gathered by U.S. fire departments, in 2007-2011, 15,400 fires were reported in high-rise buildings. These incidents caused 46 civilian fire deaths, 530 civilian fire injuries, and $219 million direct property damage. 45 percent of these fires were reported occurring in residential buildings. Studies showed that among all these fires, the risks of fire in high-rise buildings were lower compared to the other types of buildings. The greater use of fire protection systems in this type of building is believed to be the main reason. Figures 25 and 26 illustrate that 50 percent of these fires in high-rise buildings had a fire-resistive construction, and 47 percent of them were protected by sprinkler systems. This shows the importance of having a fire protection system and its effect on reducing the probability of flame and fire damages beyond the room or the floor of the origin. The control of fire from spreading to other zones has a direct relation with the material used for construction. As can be seen in figure 23, a smaller number of fires started on the lower floors as there are fewer combustible materials in basement levels of a residential building. 82 percent of the fires happened on the upper floors as these floors are less accessible and take longer for the fire department to control the fire [39].

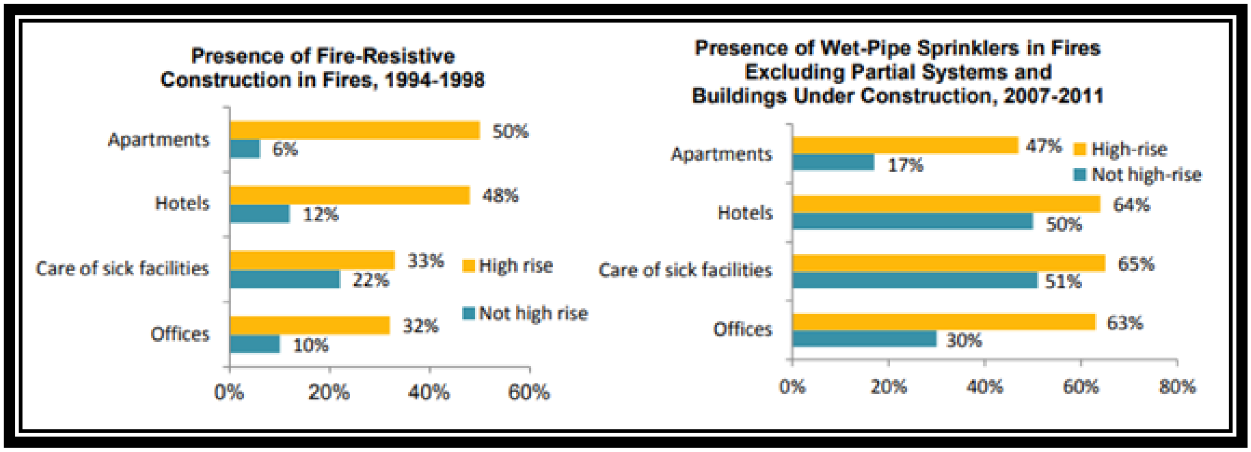

Figure 25- U.S. high-rise building fires 2007-2011 [39].

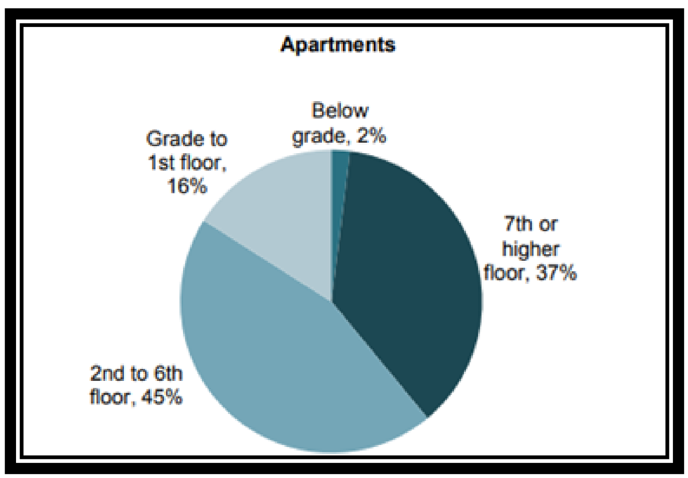

Figure 26- U.S. high-rise building fires by the level of fire origin [39].

Risk in high-rise buildings can be calculated as a ratio of a measure of fire loss to a measure of units of exposure. Exposure refers to people, space, or material that can get damaged or harmed during a fire. The percentage in Figures 25 and 26, as well as the data collected by the U.S. fire department, indicate that the high-rise buildings with sprinkler systems have a lower risk. The focus of this study is on the importance of fire protection systems in residential high-rise buildings [39].

High-rise risk is expressed as follows:

[loss in high-rise buildings]/[units of exposure of high-rise building]

= [(high-rise % of loss) × (total loss)]/[(high-rise % of exposure units) × (total exposure units)]

Equation 3- Risk calculation in high-rise building [39].

To be able to minimize the risk, it is important to identify the key behavioral factors affecting the evacuation, to understand the existing procedures and strategies in practice for high-rise buildings, and to review the capabilities of evacuation models that are in use. Studies show that the evacuation models are an effective method to plan safety programs and to find strategies to improve the safety of people. The suitability of these models depends on their flexibility in representing different evacuation patterns and complex behavioral processes. Since the 1960s, high-rise buildings are a great concern for committees working on codes. The design of exits and travel time for evacuation purposes was the main focus of code experts in the 1970s and 1980s. In 2005, with the terrorist attack of 9/11 in the World Trade Center, the importance of providing means of egress and detailed planning in case of emergency became the focus of the code experts. Evacuation models and fire incidents are used to define a structure for a safe design [41, 42]. Analyzed materials for the purpose of the World Trade Center are categorized into three main categories:

1. Human behavior in a high-rise building during fire evacuations
2. Egress components and strategies
3. Modeling studies

Like any other studies in the field of fire protection, analysis is limited to the available data from human behavior in real fire incidents. The literature review is limited to high-rise buildings evacuation studies, including human behavior in fire, occupant relocation strategies, and modeling studies. Behavioral associated with each type of building is studied. In each building, the factors that can affect the evacuation are the design, the characteristics of the population, the training given to the population, the available staff and fire safety protection systems in service. In office buildings, generally, the designs involve open floor plans which allow the fire and smoke to spread in a greater zone. Occupants are usually better prepared to evacuate and mostly trained through evacuation drills. In residential buildings, occupants might be asleep or not dressed. They are also emotionally tied to their belongings that need to be left behind. All these result in delays in the evacuation process. In most cases, occupants of the residential buildings are not trained for an emergency evacuation. One of the advantages of residential buildings compared to other types of buildings is their design that consists of smaller compartments which limit the fire and prevent it from spreading to other zones very fast [43, 44]. This allows the fire department to plan the evacuation and not have a high volume of occupants during the evacuation process.

In case of an emergency, the evacuation of a high-rise building depends on the available paths and exits. Stairs are one of the traditional methods of evacuation that is addressed by NFPA101- Life safety code. There are many aspects that need to be considered in an evacuation process, such as the gender or role of the occupants, which can affect the evacuation performance and behavioral perspective. Merging behavior has a major impact on evacuation, as well as the total time [45]. Another method of evacuation is evacuation elevators. In traditional concepts, elevators should not be used in case of an emergency. But as buildings are getting taller, evacuation using staircases is taking longer and not realistic. Also, the evacuation of people with disabilities or limitations is a concern. As a result, The American Society for Mechanical Engineers (ASME) committee is in charge of investigating the methods and technologies in order to use elevators during evacuation [46]. The behavioral factors and their impact on evacuation strategies using elevators are in the investigation. Therefore, in most designs, this method is only used as an alternative due to the limited studies performed on this topic [47, 48].

Sky-bridges and refuge floors are two other alternatives, which, due to their complex design, are not commonly practiced. Fire-bridge is used to link towers and allow occupants to travel from one tower to the safer tower. The purpose of refuge floors is to hold occupants in and give them the required time to rest and meet with service people at rescue points. These floors are also being used as a firefighting base [49, 50]. Another means of escape is helipads. However, due to the complexity of the work and extremely dangerous procedure, they are not mentioned in any standards in the U.S. and most other countries [51].

2.11 Fire Dynamics Simulator (FDS)

The Fire Dynamics Simulator and Smokeview are the products of an international collaborative effort led by the National Institute of Standards and Technology (NIST) and VTT Technical Research Center of Finland [52]. In our case, the focus of the study is on the effect of the ventilation system, pressurized staircases, and smoke control on the safe evacuation of the occupants. Smokeview allows us to see the effect of the ventilation system in a building. By describing velocity boundary conditions for each compartment, the effect of air supply on the smoke and heat transfer can be drawn. To reduce the simulation time, the air-supply system for the case can be simplified. Flow losses are proportional to the square of the velocity. As a result, an equivalent duct length and representative area of it can be used. The effective loss of the duct can be calculated using the formula 9.1 from the FDS guide, shown in equation 4.

$$\boxed{K_{\mathrm{eff}} = \sum_i K_i \frac{A_{\mathrm{eff}}}{A_i}}$$

Equation 4- Effective loss of a duct [52].

Where i is a fitting, and A_i is the area associated with the fitting loss [52].

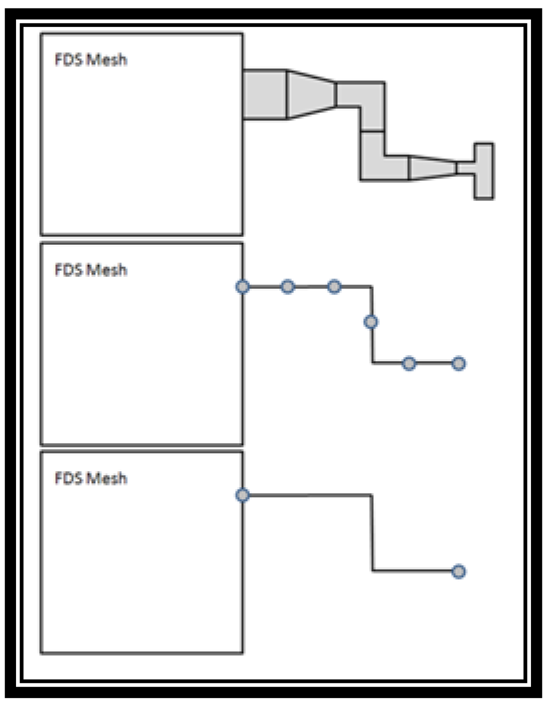

Figure 27 - An example of simplifying a complex duct [52].

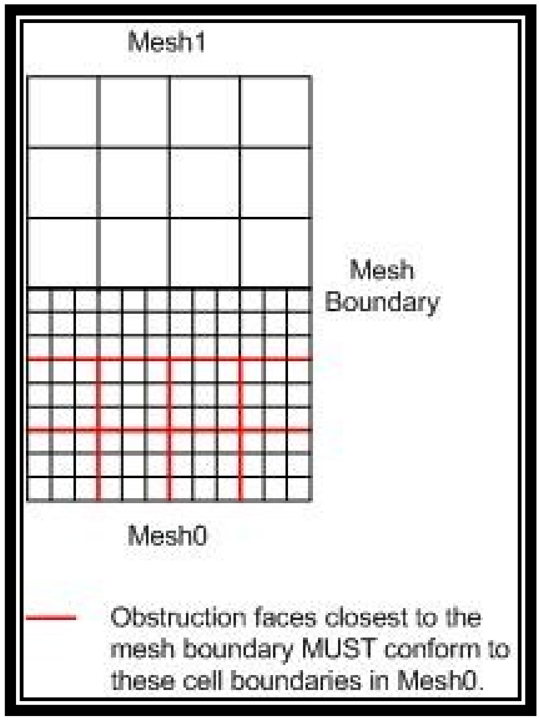

Figure 28 - FDS mesh Boundary [52].

In the HVAC model, for a supply fan with a solid boundary, the surrounding pressures are not considered, and the fan is specified with a Volume-Flow. The fan curve where the pressure drops are as shown:

$$\dot{V}_{\mathrm{fan}} = \dot{V}_{\max}\,\mathrm{sign}(\Delta p_{\max} - \Delta p)\sqrt{\frac{|\Delta p - \Delta p_{\max}|}{\Delta p_{\max}}}$$

Equation 5 - Volume-flow for a supply fan with a solid boundary [52].

Fire Dynamic Simulator (FDS) plays an important role in fire investigations. In general, the comparison of the simulation results from FDS and the actual fire scene can help the engineers and professionals in improving their design to have a safer building. Multiple strengths of FDS is proved by looking at different fire experiments. Where a small room or a large pool fire in a large-scale experiment is a risk, FDS can be used as a tool. The model results were compared with the experimental data from Factory Mutual (FM Global). The advantage of the modeling is to reduce the cost and eliminate the danger from a real test or experiment. In addition, the analysis can be run for a longer time [53, 54]. One other important data that was collected from the FDS model is the effect of the wind. In an experimental test, there is no control over the speed of the wind and the ambient temperature. Still, in the experimental model, they were able to analyze the wind effect in the worst situations. The data obtained from these simulations help to improve the code and standard requirements to reduce the risks. For the purpose of this research, the effect of the wind on the pattern of smoke spreading in the high-rise building and also its impact on the pressurization system is neglected.

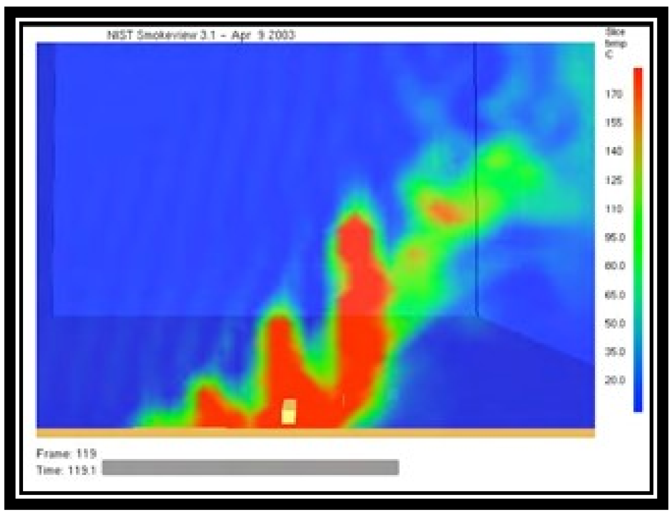

Figure 29- Temperature profile with wind effect [53].

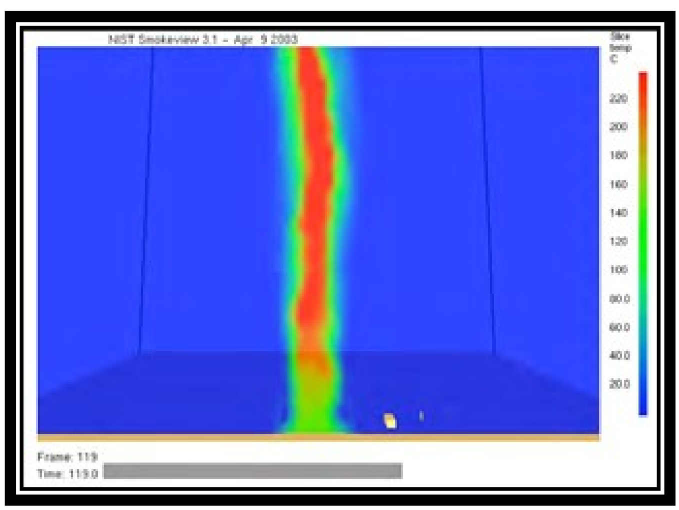

Figure 30- Temperature profile without wind effect [53].

FDS simulation of buoyant fire-induced smoke movement in a high-rise building stairwell is done to determine the required grid resolution. The results of the experimental information and simulation were compared, and it is numerically confirmed that the pressure does not increase with the height in the staircase. Based on the experiment results for temperature, it is concluded that due to fire-induced buoyancy, the smoke moves faster in simulation, and the pressure inside the staircase increases with the height. Figure 31 shows the velocity of the experimental data compares with simulation data [54].

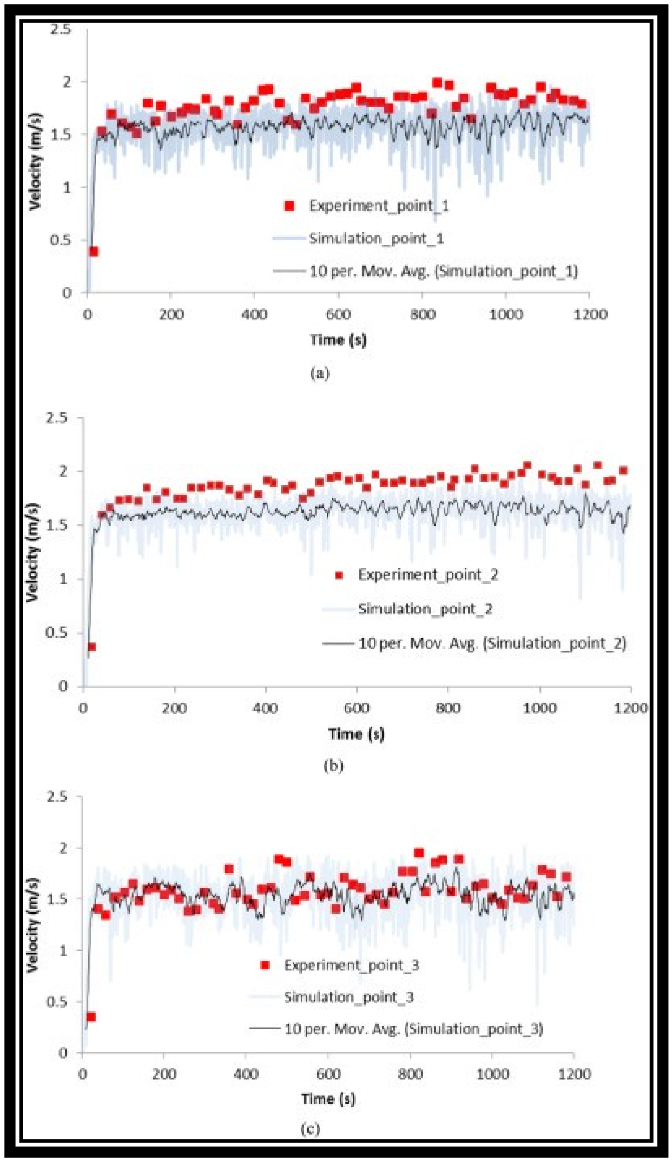

Figure 31- Experimental velocity vs. simulation [54].

Also, as can be seen, the average airflow at the bottom of the opening in the staircase in the simulation fluctuates more than the experiment. Figure 32 shows the numerical study model and the location of the opening. All the measurements for this study are taken at the middle opening on the 4th floor of a 10-story building [54].

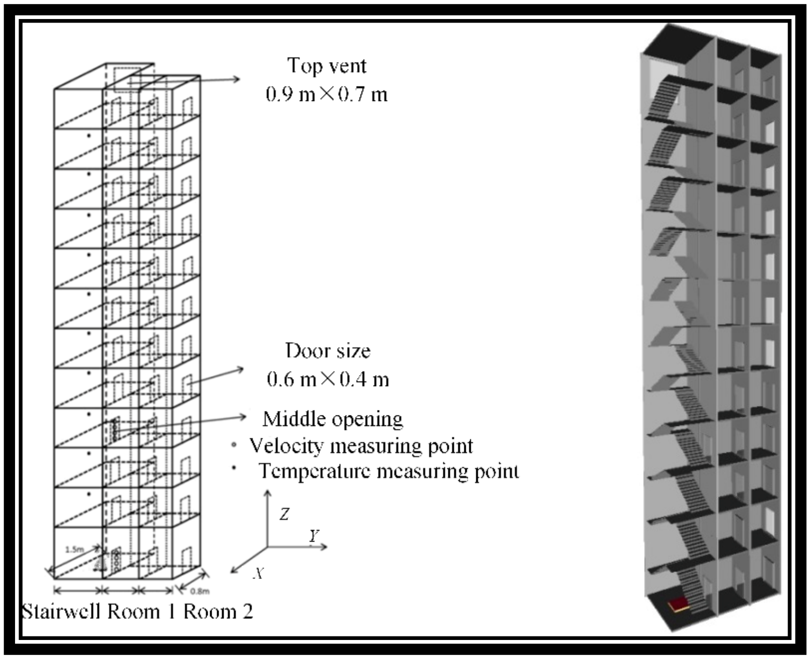

Figure 32 - Numerical study parameters [54].

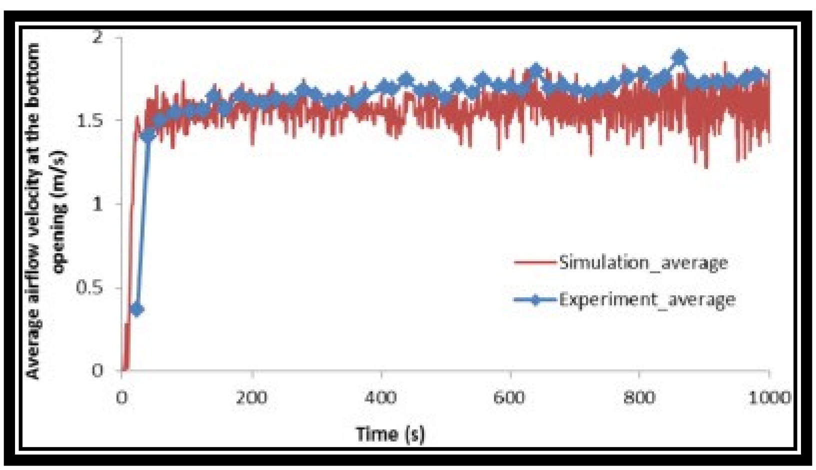

Figure 33- Average airflow velocity at the bottom of the opening [54].

2.12 Summary

In Chapter 2, different studies are reviewed and presented to show the link and importance of smoke control in high-rise buildings and human behavior. Different fire incidents were presented to show the problems involve in each case. Numerical and experimental studies were reviewed to investigate how smoke control can influence evacuation time based on other studies. In most cases, FDS simulation had more severe results compared to experimental results. On the other hand, the fire incidents studied showed that there are many items that cannot be addressed completely in a simulation. The study of the smoke pattern and its velocity showed that openings in vertical shafts could influence the speed of the smoke spreading in the building. The consequence of smoke leaking to other compartments is that the evacuation can be delayed, and the safety of the occupants will be affected.

In some studies, the effect of other fire protection systems, such as detection systems and sprinkler systems, were presented. Sprinkler systems can control the fire, and the right choice of non-combustible or limited combustible material can increase safety by reducing the chance of fire growing fast. The influence of the wind and temperature on the fire and the pattern of the smoke was reviewed using numerical and experimental methods. In Chapter 3, a theoretical study of the smoke control using pressurized staircases using supply fans will be introduced to find methods that can limit the smoke spreading in the building to maximize the safety of the occupants.

3. THEORY – METHODOLOGY

As illustrated in the literature review, the only way to understand the reason behind the fire incidents is to study each case individually. Advance researches in the lab, material testing, approval, and simulations play an important role on the construction materials selection, as well as codes and standards development and guidelines; but learning lessons from the incidents and adjustment of how everything is developed also plays an important role on the safety of the public and the environment. All items mentioned above explains the reason for the need of regulatory changes, and why local governments are forced to perform investigations, why code experts are expected to re-evaluate the local building codes regularly and not wait for an incident.

In this chapter, with the help of few firefighters working for Service Incendie de Montreal (SIM) some of the fire incidents presented in chapter 2 are reviewed. The advantages of having an automatic sprinkler system and pressurized staircases and disadvantages of combustible construction will be discussed from the life safety specialists' and building codes consultants' point of view. Data from the smoke filling process from the fire department employees' point of view, as well as the simulation results from FDS, are gathered, studied, and compared to verify the major differences of the theoretical information versus the real fire incidents. This study is done due to the importance of smoke control in high-rise buildings for the safe evacuation of the occupants.

Due to the interest of SFPE St Laurent Chapter and the department of high-rise buildings of Service Incendie de Montreal (SIM) for future training and research on this topic, this study focuses more on applicable methods that can be presented to organizations that can continue to work on this topic. Smoke control in a high-rise building was introduced to fire protection experts, including fire protection engineers, firefighters, consultants, insurance companies, and contractors during a two-hour presentation on November 28, 2019, in Levis, Quebec [55, Appendix B]. This presentation was hosted by SFPE, St-Laurent Chapter- Quebec, and presented by the author of this thesis and director at this chapter, Shamim Mashayekh Jr. Eng. As the author of the thesis, I am hoping to be able to continue this research to advance my knowledge and be a small help to our fire protection industry.

3.1 FDS fundamentals

Many studies are done focusing on the fire smoke movement inside high-rise buildings using computer simulations. Froude modeling is probably the most common method for smoke movement simulations. Froude number, which is the ratio of inertial forces to buoyancy gravity forces, is shown in Equation 6 with all the scaling relations. Froude number is the base of all the calculations used for this research.

$$\boxed{Fr = U^2/gl}$$

Equation 6- Froude number equation [28].

$$x_m = x_f\,(l_m/l_f)$$

$$Q_m = Q_f\,(l_m/l_f)^{5/2}$$

$$E_m = E_f\,(l_m/l_f)^{5/2}$$

$$m_m = m_f\,(l_m/l_f)^{5/2}$$

$$\Delta p_m = \Delta p_f\,(l_m/l_f)$$

$$T_m = T_f$$

Equation 7 - Scaling relations for Froude number [28].

3.2 Numerical case setup

As described in chapter 2, numerical methods are widely used due to the cost and dangerous nature of fire tests. New ventilation systems installed in high-rise buildings are often put out of service by the fire department as they arrive on site. This practice is followed in many cities around the world, including Montreal. The reason behind is the lack of training for occupants, as well as the uncertainty of the fire department on the reliability of the systems. As a result, in most cases, by setting the system to the manual, they take control of the HVAC system. This chapter presents a numerical model of a pressurized system with an automatic air supply that is kept in service during a fire incident. The goal is to provide supporting data and arguments on why the HVAC system must be kept in service during a fire. Before looking at the numerical model and its geometry in section 3.3.8, there are few topics that need to be addressed for a better understanding of the items that are eliminated or added to the case study. This information is provided in section 3.3.1 to 3.3.7.

3.2.1 Use of combustible materials

Use of combustible materials in the external walls, as it was also seen in Grenfell Tower fire with ACM cladding and combustible insulation and in the Address tower fire, is the reason why the fire spread so quickly on the facade of the building. Based on table 4 in chapter 2, among ten buildings studied by FM Global, only one building had non-combustible exterior construction. In most cases, the fire was able to spread through the cladding due to the presence of combustible materials. A big concern is that due to the limit of the resources and the cost of construction, complete elimination of combustible material is not an option. The combustibility of the exterior construction of the buildings in Montreal is checked by the fire department. This inspection is performed by experienced firefighters to find those buildings that have higher risks. This allows the fire department to provide better emergency planning in case of a fire incident.

Fire can occur in many different circumstances, and having combustible exterior walls will increase the risk of fire spreading through the facade vertically. Also, if the fire finds its way inside through openings, it can grow faster as it will reach areas with available combustible materials. The speed of fire spreading in a building depends on many parameters, including the presence of fuel or other combustible materials and oxygen. The only variable that can be controlled in a fire that starts on the facade of a building is the combustible material, as there is no control over the oxygen provided to the fire, which cannot be taken away. The wind has a direct influence on the fire. As it was also seen in chapter 2, the Grenfell Tower fire spread to the other facades due to the combustible exterior material and also the wind effect.

The vertical travel of the fire on the facade is different from its vertical travel in an interior shaft. Using Fluid Dynamics Simulator (FDS) and noncombustible material, the heat and speed of smoke in a non-combustible building can be calculated. This calculation helps to provide more realistic data for emergency planning. The vertical travel of heat and smoke on the facade and inside the building is a very important point to be studied since it has a direct effect on the safe evacuation of the occupants.

3.2.2 Automatic sprinkler system

From the 1970s, fire protection engineers worked hard and researched to introduce new systems and technologies such as fire alarm systems, smoke alarms, fire sprinklers, etc. to improve the home fire safety in residential buildings. The result of all these works was an important step to build the current codes and standards.

In 1979 and 1980, full-scale fire tests of a two-story dwelling in Los Angeles, California and a mobile home in Charlotte, North Carolina formed the basis of the design criteria of NFPA 13D-Installation of Sprinkle Systems Single and multi-family Dwellings [1]. Different tests were performed to design different sprinklers that each corresponds to a specific kind of occupancy. Residential sprinklers for high rise residential buildings are one of these that is the interest of this thesis. The goal of the industry is to increase the ease of installation and, as a result, reduce the cost of installation without affecting the performance. This will lead to reducing the cost of fire protection systems, increasing the number of residential buildings that are protected by the sprinkler systems, and last but not least, it will increase the safety of occupants [1].

Based on NFPA standards, any residential building with more than four stories, lands under the guidelines of NFPA 13. As it is also mentioned in article A.5.1, residential occupancies are considered a light hazard, but garage spaces, mechanical rooms, storage lockers land under the ordinary hazard occupancy.

A.5.1 Occupancy examples in the listings as shown in the various hazard classifications are intended to represent the norm for those occupancy types. Unusual or abnormal fuel loadings or combustible characteristics and susceptibility for changes in these characteristics, for a particular occupancy, are considerations that should be weighed in the selection and classification.

The light hazard classification is intended to encompass residential occupancies; however, this is not intended to preclude the use of listed residential sprinklers in residential occupancies or residential portions of other occupancies.

A.5.2 Light hazard occupancies include occupancies having uses and conditions similar to the following:

(1) Animal shelters
(2) Churches
(3) Clubs
(4) Eaves and overhangs, if of combustible construction with no combustibles beneath
(5) Educational
(6) Hospitals, including animal hospitals and veterinary facilities
(7) Institutional
(8) Kennels
(9) Libraries, except large stack rooms
(10) Museums
(11) Nursing or convalescent homes
(12) Offices, including data processing
(13) Residential
(14) Restaurant seating areas
(15) Theaters and auditoriums, excluding stages and prosceniums
(16) Unused attics

Figure 34- NFPA 13 - 2013 [7].

Figure 11.2.3.1.1, from NFPA 13, shown in figure 35 of this thesis, provides the guideline for the density requirement of all occupancies, including light hazard, ordinary hazard, and extra hazard occupancies.

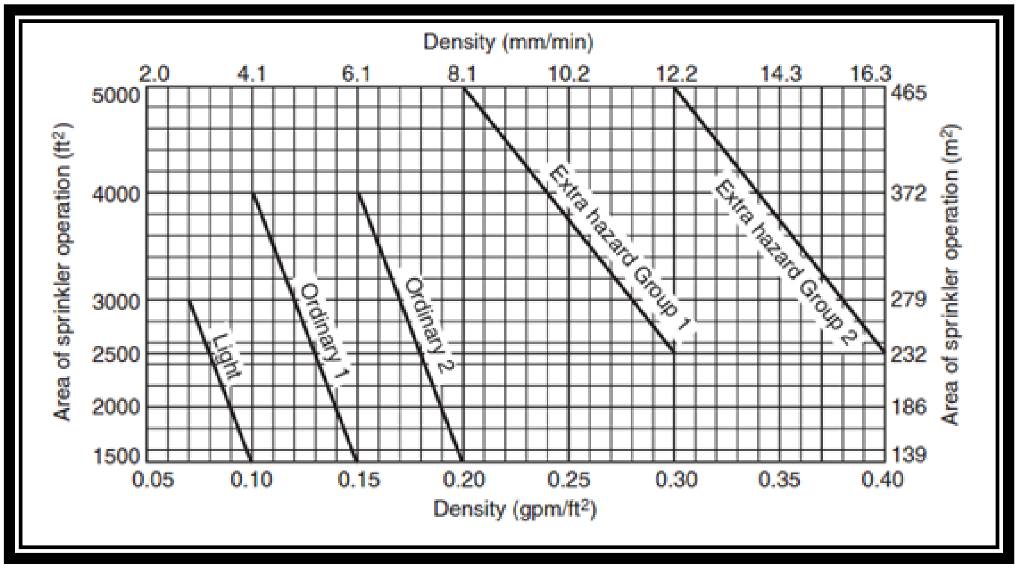

Figure 35- Density/Area curves for sprinkler system calculation [7].

The hydraulic calculation is done using the Hazan-Williams formula, as follows:

$$p_m = 6.05\left(\frac{Q_m^{1.85}}{C^{1.85} d_m^{4.87}}\right)10^5$$

where:

p_m = frictional resistance (bar/m of pipe)
Q_m = flow (L/min)
C = friction loss coefficient
d_m = actual internal diameter (mm)

Equation 8- Hazen-Williams formula [7].

Hydraulic calculation for the sprinkler system is done based on density requirements using the concept that the flow can be calculated by multiplying the area by the density or by using the pressure requirement of the sprinkler head orifice. the K-factor formula which is calculated from the flow and pressure of an orifice is calculated using the formula below:

$$K_n = \frac{Q}{\sqrt{P}}$$

where:

K_n = equivalent K at a node
Q = flow at the node
P = pressure at the node

Figure 36- K-factor formula [7].

For the purpose of this research, the focus of the design and model is on the smoke control and ventilation system. Since the sprinkler system has a direct influence on the evacuation, it is assumed that the building is not sprinkled. For the purpose of evacuation analysis using Pathfinder, the delay of the occupants and their flow time is estimated for a fully sprinkled building. These assumptions are made based on the evacuation time of the fire incidents discussed in chapter 2, sections 2.1 to 2.7. Sprinkler systems are used to control the fire, to provide enough time to occupants to evacuate and the fire department to fight the fire. Sometimes by mistake, sprinkler systems are confused with the extinguishing system. It is true that in many cases, sprinklers at the ceiling were able to extinguish the fire, but this should not create confusion with regards to their main purpose. According to NBCC, a sprinkler system is mandatory in all new construction, residential high-rise buildings. On the other hand, there are a lot of existing buildings that are not protected with a sprinkler system. Based on the fire cases discussed in chapter 2, it has been decided to look at the worst-case scenario, which does not involve sprinklers. As a result, all the analysis prepared using FDS is done with the assumption of no sprinklers in the building that can affect the pattern of the fire and smoke.

3.2.3 Detection system

In theory, all buildings that are not sprinkled are forced to at least have one or multiple detection systems, i.e., a smoke or heat detector. These detection systems can be addressable, meaning they are connected to the main alarm panel and will send a signal to the alarm panel or in some older building non-addressable, which means only the occupant near the detection system will hear the alarm. In this scenario, the occupants should use the pull stations to activate the alarm system and contact the emergency services. In Canada, there are still a lot of buildings that are not provided with sprinkler systems. However, all buildings which need to meet the criteria of NFPA13 have at least the addressable alarm system. This has been decided since notifying the occupants has a direct relation with the safe evacuation of the building; for this study, it is assumed that all occupants are notified about the fire in the first few seconds that the smoke detector is activated. Based on a survey on random people in the city of Montreal, the different delay time is set for each occupant before evacuation. A full report of this survey is provided in the appendix section. For the purpose of this research, it is assumed that the is a single interlock alarm system available that notify the occupants. As a result, all occupants, after hearing the alarm sound start to evacuate the building.

3.2.4 Stair Pressurization systems for smoke control

Staircases are considered the principal route for escaping during a building fire. To be able to maintain the staircases safe and free of smoke during the evacuation, the pressurization system is used. An initial model was simulated using FDS with the normal opening in a high-rise building and not pressurized stair shaft to present the smoke travel in most of the existing buildings. Then with the help of the ASHRAE research project (RP-559), a pressurized staircase using a supply fan is modeled to verify its effect on smoke travel patterns [56, 57, 58]. For this study, the pressure loss through the doors during an evacuation is neglected. For this model, the air supply fan is added in the staircase at every floor to provide a positive pressure. To be able to keep the balance between the positive and negative pressure in different zones, air vents are also added to the apartments and common areas. More detail about the size and location of the air supply system will be presented in the following sections.

3.2.5 Fire Dynamics Simulator

Fire Dynamics Simulator (FDS) model developed at the National Institute of Standards and Technology (NIST) in the USA is used for the purpose of this study. FDS, which is developed by McGrattan, is a large eddy simulation (LES) computational fluid dynamics (CFD) model, which numerically solves the Navier-Stocks equations for the transfer and smoke [59]. The results are visualized by Smokeview, which allows a three-dimensional view of the results. FDS gives the option to add slices in different locations to track different parameters. The slices added for this study measures the temperature and pressure difference of smoke as it spreads in the building.

3.2.6 Smoke filling

Fire Dynamics Simulator model is used to compare the simulated data with the data that is expected from the data analysis discussed in chapter 2 and information gathered from the fire department reports. According to the information available on the NFPA website, a great percentage of the deaths are caused by smoke inhalation compared to the fire itself. FDS allows calculating the smoke layer height based on the vertical temperature profile. Given the information above and using the formula below, z_s, which is the smoke layer height, can be calculated. z indicated the floor. S is the temperature. The integral I_1 and I_2 are also defined below. For details of the FDS files, refer to Appendix C.

$$Z_s = [S_1(I_1 I_2 - H^2)]/[\, I_{1} + I_2\, S_1^2 - 2S_1 H]$$

Equation 9- Smoke layer height [59].

$$I_1 = \int_0^H S(z)dz$$

Equation 10 - Integral (I) [59].

$$I_2 = \int_0^H \frac{1}{S(z)}dz$$

Equation 11 - Integral (II) [59].

3.2.7 Evacuation

The main objective in the field of fire protection is the safety of the public and saving human life. Evacuation requires planning and coordination. For every building, codes and standards specify the requirements of the evacuation routes and the requirements of a safe route. For example, the number of exits with respect to the density of people, flow of the flow (people) according to their age and need, location of fire extinguishers, emergency lights, etc. In this study, all the requirements of the emergency route for evacuation, including the evacuation path width and clearance, a sufficient number of exits, and minimum fire rating required is already applied to the building plans. However, in order to find an emergency plan for non-sprinkled existing buildings, the sprinkler system is eliminated. Having sprinklers in a new building is a credit that is not applied for the data in Chapter 4.

In this regard, a survey is conducted, and the answer of random people to a simple question of, "What do you do if you hear the alarm?" and/or "What do you do if you are not sure if you must evacuate or not?" is gathered. Considering that Canada is a multicultural country, we decided to follow a random selection system for this survey. As a result, the answer to this question does not belong to a specific group of age. Also, the selection was not based on the level of education or job status or gender, and individuals were randomly selected based on their interest in participating. For more detail about this survey, please refer to the information provided in Appendix A.

3.2.8 Geometry

A typical procedure was followed using FDS to simulate the pattern of smoke spreading in the building. Using Pathfinder, the evacuation time of the occupants is derived. The geometry of the model is derived from a combination of few residential high-rise buildings built or being built in Montreal. A forty-five-story residential building with four basement levels used as a garage and two above ground level used as common areas. The average height of each floor is estimated to be 3 meters. Walls properties are modeled as “inert.” This model is chosen as a starting base for future research on where a second tower will be added and connected through the common area floors. This model allows us to study smoke control in a high-rise building. The goal is to expand the model in the future and see how fire and smoke can spread from one tower to the other tower or any adjacent building. This goal is set due to the presence of many buildings in Downtown Montreal that are connected by underground tunnels.

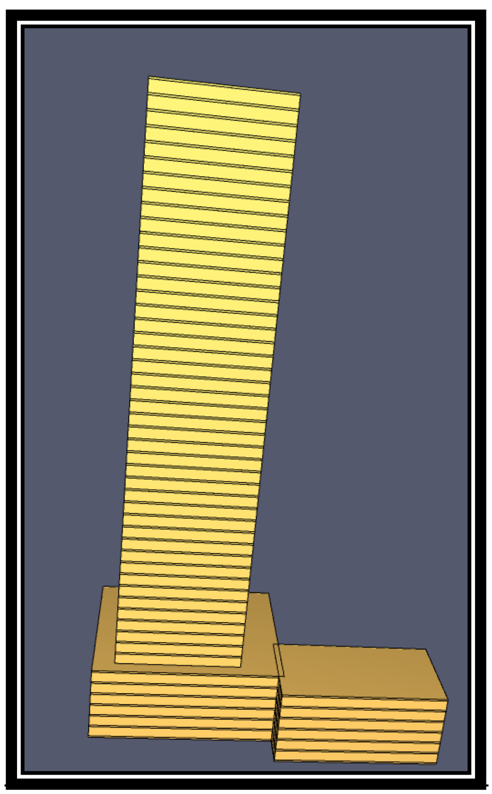

Figure 37- FDS model of the building.

The pool fire size on the residential floors is assumed to be 2 MW and in the basement level 7 MW with a dimension of 1 meter by 1 meter. Simulation is completed for 1000 seconds, considering that, on average, the fire department should arrive on-site in less than 10 minutes. Pathfinder is completed for 1103 seconds, which is the time it takes for all those occupants to evacuate the building. 1 CFM of airflow is assumed per each square meter of the unit. The size of the vents is all assumed to be 0.5 meters by 0.5 meters, e.g., the supply of 6.18 m^3/s, exhaust 0.3 m^3/s. Because of the vent quantity and the layout of each apartment that is unique, some airflow is different. For FDS simulation, no opening to the outside is considered, and the only force is the mechanical ventilation units shown in yellow in figure 38. For supply vent, one supply is assumed per floor in the staircase. For Pathfinder and evacuation process, the main exit is considered the main door to the residential tower shown in green in Figure 39. It is assumed that the other emergency exits are not used, and all occupants evacuate the building from the main entrance/exit.

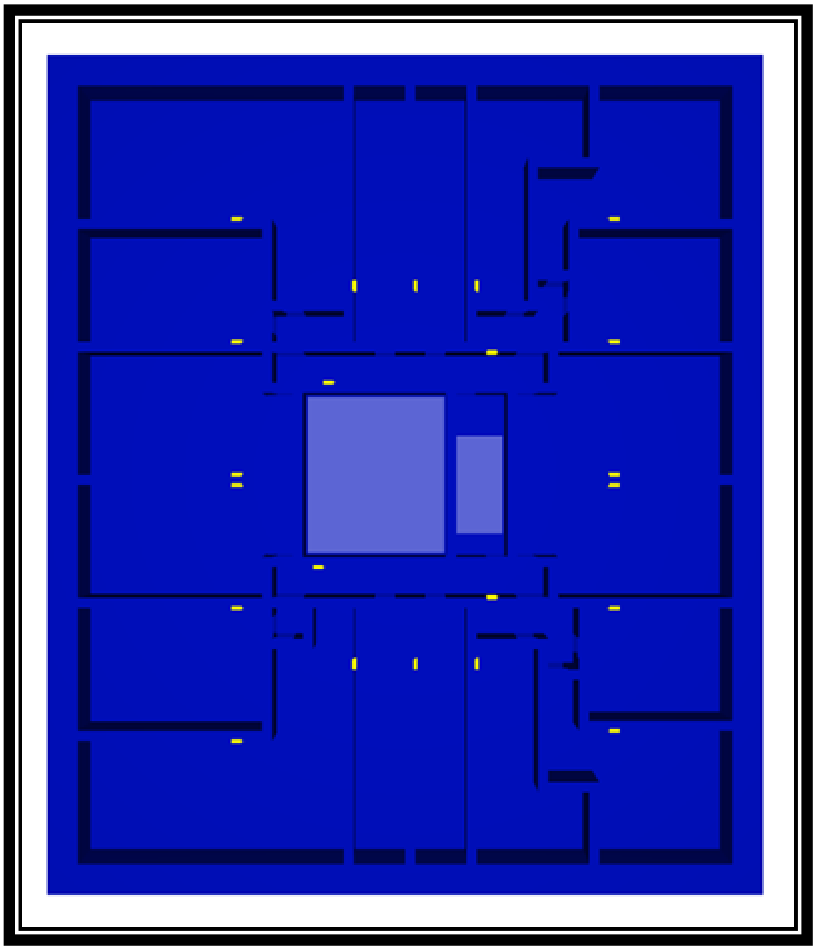

Figure 38- FDS vent locations.

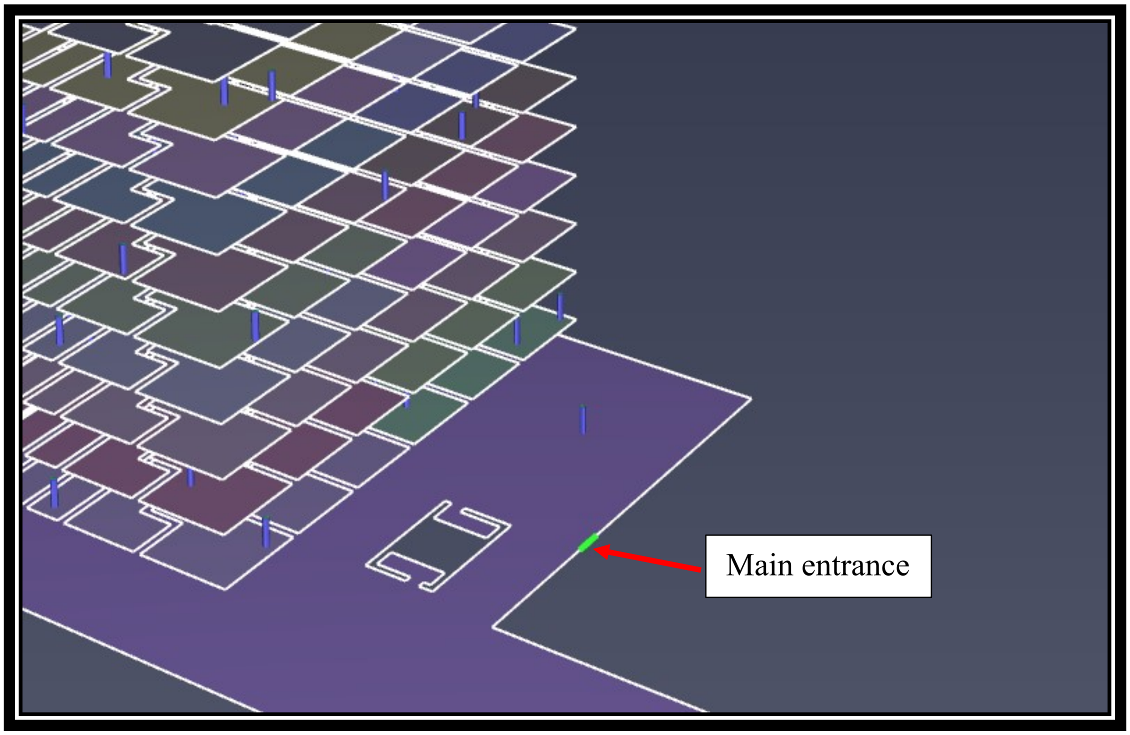

Figure 39- Pathfinder opening.

Table 5- Geometry of the pull fire.

Occupancy	Pool fire size	Location
Residential	2 MW	10th floor and 45th floor
Garage	7 MW	2nd basement

In high-rise buildings compared to other buildings, there are several attributes that increase the probability and severity of the fire incidents. These characteristics are listed below:

- Higher occupant loads (In this case study, there are 45 floors of occupied residential units)
- Longer evacuation times
- Access issues for fire departments (In this case study, there is limited access from the street to the building)
- Potential water pressure issues (City supply source might have a drop in the pressure depending on the weather and underground system conditions)

- The potential parallel occupancies (In this case study, there is a mix of residential occupancy which is considered Light Hazard and parking space that is considered Ordinary Hazard Group I occupancy)
- The wind effect on the pattern of smoke inside, and fire and smoke movement on the exterior walls and façade.
- The temperature difference between the interior and exterior.

In the early building codes, at least one exit stair in buildings over a certain height was required. In the present code, buildings similar to our model building require to have at least two pressurized staircases. Any building that has an occupied floor of 23 meters (75 ft) or more above the lowest level that fire department truck can access requires to have a positive pressure of a minimum of 0.10 inches water (25 PA) and a maximum of 0.35 inches of water (87 Pa). The vestibules are required to be ventilated. For buildings exceeding 128 meters (420 ft), no additional smoke control system was added in the code. The goal of this study is to provide numerical results to show the necessity of a change. The following article is proof of what Erik Anderson, P.E. is addressing as a concern in the smoke control in very tall buildings [60, 61, 62]:

"Recent editions of the IBC have included additional requirements for buildings exceeding 420 ft (128 meters) in height, such as increases in the minimum construction type permitted, increases in required fire resistance ratings, and requirements for more robust stair and elevator shaft construction. However, no additional smoke control system requirements were added. Thus, regardless of the height of the building, the IBC has never required zone smoked control systems due to building height alone. However, since 2009, the IBC has incorporated language that requires the provision of a natural or mechanical system or method to assist with smoke removal during post-fire incidents clean-up operations in high-rise buildings." [62].

When designing for very tall buildings, we need to consider the buoyancy, expansion, ventilation systems, elevator piston effect, stack effect, and wind effect that drive smoke movement in the building. In this case study, the stack effect, which is the vertical air movement within a building, is calculated. This movement is caused by the air density differences between different compartments and the building interior and exterior.

The pressure difference due to stack effect is calculated using the formula below:

$\Delta p = 3840\ (1/T_0 - 1/T_s)\ h$

Where:

Δp = pressure difference [Pa]

T_0 = absolute temperature of outside air [degree k]

T_s = absolute temperature of air inside shaft [degree k]

H = distance above neutral plan [m]

Equation 12 - Pressure difference [61].

Table 6 illustrates the impact of the height on the stack effect. In this study, the supply air is kept constant by adding a supply fan to every floor in the staircase, but the pressure difference is increasing as the smoke reaches the higher floors. Table 6 shows the effect of the height at a fixed temperature on the pressure difference. As can be seen, as the height decreases, the pressure difference will decrease too.

Table 6 - Stack effect induced pressure differential by building height for a constant temperature [60].

Building height	Outside Temp [˚F] (˚C)	Outside Temp [˚F] (˚C)	Δp [in. w.c.] (Pa)
75 ft (23 m)	0 (-18)	70 (21)	0.08 (20)
300 ft (91 m)	0 (-18)	70 (21)	0.33 (82)
984 ft (300 m)	0 (-18)	70 (21)	0.54 (130)
2133 ft (650 m)	0 (-18)	70 (21)	0.72 (180)

Four different fire scenarios are introduced to FDS:

1. 45th floor, fire starting in the corner unit.
2. 45th floor, fire starting in the center unit.
3. 10th floor, fire starting in the corner unit.
4. Basement 2, a fire starts in the furthest corner from the tower staircase.

For all four different fire scenarios mentioned above, two Pathfinder files are prepared. One during the day was assuming 30 percent occupancy and one during nighttime assuming 90 percent occupancy. There are sixteen units on each floor, and it is assumed that there is a limit of a maximum of two residents per unit. This assumption is made based on the size of the units, the number of bedrooms, and the potential vacancies of some units.

- Occupancy percentage of day time is 30%
- Occupancy percentage of Nigh time is 90 %
- Maximum number of residents per unit: 2 people
- Total number of units on each floor: 16 apartments

Figures 40 and 41 show the layout of the residential floors and the basement plan. On residential floors, the interior partitions in the units are eliminated to facilitate the simulation. Before making this decision, a fire case for an apartment with all partitions was compared with the layout shown in Figure 40. This simulation was run for 160 seconds, and no major difference was observed between the two. As a result, interior partitions are removed. By doing so, simulation time decreased and allowed us to reduce the mesh sizes for more precise results for the same 1000 second simulation.

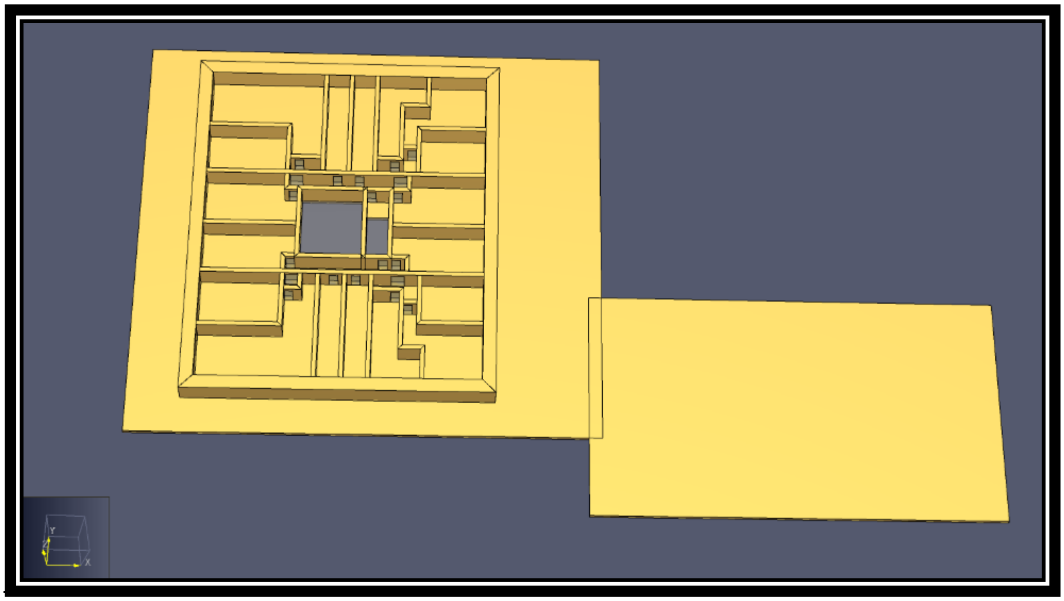

Figure 40- Typical residential floor plan.

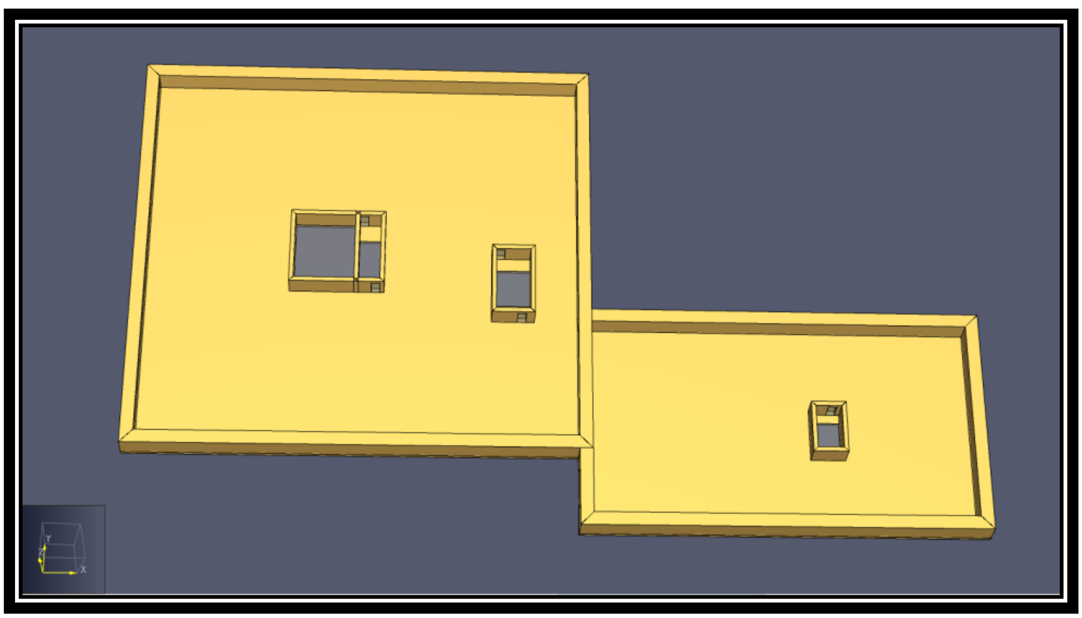

Figure 41-Typical basement floor plan.

Table 7 - Parametersfor FDS simulation.

Mesh size	4,186,688	
Pool fire size	1 m × 1 m	2MW (residential floors) 7 MW (Garage)
Vent size	0.5 m × 0.5 m	
Device locations	Supply vent (one per floor in the staircase) Exhaust vent (as shown in Figure 12)	
Total simulation time	FDS (1000 seconds)	Pathfinder (1103 seconds, full evacuation)
Average total computational time	Three days on a cluster	10 minutes

Mesh size or grid resolution is an important parameter in FDS. Due to the complexity of the airflow based on the assumption of the air supply and exhaust, choosing a higher grid resolution that generates more accurate results is very time-consuming. In this study, since the simulation is limited to 1000 seconds, we were able to keep a balance between the required numerical results output and time. The same grid size and parameters are used for all analyses since the goal is to run multiple fire cases on different floors, assuming that fire department arrival happens right before 10 min. In some cities like Montreal, the fire department switches the ventilation system to manual mode as soon as they arrive on site. This decision has a direct influence on the fire and smoke control. As a result, all the analysis is done assuming that the fire department arrives 10 minutes after the start time of the fire to be able to see the performance of the pressurized staircases and its effect on the smoke pattern. There are many factors that affect the arrival time of the fire department, which will be discussed more in detail in chapter 5, but to be able to achieve our objective, this 10-minute delay does not influence the results at all.

Some parameters, including the location of the heat detection devices, were predicted based on the information gathered from fire incidents. The same parameters are used for all simulations in order to facilitate the understanding of the effect of the size of the fire zone and the location of the pool fire in a high-rise building.

Based on the requirements of NFPA 92- 2012, the pressure differential across smoke barriers shall be 12.5 Pa for a fully sprinkled building. Also, the pressurized staircases have to have a maximum level of pressure that cause the door opening forces to be less than 133 N. Based on the suggested values also shown in Table 8, the design pressure difference for this case study is calculated to be 12.4 Pa. This number is calculated using equation 13 [63].

Δp_{max} = [2 (W-d) (F - F_{dc})]/CWA

Where:

Δp = Maximum design pressure difference [in. H2O] (Pa)

W = door width [ft] (m)

d = distance from a doorknob to knob side of door [ft] (m)

F = total door-opening force [lb] (N)

F_{dc} = door closer force [lb] (N)

C = coefficient [1] (5.2)

A = door area [ft^2] (m^2)

Equation 13- Maximum design pressure [63].

Table 8 - Suggested minimum pressure design differences [63].

Building type	Ceiling height		Design pressure difference	
Sprinklered	Any height		0.05 in. H_2O	12.4 Pa
Not sprinklered	9 ft	2.7 m	0.10 in. H_2O	24.9 Pa
Not sprinklered	15 ft	4.6 m	0.14 in. H_2O	34.8 Pa
Not sprinklered	21 ft	6.4 m	0.18 in. H_2O	44.8 Pa

The effect of the height on the heat release rate and pressure differences in relation to the time will be discussed in detail in the next chapter.

4. RESULTS AND CONCLUSIONS

In this chapter, the results from both Pyrosim (FDS) and Pathfinder will be discussed. For all the detailed output of the software, see Appendix C and D. Due to time limits and similarity of the result of the first and second scenarios, only the result of the second scenario (fire case on 45th-floor fire starting in the central unit) is presented. The only difference is that in this scenario, the fire starts in a unit more towards the middle.

4.1 Smoke pattern

The result from this study shows that the fires starting on the lower floors have more smoke damage to the building, while it leaves more time for occupants on the lower floors to evacuate the building. On the other hand, considering some of the fire cases mentioned in chapter 2, if the fire is not controlled on the lower floors, it might block the passage for the occupants and might also be considered as a danger for firefighters that need to access the upper floors during the evacuation process. Most of the fire deaths are caused by smoke inhalation. Based on the study by Kevin Geidel – CFPS, CET, 57 % of the fire deaths occur outside of the room of fire origin, and 47% of the survivors claimed that they could not see more than 3 meters as they were escaping [60]. Considering that based on the simulation, smoke can travel between 40 and 80 meters per minute if it is not interrupted, the visibility of 3 meters claimed by survivors is a reasonable number [64].

Figure 42 shows the structure of the building. The staircase connecting the basement level and the two common floors are shown in green, and the two scissor staircases connecting the upper floors to the ground floor are shown in red. It is important to know that the staircase shown in red stops at ground level and recontinue under the same shaft but with a minim 1-hour fire separation. This allows us to control the fire and smoke spreading from the higher hazard areas such as garage space and mechanical room to the residential floors.

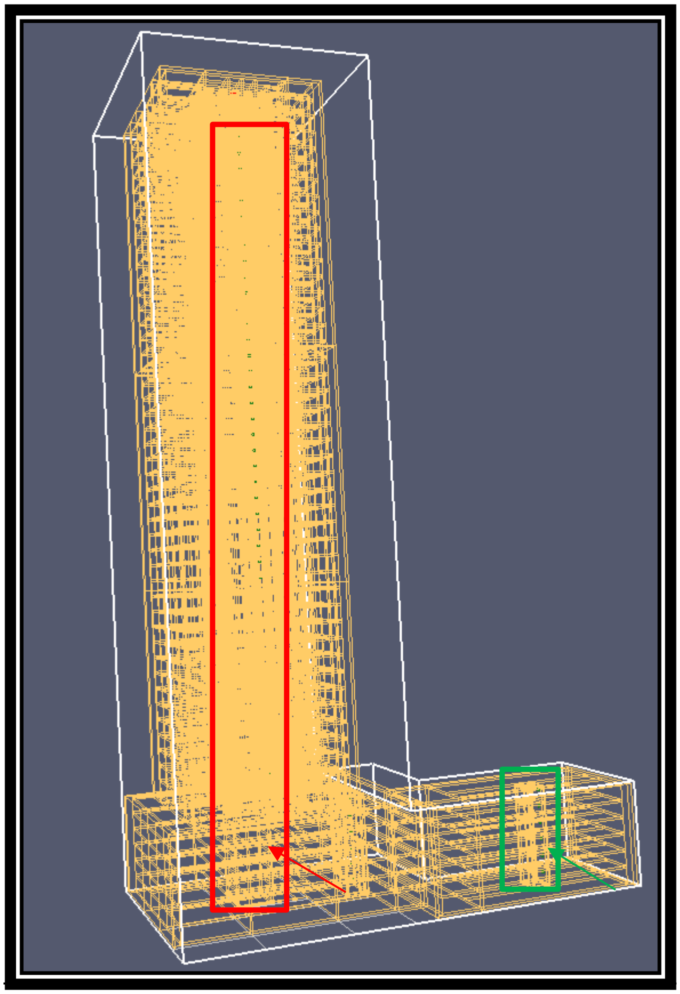

Figure 42 - FDS model staircase locations.

The smoke pattern is studied for each scenario twice; once for when there is no supply air in the staircase similar to many existing buildings built before the 1960s, and once for when the staircase is pressurized, and air supply is added to each level. It is important to remember that the wind effect is not considered for any of the simulations discussed in this chapter. Both figures on the next page (Figures 43 and 44) show the smoke pattern on the fire floor. As can be seen, the smoke spreads on the floor and fills the space. Due to openings including doors, the smoke starts finding its path to the vertical shafts, i.e., staircase. The pressurization system is intended to prevent smoke leaking to other zones or floors by supplying air. Since fans are sensitive to the ambient temperature, the location of the supply fan is very important. As a result, the supply fan for this model is placed inside the staircase on every floor near the doors. Comparing figures 43 and 44 helps to visually see how, without an air supply, the smoke spreads to other floors. This shows that adding a fan has a positive effect on the pressure and the smoke layer.

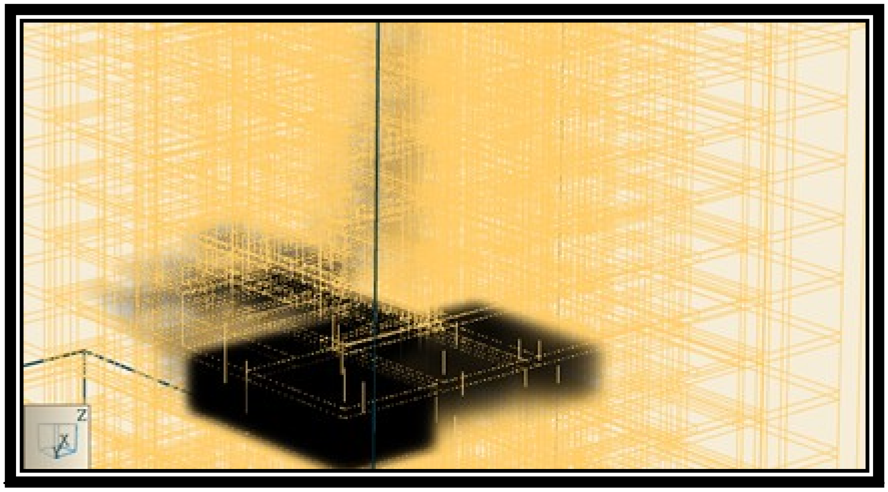

Figure 43- Fire floor without air supply in staircase 68 seconds.

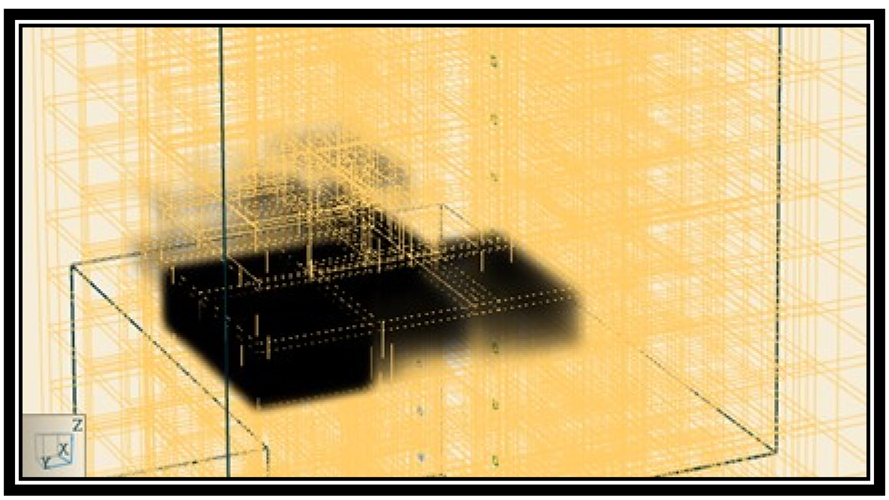

Figure 44- Fire floor with an air supply in staircase 68 seconds.

Both shots are taken at 68 seconds after the fire started, but the only major difference is the smoke that is entering the staircase. But if we compare these two figures with Figures 45 and 46, we can see a major difference between the amount of the smoke accumulating in the staircase at 140 seconds after the fire started where there is no air supply in the staircase.

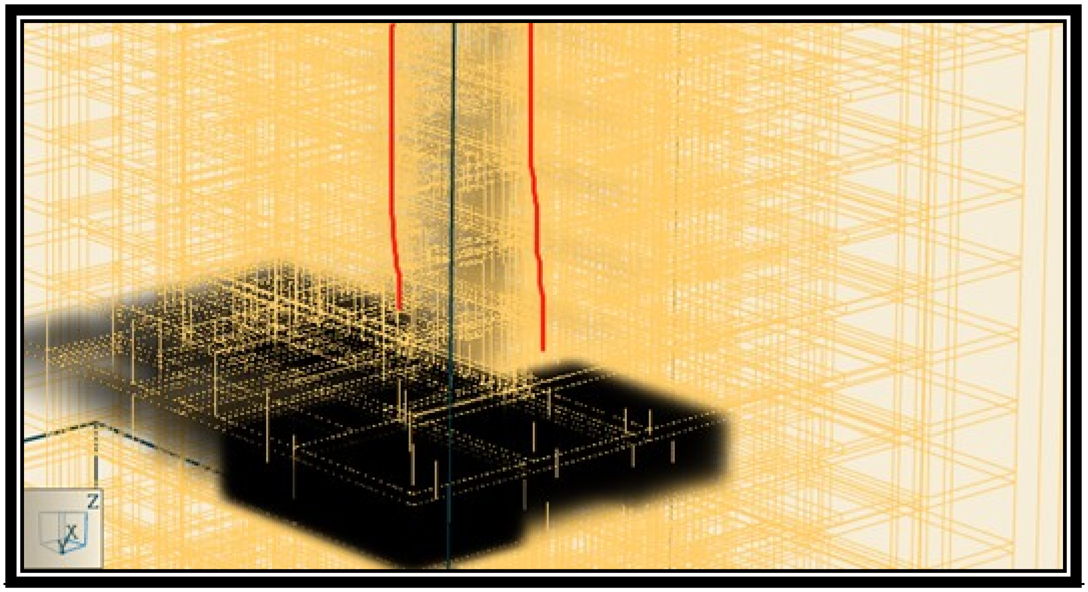

Figure 45- Fire floor without air supply in staircase 140.0 seconds.

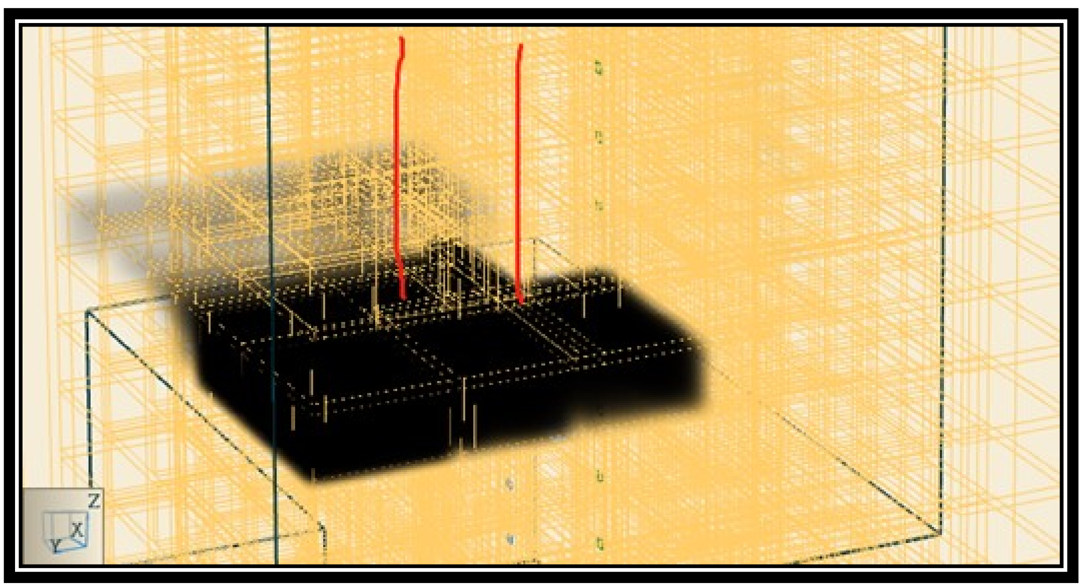

Figure 46- Fire floor with an air supply in staircase 140.0 seconds.

The amount of smoke produced has a direct relationship with the construction material. The smoke production is calculated using Equation 14. Also, the plume temperature is calculated using equation 15. Using the two formulas and the data collected from the detectors in the model, the relation between the height and temperature can be described as shown in Figure 47.

$m = 0.071\ k^{2/3}\ Q_c^{1/3}\ z^{5/3} + 0.0018\ Q_c$

m = mass flow in plume at height z (kg/sec)

k = wall factor (1, ¾, ½, ¼)

Q_c = convective heat release rate of fire (kW)

Z = height above top of fuel (m)

Equation 14- Smoke Production [63].

$T_p = [Q_c / (m\ C_p)] + T_0$

T_p = average plume temperature (˚C)

m = mass flow in plume at height z (kg/sec)

Q_c = convective heat release rate of fire (kW)

C_p = specific heat of plume gases, 1.00 kJ/kg˚C

T_0 = ambient temperature (˚C)

Equation 15- Plume temperature [63].

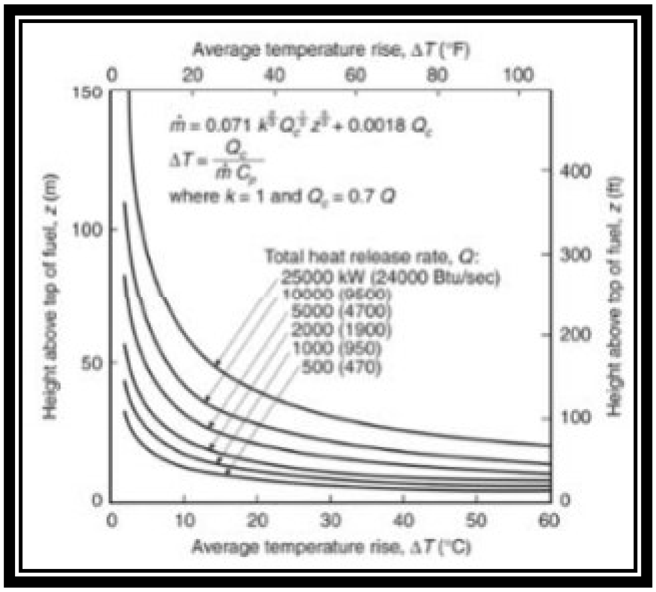

Figure 47- Plume temperature with respect to height [35].

4.2 Smoke layer height comparison

The smoke layer height has a direct relation with the temperature, so it is important to be able to use the proper pressurization system in the staircase to avoid letting the smoke enter the other floor. Also, it is important to use the clean air supply to keep the evacuation path, in case of this research the staircase, free of smoke and heat.

In many existing buildings, self-closing fire doors are in place to limit the fire and smoke in the zone. However, many of these buildings' staircases are not pressurized. For this study, a perfect case that keeps the pressure in the staircase as positive is introduced to achieve the objective of this research. Additionally, due to the presence of many buildings with no pressurized staircases, both cases of pressurized and non-pressurized staircases are studied in order to confirm which works better.

Another important topic to look into is the ways fire departments handle the situation in case of fire. In different cities, because of the variety of types of buildings and fire protection systems, firefighters must take different actions with regard to the incident. For example, in Montreal, SIM takes control of the ventilation system by setting it to the manual mode. As a result, newer mechanical systems such as pressurization systems are set to manual or put out of service upon their arrival. A lot of developers and building owners are aware of this situation. The consequence of this practice by the fire department is that the developers, designers, and professionals consider eliminating this type of system in their design, and we believe this is a step backward.

Looking at open spaces like parking areas, pressurization of the staircases only helps to avoid smoke and heat to enter other upper floors, but the openings such as ramps cannot be eliminated but can be controlled. Figure 48 shows how the smoke-filled the fire floor at 200 seconds after the fire started. Also, the perfect effect of the air supply is illustrated in this figure. As can be seen, smoke was not spread into the lower floors because of the pressurized staircases and also positive pressure provided by air supply fans on each floor.

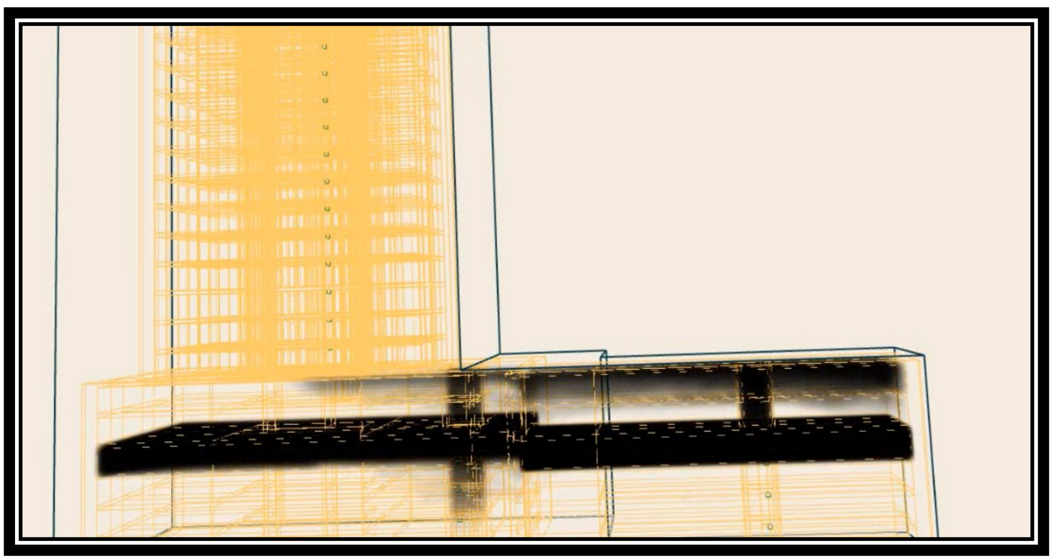

Figure 48- Fire floor with air supply in staircase 200 seconds.

The stack effect that was explained in section 3.3.8 is the main reason why the smoke layer height changes as the smoke reach a vertical shaft from the smoke floor. The stack effect has a direct relation with the temperature, and this can simply be explained in Figure 49. If the neutral plane is set between 49% to 51% of the building height, it can be concluded that the indoor warm air will rise in winter, and the cold indoor air will move downward during summer [63].

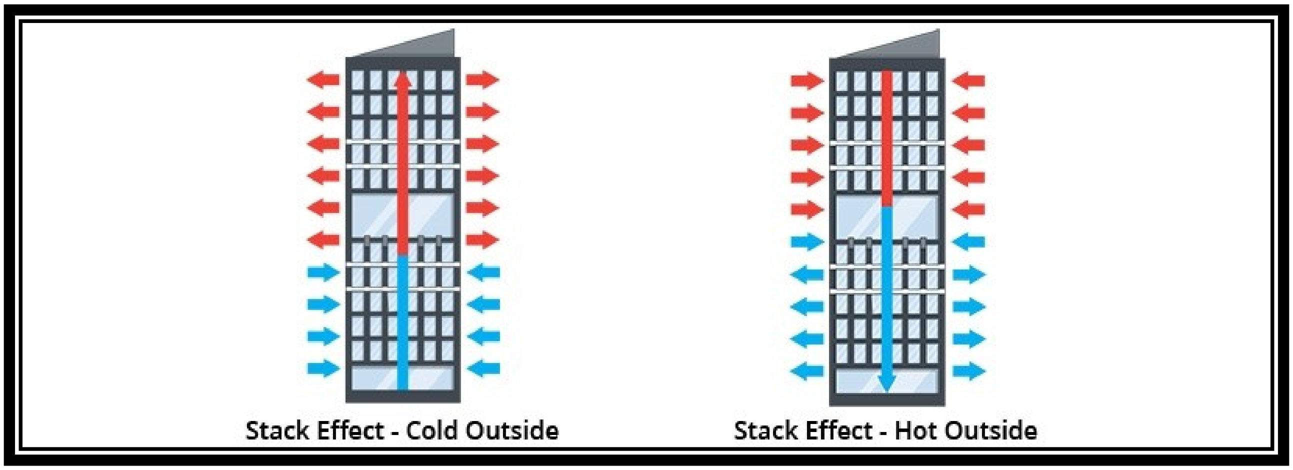

Figure 49 - Stack effect during winter and summer [63].

The heat release rate for case 2 of this study, where the fire starts on the 45th floor in a central unit, is shown in the graph below (Figure 50). Comparing this data and the Smokeview from FDS, we can conclude that from time zero to 200 seconds, the fire was steady. Between 200 seconds and 320 seconds, the HRR increased as the occupants started to evacuate. This is due to the opening of the doors, including the apartment doors and staircase doors on different levels. At 320 seconds, when the fresh air supply starts kicking in, the HRR becomes steady and reduces a bit due to negative pressure on the fire floor.

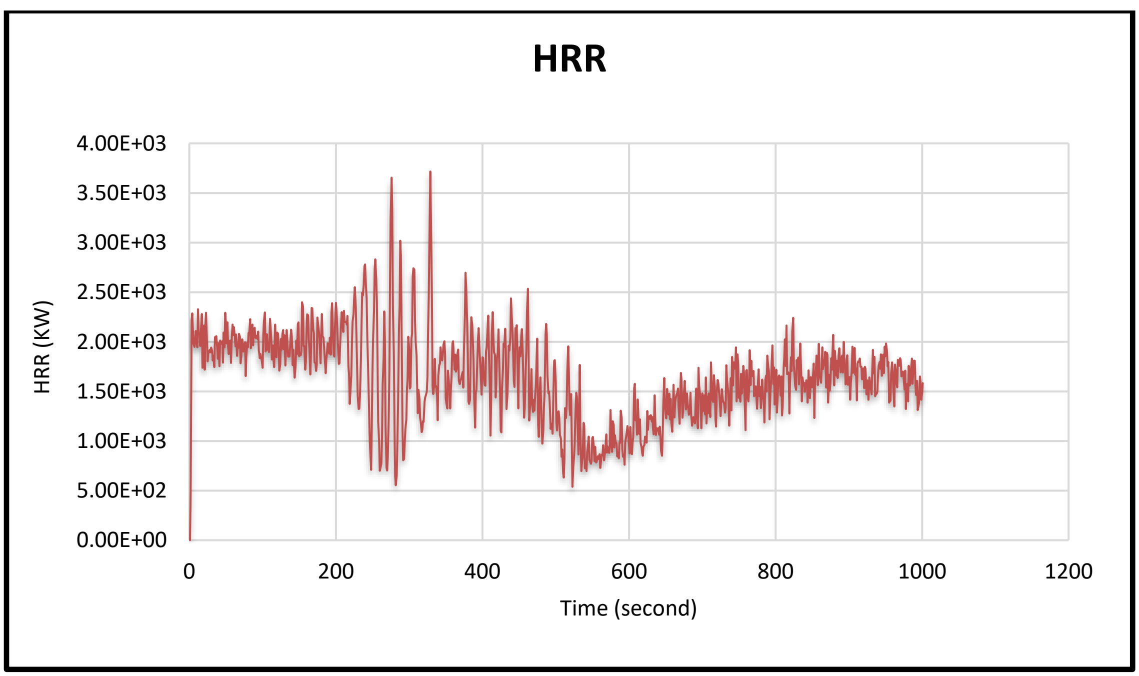

Figure 50 - HRR - Case 2 - 45th floor.

The same conclusion can be drawn for the fire that happened on the 10th floor. The only difference is that the fire on the 10th floor has a lower Heat Release Rate (measured in KW). As already seen in Equation 12 and discussed the stack effect, the movement of the smoke is caused by the air density differences between different compartments. This pressure difference can be calculated using $\Delta p = 3840\ (1/T_0 - 1/T_s)\ h$ [61]. Where h is the distance above the neutral plane. The impact of the height on stack effect and pressure difference explains the reason why the HRR varies.

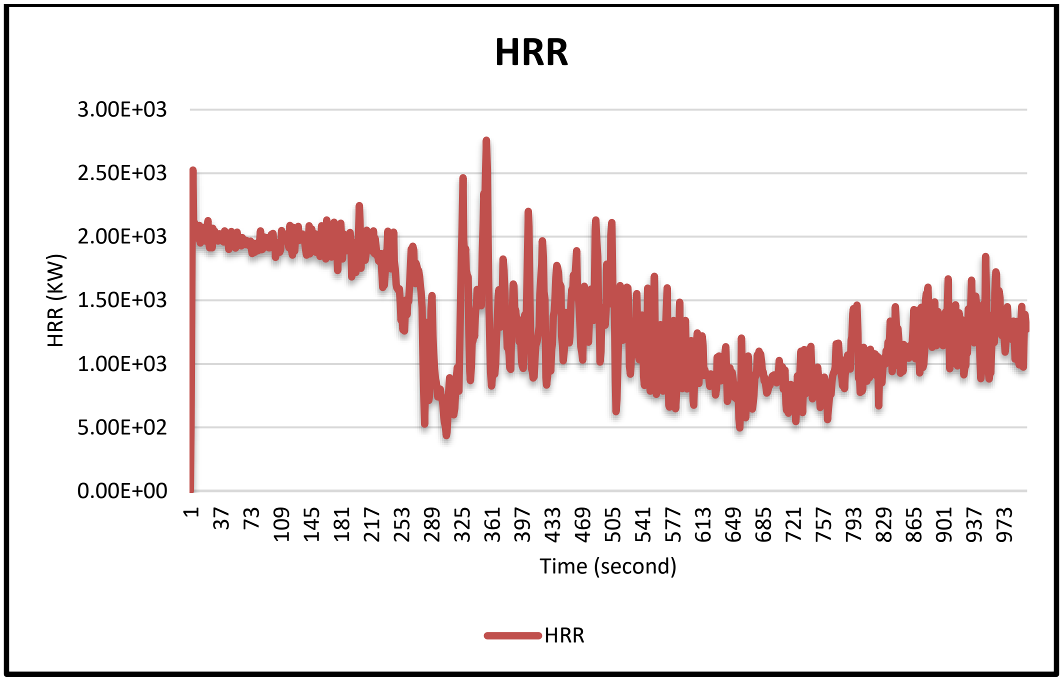

Figure 51 - HRR - Case 3 - 10th floor.

The same conclusion can be drawn for case 3, where the fire starts in the basement, which is considered as an open space and has limited access to the higher floors. Figure 52 shows this difference very well. As can be seen, since the garage space is an open space, the pressure difference between the floors which communicate through the garage ramp is not a lot. As a result, there is not a significant pressure difference that can affect the HRR.

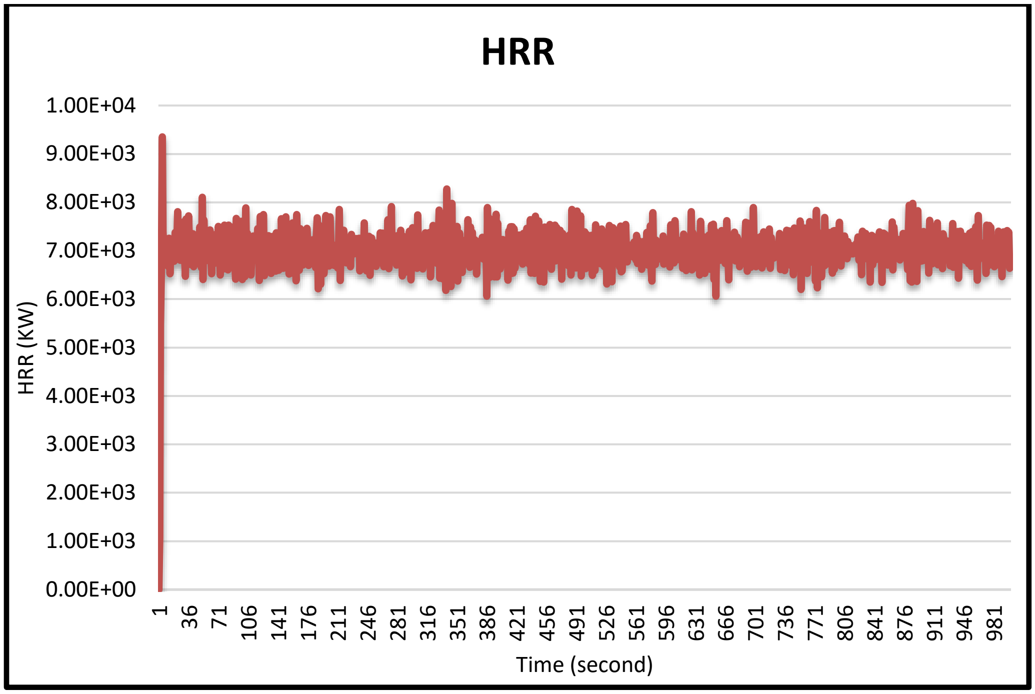

Figure 52- HRR - Case 4 - Basement 2.

4.3 Evacuation and escape time

The escape time depends on many factors, including the knowledge of the occupants on the actions to take in case of emergency, time of detection compared to the start time of the fire, and the ability of the occupants to detect the right path. In residential buildings, the duration of the escape process also depends on the age and physical condition of the residents. The time of the day in which the fire starts is another variable that has an important influence on the evacuation, i.e., at nighttime, people are less aware of their surroundings, which adds more delay.

As a result of this study and a discussion with the employees of SIM and comparing our results with the fire incidents reports discussed in Chapter 2, we can conclude that in a perfect scenario, the detection system will send a signal to the alarm panel which activates the alarm system and the occupants will start evacuating the building in the first 5 minutes. It is essential to consider that during the daytime, there are fewer people in a residential building compared to the evening and nighttime that everyone returns home.

What if the fire is not big and can be easily controlled by the fire department? What if it is better for the occupants to stay in their apartments until the fire department evacuate the fire floors? Based on many research done to generate the codes for buildings equipped with pressurized systems, these systems are in place to help the fire department to evacuate people in phases to avoid issues like all occupants running towards the staircase at the same time. Based on the surveys, and fire drill information from buildings in Montreal, and fire incidents studied for this research, People have different behaviors in real fire situations versus fire drills. In general, fire drills are performed in commercial buildings with advance notice to occupants. But in the case of residential buildings, especially high-rise buildings, a necessitate for public education is felt.

For the purpose of this research, the escape time for each of the fire scenarios of residential buildings was studied. Considering the effect of time on the number of occupants, the simulations were run once during the daytime and once at nighttime, considering that the time of the day affects the number of occupants. The details of the evacuation duration and active time are given in Appendix D. Table 9 shows the exit time, active time, and distance from the closest exit of the first 50 occupants evacuating the building during the daytime evacuation among 486 occupants. As shown in the table, considering the age and physical condition of the occupants, different delays were assumed for the exit time of each person. Most of the delays considered all designed based on the fire incident at Grenfell Tower and World Trade Center. This information is discussed with employees from the Highrise department of SIM, and we believe that the numbers that are drawn are better than fire incidents since the air supply fan helped the evacuation. One other result that confirmed the success of this simulation is the comparison between the exit time and distance of each occupant to the exit, with the Grenfell Tower narrative of people evacuating the building. As also confirmed by the results, the occupants that have a shorter distance to cover for evacuation are not always the first ones that exit. Based on assumptions, some occupants had delays longer than 10 minutes before the fire department take control of the evacuation process. As a result, residents 3, 9, 42, 45, and 48 did not evacuate the building during the expected time, and the fire department has to help them to evacuate. Based on the analysis, most of the occupants that could not evacuate as expected were in one of the units on the fire floors or the floors above the fire origin.

Table 9 - Evacuation result of daytime (first 50 occupants among 486 people).

ID (Occupant)	Exit time(s)	Active time(s)	Jam time total(s)	distance (m)
0	814.95	394.925	0.225	372.902
1	684.45	444.425	0.925	392.929
2	776.225	536.2	0.325	391.033
3	-	0	0	0
4	523.275	433.25	0.425	385.183
5	545.5	425.475	0.875	397.32
6	-	0	0	0
7	786.75	486.725	3.15	409.311
8	816.975	396.95	0.25	374.395
9	-	0	0	0
10	439.85	409.825	0.925	368.857
11	639.175	399.15	0.5	374.787
12	795.15	435.125	1.3	390.967
13	1017.3	417.275	0.35	382.054
14	860.8	380.775	0.2	409.425
15	444.3	414.275	0.4	370.182
16	690.825	390.8	0.7	397.879
17	806.975	386.95	0.225	365.603
18	940.05	400.025	0.25	380.844
19	792.125	432.1	1.525	381.749
20	882.5	402.475	0.525	382.374
21	858.85	378.825	0.25	358.065
22	538.175	418.15	0.475	378.297
23	861.25	381.225	0.25	359.983
24	563	382.975	0.25	363.063
25	1103.1	503.075	0.325	364.953
26	538.275	418.25	0.25	381.863
27	454.2	364.175	1.15	415.441
28	516.375	456.35	0.525	396.887
29	808.825	388.8	0.775	366.294
30	627.9	417.875	0.5	383.278
31	862.225	382.2	0.25	361.985
32	614.9	434.875	0.325	375.672
33	777.325	477.3	3.1	399.011
34	774.3	474.275	1.525	401.197
35	414.2	384.175	0.525	418.743
36	695.925	395.9	0.25	363.856
37	963.575	363.55	0.2	398.095

38	917.05	377.025	0.25	357.522
39	616.375	436.35	0.275	377.966
ID (Occupant)	Exit time(s)	Active time(s)	Jam time total(s)	distance (m)
40	517.75	457.725	0.85	391.687
41	620.8	410.775	1.725	368.421
42	-	0	0	0
43	458.65	368.625	0.25	348.576
44	966.425	366.4	0.25	345.226
45	-	0	0	0
46	706.575	376.55	0.65	349.735
47	1019.725	479.175	0.325	346.752
48	-	0	0	0
49	904.65	364.625	0.25	345.194
50	749.65	329.625	1.375	401.217

Table 10 shows the results of Pathfinder for the evacuation of the first 50 occupants among the 1586 occupants evacuating the building during nighttime. Like daytime results, shorter distance to exit did not lead to faster evacuation. The delays that were introduced to the software worked very similarly to what was expected from fire incidents. Due to the presence of smoke, and based on the number of people, there are times that the occupants are slower in the evacuation. This is shown in the table below under the column labeled as “Jam time.” The “Jam time” is the ensemble of delays caused by people running outside as they hear the alarm, smoke filling the area, and reaching exits or emergency paths that are narrower. Again, similar to daytime, residents 14, 24, 34, and 35 did not evacuate the building during the expected time. Based on the discussion with SIM, while people are less aware of their surroundings during nighttime, they have a better response to the alarm system. However, it still takes longer for the evacuation. These theories might be unique to the cases seen in Montreal and, as a result, are not considered in the Pathfinder simulation.

Table 10- Evacuation result of nighttime (first 50 occupants among 1586 people).

ID (Occupant)	Exit time(s)	Active time(s)	Jam time total(s)	distance (m)
0	997.8	577.775	7.925	420.298
1	1056.275	456.25	0.95	402.314
2	597.65	567.625	12.225	411.225
3	825.55	585.525	21.1	411.924
4	1044.475	504.45	3.5	416.542
5	1041.7	501.15	0.65	414.559
6	892.6	652.575	21.775	396.3
7	613.175	553.15	26.25	417.758
8	680.55	560.525	19.375	417.031
9	1026.4	486.375	1.6	453.034
10	876.9	576.875	11.625	413.139
11	631.05	511.025	12.475	454.651
12	1020.075	540.05	9.025	398.46
13	1021.15	541.125	13.1	393.603
14	-	0	0	0
15	668.85	578.825	25.625	403.975
16	663.85	573.825	23.7	402.457
17	679.575	559.55	20.975	401.543
18	958.725	598.7	33.4	423.636
19	923.375	623.35	21.875	419.618
20	953.775	593.75	25.175	418.772
21	1056	515.975	8.625	409.848
22	660.025	570	23.425	420.923
23	617.75	527.725	13.45	427.988
24	-	0	0	0
25	915.075	615.05	21.825	414.772
26	921.475	591.45	8.475	418.849
27	996.7	576.675	11.375	418.621
28	1057.175	457.15	1.225	394.002
29	829.075	589.05	21.775	411.728
30	757.975	577.95	15.2	405.951
31	1109.15	509.125	1.2	426.368
32	1029.35	549.325	11.95	396.405
33	1032.675	552.65	10.475	405.725
34	-	0	0	0
35	-	0	0	0
36	539.575	509.55	16.7	398.368
37	984.175	564.15	21.9	386.64

38	820.425	580.4	29.275	390.41
39	812.225	572.2	21.775	400.517
ID (Occupant)	Exit time(s)	Active time(s)	Jam time total(s)	distance (m)
40	1106.375	506.35	0.375	421.477
41	649.475	559.45	14.9	395.101
42	912.075	612.05	28.725	409.054
43	1006.375	586.35	6.825	375.51
44	957.975	597.95	22.6	402.506
45	628.5	568.475	13.8	404.399
46	984.625	504.6	11.15	423.094
47	1059.975	459.95	3.15	391.194
48	661.675	541.65	19.425	453.657
49	1107.725	507.7	0.725	414.625
50	993.35	573.325	8.775	412.677

The flow time of the occupants is the time that the occupants take to flow through the exits and escape. This includes the time period in which the occupants are not aware of the fire. They receive a notice, they wait-for guidelines and announcements, and finally, they act and respond to it. From the response time to full escape, the most unexpected factor is human behavior. Therefore, the combination of the results from the observation of occupants' behaviors in real fire incidents and fire emergency situations would provide the best possible solution.

Figure 53 shows the relation between the distance of each occupant to the main exit to the outside and the time that it takes to evacuate. As can be seen, for 487 occupants evacuating the building during the daytime, the exit time (shown in blue) fluctuates even though the distance is shorter (shown in red). So, it cannot be concluded that the occupants that live on the lower floors are able to evacuate faster. We believe that this unexpected result is due to the traffic caused by the higher floors' occupants flowing towards the lower floors while trying to exit the building. The result of the evacuation from Grenfell tower also confirms this. Based on the Grenfell Tower narrative, the last survivor exited the building at 8.07 among 297 occupants. Among 297 people, this person was the 168 person who was able to escape this 24-story building. This person left his flat on the 11th floor at 6.72 and was only able to exit at 8.07. Although this issue can be simply resolved by adding a multi-stage alarm system, due to the cost limitations, it is not practiced in most residential buildings. Multi-stage systems require a full-time staff to be able to respond to alarm panels in case of emergency, and this is not a feasible option in regular apartment buildings. Also, it requires more space in the lobby or entrance for full-time security or service person. In most big cities with high-rise buildings, there is a limit of space, and architects and developers are always in search of more room.

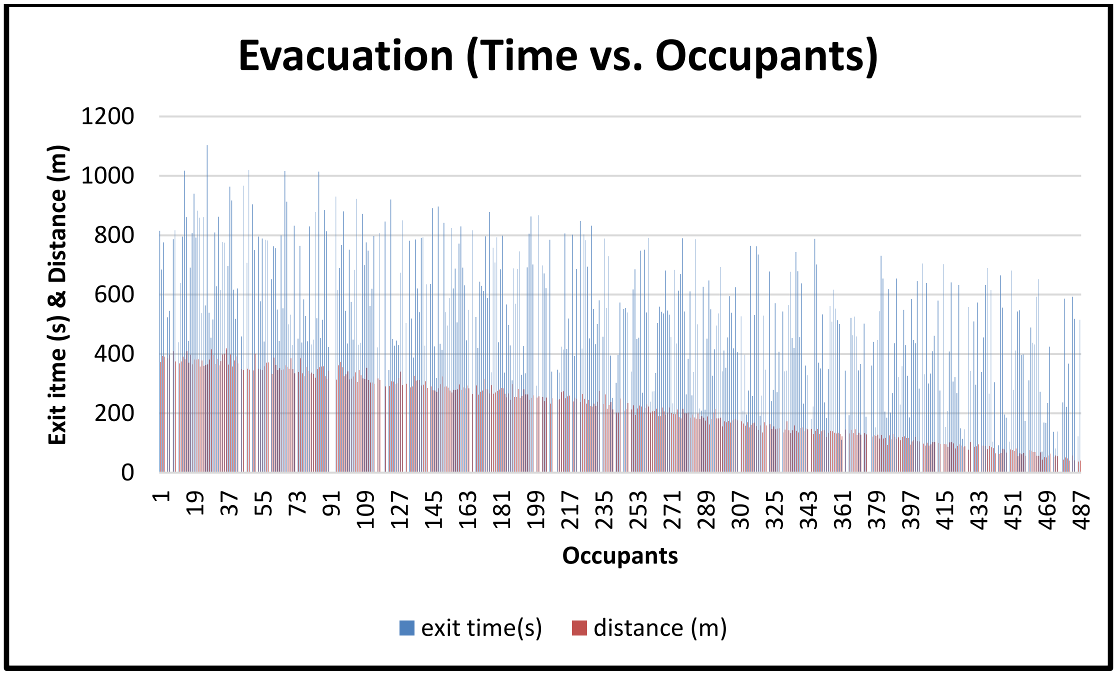

Figure 53 - Evacuation daytime.

The same study is done on the evacuation time versus the distance from the exit for 1586 occupants. The result of this study for nighttime shown in figure 54 is very similar to the daytime result shown above. Hence, the same conclusion can be derived.

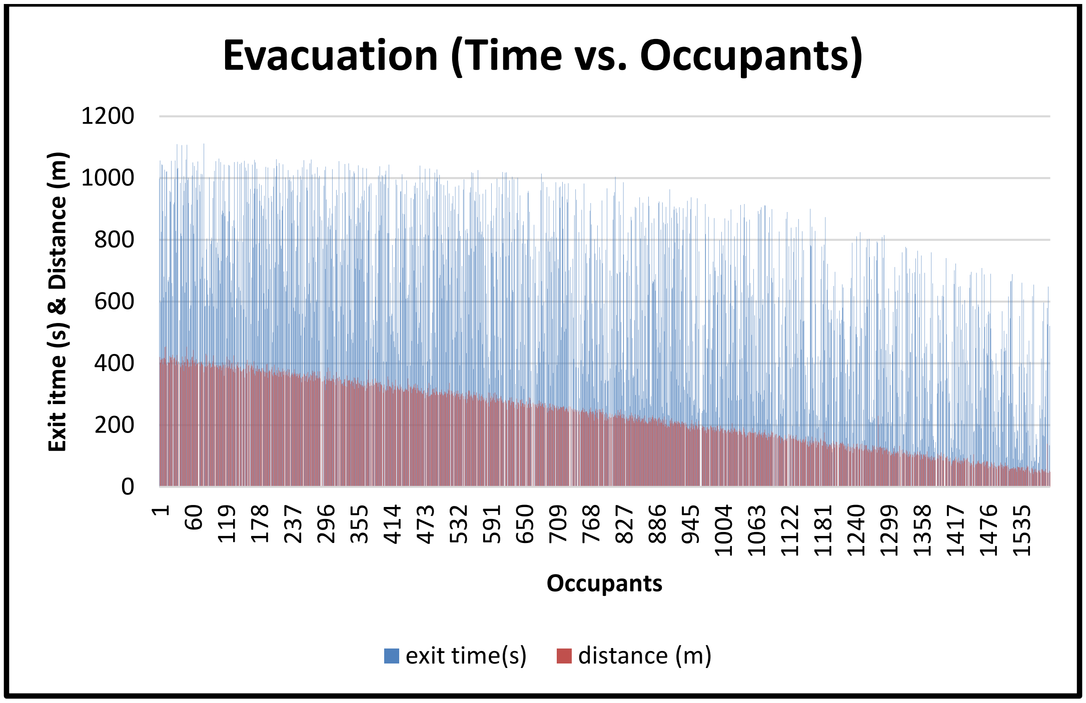

Figure 54 - Evacuation nighttime.

For the purpose of this research, we tried to take all the above points into consideration. For the nighttime case, based on the output of the simulation, the first occupant opened the first door at 68 seconds after the fire started. Considering that occupants had to evacuate the building from the 45th floor, we added some delays to make the model closer to a real fire case. It is estimated that the building was fully evacuated in 1112 seconds, with 1586 occupants. This estimate doesn't consider the residents with mobility problems. Also, it does not consider the fact that some exits might be trapped, and occupants are forced to reroute in order to evacuate.

The same simulation was run during the daytime. In this analysis, we assumed fewer people in the building but a faster response to the alarm signal and evacuation guidelines. Based on the output of the software, the building was fully evacuated in 1103 seconds, with 432 occupants.

Figure 55 shows the visual evacuation path of the occupants evacuating the 10th floor. This model is used to compare the result of the evacuation of the building, assuming the fire department takes control and evacuates only one specific floor. The output of the simulation for occupants of the 10th floor evacuating the building is simulated to be 412 seconds. This time includes the wait time from the time that alarm goes off till the time the fire department starts evacuating this specific floor.

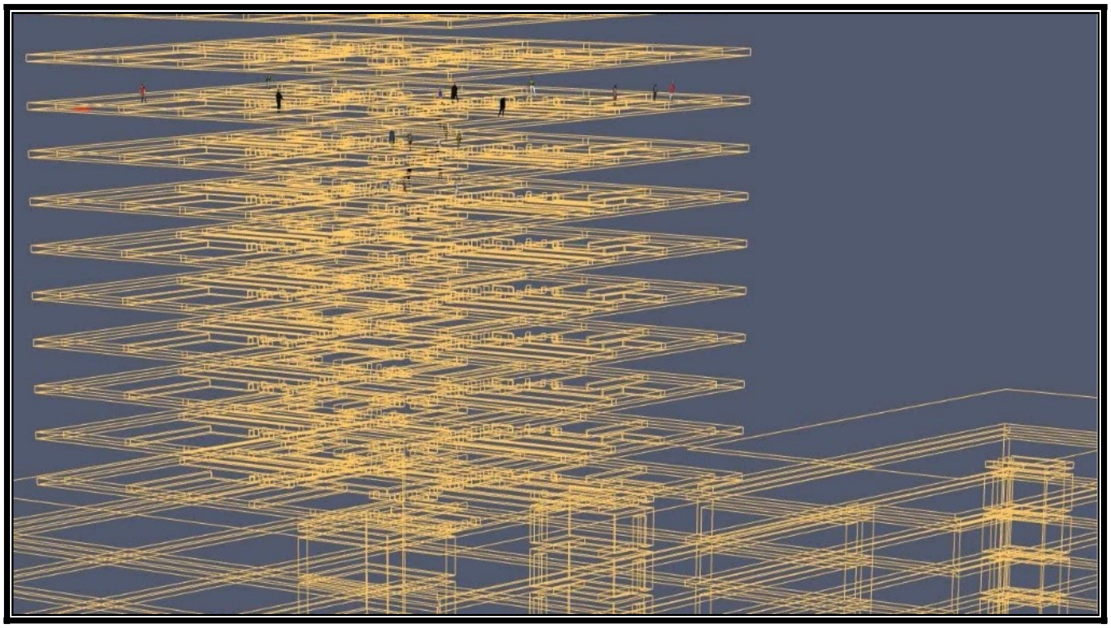

Figure 55- Pathfinder -the evacuation of the occupant from the 10th floor only.

Using a two-stage alarm system compared to a single-stage alarm system that is commonly used in residential buildings can help to resolve some of the problems involved with evacuation. In general, in residential buildings, a single alarm system is used. In this type of system, as a detector detects a signal, occupants are notified by an alarm sound to evacuate the building. The two-stage alarm system is mostly used in residential and commercial buildings where there is always a guard or service person available during day and night. The number of service people depends on the number of occupants. That is why even though this system provides better security, it is not always practical.

4.4 SUMMARY

There is a big discrepancy between real incidents and what studies show. The interest of this research is to verify how the decision of professionals will influence the design and how it affects public safety in case of an emergency. We wanted to point out the importance of human behavior, including the designers, professionals, occupants, and fire service people.

Based on the available data about high-rise buildings, in Canada, there were not many big fires similar to the cases studied in Chapter 2. However, all subjects discussed can have significant impacts in the case of a fire incident. The choice of the construction material, the fire protection systems including sprinklers and detection systems, ventilation system and pressurized staircases, and conformity to the code and standards are the topics that were studied. In a perfect scenario, all building owners would respond positively to AHJ's request on adopting the new codes and standards. Due to the cost of adapting the buildings to the most recent codes, educating the public is a positive step towards the improvement of human safety and reducing the number of tragedies.

In the province of Quebec, there is new legislation about the senior residences that came to effect after a tragedy that happened in January 2014. In this incident, 32 seniors lost their lives due to a lack of a sprinkler system in a section of the building. Based on this legislation, senior houses that do not have sprinkler systems are forced to update their facilities by adding sprinklers. To avoid similar tragedies, there are many actions that can be taken by professionals, authorities, and code experts in order to improve the safety of the public in which high-rise buildings are not excluded from them.

There are a lot of FDS fire and smoke models that were studied, but for the purpose of this thesis, a new approach is used to find the missing link between the design phase and reality. As someone who always had an interest in the safety of the public and has seven years of experience in the field of fire protection, I came across many issues that, in my opinion, need improvement. With the help of some professionals practicing in the field of fire protection, we tried to find a common interest between the university-level research and the industry. The goal is to lead the research toward the need of society. Simulation cases show how air supply quantity and smoke control strategies can affect the smoke patterns and evacuation processes. Using automatic smoke control systems, similar to the air supply system used for this study, we can reduce the temperature in the fire zone.

On the other hand, reducing the temperature by supplying air can change the smoke flow and pattern, and therefore might disturb the evacuation process. Based on other studies by using the HVAC system and smoke exhaust system in the same room, it is possible to delay the smoke penetration to the different zones. Considering that this type of system is very costly, it is not always possible to support the idea. For the same reason as the cost and complication of the system, we believe that by changing the combustible building construction material, using simple air supply fans in the staircase and having an exhaust system on top of the staircase we can provide a safer evacuation path with a lower cost and more feasible methods. This is a subject to be studied in the future.

5. CONCLUSION AND FUTURE WORK

It is believed that the lack of fire safety systems, delay of the fire department response, and lack of supervision by experts during the construction are the three main reasons that a fire incident can turn into a tragedy. Human is always interested in building higher buildings. Due to the limit of available land and space, buildings are built very close to one another. The derogation that is given to builders that contradict the regulations increases the risk. It also makes it more complicated for the fire department to have a unique emergency plan that applies to all high-rise buildings. There are many factors that affect the arrival time of the fire department, such as road conditions, accessibility of the building, and proper equipment, which each of them must be studied by experts and professionals working in each field. In this thesis, for the purpose of the research, all the analysis is done assuming that the fire department arrives more than 10 minutes after the start time of the fire to allow the HVAC system to stay in service.

As it is mentioned in chapter 3, Section 3.2.8, four fire scenarios were introduced to FDS. With the help of the software, the speed and pattern of the smoke spreading in the building for each case is studied. Also, eight scenarios were simulated using Pathfinder to study the effect of smoke control on evacuation time. The work involved in this research to claim on the importance of keeping the ventilation system in service during an evacuation are as follows:

- Modeling a 45-story high-rise building using FDS and Pathfinder.
- Reviewing twenty-seven fire incident reports in Montreal.
- Reviewing major fire incident reports from all around the world.
- Reviewing major emergency evacuation reports from all around the world.
- Performing surveys and studying evacuation/fire drill reports to analyze the effect of human behavior on the evacuation process.
- Analyzing the effect of the fire origin on the smoke pattern and safe evacuation of the occupants using FDS and Pathfinder.
- Perform multiple simulations and make a comparison with real fire incident reports to prove the importance of pressurized staircases and the HVAC systems in case of emergency.

The design of the fire protection system depends on both competent and ethical design. Codes and standards are limited. Often engineers must make decisions based on the available methods. Usually, fire tests are extremely expensive and difficult. Also, some tests cannot be conducted since they might cause danger to the safety of the public and the environment. As a result, it is the engineers' responsibility to study the fundamental principles, and do the work based on their knowledge and skills. To do so, the engineers are responsible for educating themselves and attending training and seminars that can improve their perspective and give them a better understanding of the challenges and problems. This perspective allows the professionals to upgrade their designs and to consider solutions that are not required by the code, but it is to the advantage of the safety of the public.

For future studies, it is suggested to study the existing buildings with older construction. The reason is that in most of the incidents, the occupants of these types of buildings are more often a victim of fire compared to new construction buildings. Since it is not possible to apply all the new requirements of the code to the existing buildings, it is important to perform more fire drills and to do more training to increase public awareness.

Based on this study, we were able to gather some data from the simulation software to demonstrate the importance of the pressurized staircases and the HVAC system, which has a positive effect on the smoke control in case of emergency. By completing this model in the future and applying the wind effect and other parameters, we are planning to be able to prove that it is better to keep the HVAC system on active mode during a fire incident. For the HVAC systems control and fire department response method, it is planned to start a study to prepare a guide for occupants and fire department employees. This allows the fire department to keep the HVAC system in service during the evacuation process, and to examine how the system can help them by controlling the smoke during the evacuation. We believe the data collected from this study will be a great source of information for future studies. Due to the high risk of using a new method during a real fire incident, further studies and discussions with experienced people in the field are required.

In future studies, the sprinkler system needs to be also added to the simulation to see the effect of sprinklers on the smoke pattern and evacuation process. After adding the sprinklers and examining all the possibilities, it is suggested to add a second tower connected on the lower floors. This allows preparing a base for future studies where multiple buildings are interconnected at the lower levels, i.e., Montreal underground tunnels.

Future studies at the university and professional level should involve:

- Study of the key factors such as the occupant's behavior, different construction materials, climate, culture, and education of the public that has a direct influence on the result.
- Study the current procedures and strategies adopted in high-rise buildings in different cities, considering the effect of construction material and available equipment.
- Performing more numerical analysis to study the impact of group dynamics and the effect of occupants with disabilities.
- Preparing a guideline that can be adopted worldwide and can be used for public education.
- Collecting data from professionals working in the field to understand the ongoing challenges.

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APPENDIX A – Survey of human response to evacuation (Montreal)

A survey is performed to understand the human behavior in case of emergency. Annually many fire drills are performed in public buildings such as office buildings, universities, schools, etc. These fire drills are performed to practice the evacuation of the building in the event of fire or other emergencies. However, since these drills are planned in advance, the end result might be different from a real emergency time. The variables that might affect the results are listed below:

- Condition of the building at the time of the drill versus during an emergency.
- Presence of fire, heat or smoke that might influence the evacuation.
- The level of stress experienced by the occupants during a real fire.
- Time of the day when the drill is performed
- Being informed and prepared to evacuate the building for a fire drill.

The following table is the result of a survey performed on a random group of people. Based on the information provided in this table, it is almost impossible to ensure that everyone has experienced or have been involved in at least one fire drill. Also, more than 80% of the people surveyed, claim that in case of emergency they will evacuate the building without considering the announcements. Some people mentioned that announcements are not always clear, some were not sure what needs to be done in case of the alarm. As a result, most of the people who took the survey believed evacuating is the best option. Only a small percentage that mostly belong to the group of age of 60 -99 years old mentioned that they will stay in their apartments Finally, the most important conclusion that can be drawn from this survey and the conversations with the respondents is that most people are influenced by others' answers and actions. The survey result is available on the following pages.

	Female /Male	Age (year)			Fire drill experience		Will stay inside	Right away evacuate
		5 - 18	18 - 60	60 - 99	Yes	No		
1	F							
2	F							
3	M							
4	F							
5	F							
6	M							
7	M							
8	M							
9	M							
10	M							
11	M							
12	F							
13	F							
14	F							
15	F							
16	F							
17	F							
18	F							
19	F							
20	M							
21	M							

22	F							
23	M							
24	M							
25	M							
26	M							
27	M							
28	F							
29	F							
30	F							
31	F							
32	F							
33	F							
34	M							
35	F							
36	M							
37	M							
38	M							
39	M							
40	M							
41	M							
42	F							
43	F							
44	F							

45	F							
46	F							
47	F							
48	F							
49	M							
50	F							
51	F							
52	M							
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63	F							
64	M							
65	M							
66	M							
67	M							

68	M							
69	F							
70	M							
71	F							
72	F							
73	M							
74	F							
75	F							
76	M							
77	F							
78	M							
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80	F							
81	M							
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88	F							
89	F							
90	F							

91	M							
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106	M							
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108	F							
109	M							
110	M							
111	M							
112	F							
113	F							

114	F							
115	F							
116	M							
117	M							
118	F							
119	M							
120	F							
121	M							
122	F							
123	M							
124	M							
125	M							
126	M							
127	M							
128	M							
129	M							
130	F							

APPENDIX B - SFPE PRESENTATION (LEVIS, QUEBEC)

Smoke control in high-rise building was introduced to fire protection experts including fire protection engineers, fire fighters, consultants, insurance companies and contractors during a two-hour presentation on November 28, 2019, in Levis, Quebec. This presentation was hosted by SFPE, St-Laurent Chapter- Quebec and presented by the author of this thesis and director at this chapter.


Society of Fire Protection Engineers
Conseil Saint-Laurent
ASSOCIATION DES PROFESSIONNELS EN SÉCURITÉ INCENDIE
Invitation
S.V.P. faire circuler aux personnes intéressées, merci.

Séminaire d'information
Jeudi, 28 novembre 2019

9h30 à 10h30 : Accueil - Inscription et café gracieuseté de
10h30 à 15h00: Séminaires (Frais: 40$ /Personne)
10h30 à 12h00

Contrôle de fumée pour bâtiments de grande hauteur et évacuation sécuritaire des occupants

Mme Shamim Mashayekh, ing. jr. va présenter son projet de recherche portant sur le contrôle de fumée pour bâtiments de grande hauteur et l'évacuation sécuritaire des occupants. Son projet met à contribution, l'utilisation de modélisation dynamique de propagation d'incendie («Fire Dynamic Simulator» en modélisant trois niveaux différents (partie élevée, moyenne et basse) d'un bâtiment de grande hauteur).

L'objectif est de reproduire un incendie dans un bâtiment dont la conception repose entièrement sur les exigences applicables du Code national du bâtiment (CNB) ainsi que celles des normes de la National Fire Protection Association (NFPA) et voir, quelles sont les améliorations possibles pour permettre des conceptions plus sécuritaires pour les occupants. Par la modélisation, ce projet étudie la propagation de la fumée à l'intérieur de bâtiments ainsi que le temps requis pour l'évacuation des occupants. Cette présentation permettra de se renseigner sur les nouvelles technologies de modélisation qui sont disponibles.

13h00 à 14h30

La tuyauterie d'acier et ses avantages dans les bâtiments d'habitation

De Victaulic, M. Matt Mastroberardino, responsable de la division incendie dans la région de Montréal et Mr. Clancy Roberts, responsable de la division incendie dans la région de Toronto, nous ferons une présentation technique sur les avantages d'utiliser la tuyauterie en acier dans les bâtiments d'usage du groupe C , habitation/appartements.

Comme concepteur ou chargé de projet, il est important de suivre l'évolution de ces produits. Les nouveaux produits dans le domaine de la protection incendie et les nouvelles techniques d'installation de la tuyauterie en acier permettent de réduire le temps d'installation et de diminuer les risque d'accidents sur les chantiers de constructuction.

SFPE
Saint-Laurent

Jeudi, 28 novembre 2019

Hôtel L'Oiselière
salle Grand Chevalier au 4e
165A Président Kennedy, Lévis, Québec, Canada, G6V 6E2
Stationnement gratuit

1ère Conférence
10h30 à 12h00
Contrôle de la fumée
Mme Shamim Mashayekh, ing. jr.

Dîner (à votre discrétion)
12h00 à 13h00
(possibilité sur place)

2 ième Conférence
13h00 à 14h30
La tuyauterie d'acier et ses avantages dans les bâtiments d'habitation
(présentation en anglais)
M. Matt Mastroberardino et Mr Clancy Roberts, responsables de la division incendie

Coût: 40$ payable en argent sur place ou par la poste par un chèque avant le 25 novembre 2019, libellé au nom de "SFPE Conseil St-Laurent" à l'adresse suivante: 588, Route Bégin, suite #200, St-Anselme, Qc G0R 2N0

Inscription : Vous devez faire parvenir par courriel vos coordonnées AVANT LE 25 novembre2019 à: Gilles Carrier T.P., g.carrier@pgaexperts.com ou au (418) 885-9671 pour information supplémentaire

Venez vous renseigner et échanger sur ces intéressants sujets de sécurité incendie!
Ajoutez à vos heures de formation. S.V.P. Réservez tôt car le nombre de participants est limité.

APPENDIX C - FDS

* Additional information can be provided upon request.

Pyrosim	Fire location	Exhaust fan activated after 5min	Supply fan in staircases
Done	45th corner	N/A	N/A
Done	45th studio units	N/A	N/A
Done	10th corner	N/A	N/A
Done	Basement corner	N/A	N/A

Results Date			
2020-01-20	45th corner	Basement and Occupants Space	1CFM / Sq ft
2020-01-20	45th studio units	Basement and Occupants Space	1CFM / Sq ft
2020-01-20	10th corner	Basement and Occupants Space	1CFM / Sq ft
2020-01-20	Basement corner	Basement and Occupants Space	1CFM / Sq ft

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Generated by PyroSim - Version 2019.2.1002
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&SLCF QUANTITY='HRRPUV', PBZ=155.5/


&TAIL /
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APPENDIX D – Pathfinder Results

* Additional information can be provided upon request.

Daytime – Occupants

id	exit time(s)	active time(s)	jam time total(s)	jam time max continuous (s)	level jam time	stair jam time	distance (m)	last_goal_started time(s)
0	814.95	394.925	0.225	0.225	0.225	0	372.902	420.025
1	684.45	444.425	0.925	0.25	0.925	0	392.929	240.025
2	776.225	536.2	0.325	0.325	0.325	0	391.033	240.025
3		0	0	0	0	0	0	
4	523.275	433.25	0.425	0.25	0.425	0	385.183	90.025
5	545.5	425.475	0.875	0.25	0.875	0	397.32	120.025
6		0	0	0	0	0	0	
7	786.75	486.725	3.15	0.6	3.15	0	409.311	300.025
8	816.975	396.95	0.25	0.25	0.25	0	374.395	420.025
9		0	0	0	0	0	0	
10	439.85	409.825	0.925	0.375	0.925	0	368.857	30.025
11	639.175	399.15	0.5	0.25	0.5	0	374.787	240.025
12	795.15	435.125	1.3	0.325	1.3	0	390.967	360.025
13	1017.3	417.275	0.35	0.225	0.35	0	382.054	600.025
14	860.8	380.775	0.2	0.2	0.2	0	409.425	480.025
15	444.3	414.275	0.4	0.25	0.4	0	370.182	30.025
16	690.825	390.8	0.7	0.325	0.7	0	397.879	300.025
17	806.975	386.95	0.225	0.225	0.225	0	365.603	420.025
18	940.05	400.025	0.25	0.25	0.25	0	380.844	540.025
19	792.125	432.1	1.525	0.75	1.425	0.1	381.749	360.025
20	882.5	402.475	0.525	0.25	0.525	0	382.374	480.025
21	858.85	378.825	0.25	0.25	0.25	0	358.065	480.025
22	538.175	418.15	0.475	0.25	0.475	0	378.297	120.025
23	861.25	381.225	0.25	0.25	0.25	0	359.983	480.025
24	563	382.975	0.25	0.25	0.25	0	363.063	180.025
25	1103.1	503.075	0.325	0.325	0.325	0	364.953	600.025
26	538.275	418.25	0.25	0.25	0.25	0	381.863	120.025
27	454.2	364.175	1.15	0.2	1.15	0	415.441	90.025
28	516.375	456.35	0.525	0.25	0.525	0	396.887	60.025
29	808.825	388.8	0.775	0.25	0.775	0	366.294	420.025
30	627.9	417.875	0.5	0.25	0.5	0	383.278	210.025
31	862.225	382.2	0.25	0.25	0.25	0	361.985	480.025

32	614.9	434.875	0.325	0.25	0.325	0	375.672	180.025
33	777.325	477.3	3.1	0.525	3.075	0.025	399.011	300.025
34	774.3	474.275	1.525	0.35	1.45	0.075	401.197	300.025
35	414.2	384.175	0.525	0.15	0.4	0.125	418.743	30.025
36	695.925	395.9	0.25	0.25	0.25	0	363.856	300.025
37	963.575	363.55	0.2	0.2	0.2	0	398.095	600.025
38	917.05	377.025	0.25	0.25	0.25	0	357.522	540.025
39	616.375	436.35	0.275	0.25	0.275	0	377.966	180.025
40	517.75	457.725	0.85	0.25	0.85	0	391.687	60.025
41	620.8	410.775	1.725	1.375	1.725	0	368.421	210.025
42		0	0	0	0	0	0	
43	458.65	368.625	0.25	0.25	0.25	0	348.576	90.025
44	966.425	366.4	0.25	0.25	0.25	0	345.226	600.025
45		0	0	0	0	0	0	
46	706.575	376.55	0.65	0.25	0.65	0	349.735	330.025
47	1019.725	479.175	0.325	0.325	0.325	0	346.752	540.55
48		0	0	0	0	0	0	
49	904.65	364.625	0.25	0.25	0.25	0	345.194	540.025
50	749.65	329.625	1.375	0.2	1.325	0.05	401.217	420.025
51		0	0	0	0	0	0	
52	795.15	375.125	0.675	0.275	0.4	0.275	350.209	420.025
53	577.4	367.375	0.25	0.25	0.25	0	348.334	210.025
54	789.075	369.05	0.9	0.45	0.9	0	345.719	420.025
55	441.45	411.425	1.975	0.525	1.975	0	358.545	30.025
56	784.15	424.125	0.375	0.25	0.375	0	370.264	360.025
57	782.85	452.825	0.85	0.25	0.85	0	371.293	330.025
58		0	0	0	0	0	0	
59	651.9	351.875	0.25	0.25	0.25	0	332.824	300.025
60	762.625	432.6	2.625	0.325	2.425	0.2	387.903	330.025
61	756.75	336.725	1.275	0.2	1.275	0	362.735	420.025
62	549.95	369.925	0.25	0.25	0.25	0	345.37	180.025
63	443.65	383.625	0.6	0.25	0.6	0	352.071	60.025
64	799.65	379.625	0.775	0.25	0.775	0	346.261	420.025
65	553.3	373.275	1.6	0.925	1.6	0	348.346	180.025
66	1015.95	415.925	0.575	0.225	0.575	0	362.055	600.025
67	912.325	371.775	0.25	0.25	0.25	0	356.303	540.55
68	499.55	379.525	0.95	0.65	0.95	0	350.371	120.025
69	532.25	352.225	0.95	0.15	0.825	0.125	385.191	180.025
70	429.45	399.425	1.225	0.4	1.225	0	349.363	30.025
71	832.3	352.275	0.25	0.25	0.25	0	335.085	480.025
72		0	0	0	0	0	0	
73	451.875	361.85	0.25	0.25	0.25	0	339.72	90.025
74	764.075	434.05	1.95	0.175	1.775	0.175	385.646	330.025

75	438.85	378.825	0.925	0.25	0.925	0	334.902	60.025
76	584.275	344.25	0.25	0.25	0.25	0	325.512	240.025
77	527.725	407.7	1.65	0.4	1.3	0.35	356.24	120.025
78	442.75	382.725	0.575	0.25	0.575	0	342.676	60.025
79	829.75	349.725	0.25	0.25	0.25	0	332.564	480.025
80	431.775	371.75	0.825	0.25	0.825	0	337.494	60.025
81	448.45	358.425	0.575	0.25	0.575	0	332.85	90.025
82	878.225	337.675	0.25	0.25	0.25	0	320.173	540.55
83	520.35	400.325	1	0.325	0.975	0.025	348.594	120.025
84	1014.55	414.525	0.325	0.25	0.325	0	355.818	600.025
85	453.55	333.525	2.325	0.45	2.325	0	357.203	120.025
86	514.975	424.95	0.425	0.25	0.4	0.025	359.184	90.025
87	884.6	344.575	0.375	0.25	0.375	0	325.186	540.025
88	813.425	333.4	0.25	0.25	0.25	0	315.274	480.025
89	423.225	393.2	3.05	1.125	3.05	0	343.788	30.025
90		0	0	0	0	0	0	
91		0	0	0	0	0	0	
92		0	0	0	0	0	0	
93	930.45	330.425	0.25	0.25	0.25	0	313.179	600.025
94	615.475	315.45	0.25	0.15	0.25	0	361.44	300.025
95	689.15	329.125	1.2	0.15	1.125	0.075	372.557	360.025
96	767.725	407.7	1.2	0.2	1.125	0.075	355.787	360.025
97	880.325	340.3	0.25	0.25	0.25	0	325.553	540.025
98	544.75	364.725	1.6	0.275	1.6	0	331.474	180.025
99	434.875	374.85	1.15	0.35	1.075	0.075	341.819	60.025
100	751.05	331.025	0.25	0.25	0.25	0	314.211	420.025
101	575.05	335.025	0.25	0.25	0.25	0	316.654	240.025
102	448.5	358.475	1.825	0.7	1.825	0	324.349	90.025
103	683.125	383.1	0.325	0.25	0.325	0	338.24	300.025
104	922.6	322.575	0.25	0.25	0.25	0	306.332	600.025
105	430.8	400.775	1.775	0.625	1.7	0.075	346.163	30.025
106	437.65	347.625	0.7	0.225	0.7	0	328.291	90.025
107	871.75	331.725	0.25	0.25	0.25	0	317.568	540.025
108	699.875	339.85	0.575	0.25	0.575	0	315.718	360.025
109	776.125	416.1	1.1	0.25	1.1	0	353.707	360.025
110	748	327.975	0.25	0.25	0.25	0	312.31	420.025
111	561.375	321.35	0.25	0.25	0.25	0	304.129	240.025
112	619.275	319.25	0.25	0.25	0.25	0	303.732	300.025
113	797.175	317.15	0.25	0.25	0.25	0	299.429	480.025
114		0	0	0	0	0	0	
115	421.925	361.9	1.2	0.25	1.1	0.1	317.723	60.025
116	807.45	327.425	0.25	0.25	0.25	0	311.827	480.025
117		0	0	0	0	0	0	

118		0	0	0	0	0	0	
119	845.675	305.65	0.25	0.25	0.25	0	290.817	540.025
120		0	0	0	0	0	0	
121	345.85	315.825	0.5	0.25	0.5	0	291.631	30.025
122	920.5	320.475	0.25	0.25	0.25	0	308.357	600.025
123	450.15	330.125	0.25	0.25	0.25	0	306.63	120.025
124	427.55	337.525	0.9	0.375	0.9	0	297.8	90.025
125	445.175	325.15	1.75	0.95	1.75	0	301.905	120.025
126	430.1	340.075	1.3	0.225	1.275	0.025	319.037	90.025
127	673.4	343.375	0.8	0.175	0.7	0.1	340.492	330.025
128	849.775	309.75	0.25	0.25	0.25	0	294.98	540.025
129		0	0	0	0	0	0	
130	504.3	324.275	0.275	0.25	0.275	0	299.447	180.025
131		0	0	0	0	0	0	
132	780.85	300.825	0.25	0.25	0.25	0	287.152	480.025
133	519.025	399	0.325	0.325	0.325	0	291.098	120.025
134	387.8	357.775	1.075	0.3	0.875	0.2	326.799	30.025
135	785.425	365.4	0.675	0.25	0.525	0.15	310.116	420.025
136	620.95	320.925	1.025	0.3	1.025	0	311.849	300.025
137	540.75	330.725	1.1	0.3	0.825	0.275	312.287	210.025
138	791.075	311.05	0.475	0.225	0.475	0	294.066	480.025
139	793.05	313.025	0.25	0.25	0.25	0	295.98	480.025
140	428.05	368.025	2	0.525	2	0	307.722	60.025
141	634.2	304.175	0.575	0.225	0.575	0	285.253	330.025
142		0	0	0	0	0	0	
143	635.95	305.925	0.25	0.25	0.25	0	290.75	330.025
144	891.6	291.575	0.25	0.25	0.25	0	278.339	600.025
145	426.05	306.025	2.6	0.625	2.6	0	277.081	120.025
146	318.75	288.725	0.275	0.25	0.275	0	272.818	30.025
147	896.95	296.925	0.325	0.25	0.325	0	284.307	600.025
148	433.7	343.675	1.075	0.25	0.975	0.1	298.392	90.025
149	413.575	323.55	1.55	0.2	1.375	0.175	323.699	90.025
150	841.7	301.675	0.25	0.25	0.25	0	290.221	540.025
151	540.4	330.375	1.525	0.575	1.45	0.075	290.407	210.025
152	495.8	315.775	0.35	0.225	0.35	0	286.721	180.025
153	588.275	288.25	0.25	0.25	0.25	0	276.876	300.025
154	823.975	283.425	0.25	0.25	0.25	0	270.805	540.55
155	620.275	380.25	0.325	0.325	0.325	0	278.57	240.025
156	687.95	327.925	2.975	0.5	2.975	0	278.921	360.025
157	506	295.975	0.25	0.25	0.25	0	281.298	210.025
158	771.25	351.225	1.175	0.225	1.1	0.075	297.615	420.025
159	830.075	290.05	0.25	0.25	0.25	0	278.529	540.025
160	690.675	330.65	1	0.25	1	0	287.723	360.025

161	631.1	301.075	0.675	0.275	0.675	0	284.357	330.025
162	445.7	325.675	0.675	0.3	0.65	0.025	294.505	120.025
163	548.6	308.575	1.3	0.925	1.3	0	283.848	240.025
164		0	0	0	0	0	0	
165	817	276.975	0.225	0.225	0.225	0	265.258	540.025
166		0	0	0	0	0	0	
167	524.625	344.6	1.1	0.25	1.1	0	293.549	180.025
168	420.5	360.475	0.325	0.325	0.325	0	262.335	60.025
169	643.35	283.325	0.25	0.25	0.25	0	272.807	360.025
170	629.575	299.55	0.575	0.25	0.575	0	276.246	330.025
171	611.55	281.525	0.725	0.15	0.5	0.225	316.571	330.025
172	796.525	316.5	0.5	0.25	0.5	0	282.413	480.025
173	588.15	258.125	0.375	0.2	0.375	0	281.113	330.025
174	878.375	278.35	0.25	0.25	0.25	0	266.736	600.025
175	337.9	277.875	0.3	0.2	0.3	0	295.495	60.025
176	757.35	277.325	0.25	0.25	0.25	0	266.282	480.025
177	707.9	287.875	0.4	0.25	0.4	0	270.364	420.025
178	793.5	313.475	1.175	0.25	1.125	0.05	275.352	480.025
179	439.925	319.9	2.225	1.525	2.225	0	279.905	120.025
180	685.8	325.775	0.4	0.25	0.4	0	284.867	360.025
181	798.25	318.225	1.525	0.275	1.525	0	283.81	480.025
182	336.825	276.8	0.55	0.3	0.55	0	266.074	60.025
183	566.975	266.95	0.25	0.25	0.25	0	253.823	300.025
184	498.275	288.25	0.525	0.25	0.525	0	267.536	210.025
185	429.175	339.15	0.325	0.325	0.325	0	245.76	90.025
186	311.1	251.075	0.125	0.125	0.125	0	298.696	60.025
187	688.1	268.075	0.25	0.25	0.25	0	255.213	420.025
188	568.95	268.925	0.65	0.25	0.65	0	255.649	300.025
189	686.85	266.825	0.375	0.2	0.375	0	282.073	420.025
190	745.55	265.525	0.6	0.25	0.6	0	252.423	480.025
191	329.95	269.925	0.25	0.25	0.25	0	258.78	60.025
192	426.575	336.55	0.775	0.25	0.675	0.1	281.203	90.025
193	334.75	304.725	0.35	0.25	0.35	0	263.984	30.025
194	692.05	272.025	0.25	0.25	0.25	0	263.8	420.025
195	804.475	264.45	0.25	0.25	0.25	0	245.458	540.025
196	863.55	263.525	0.25	0.25	0.25	0	251.576	600.025
197	701.35	281.325	0.675	0.275	0.675	0	260.957	420.025
198		0	0	0	0	0	0	
199	293.25	263.225	0.25	0.25	0.25	0	253.112	30.025
200	867.05	267.025	0.25	0.25	0.25	0	257.504	600.025
201		0	0	0	0	0	0	
202	698.35	278.325	0.275	0.225	0.275	0	255.164	420.025
203	671.325	251.3	0.25	0.25	0.25	0	240.905	420.025

204	622.15	292.125	0.9	0.25	0.9	0	253.221	330.025
205		0	0	0	0	0	0	
206	784.975	244.95	0.25	0.25	0.25	0	232.211	540.025
207	340.35	280.325	1.125	0.825	1.125	0	250.39	60.025
208		0	0	0	0	0	0	
209		0	0	0	0	0	0	
210	346.45	256.425	0.4	0.25	0.4	0	245.986	90.025
211	337.55	277.525	1.175	0.65	1.075	0.1	248.165	60.025
212	424.775	304.75	0.9	0.45	0.9	0	271.738	120.025
213	415.025	325	0.55	0.25	0.55	0	274.43	90.025
214	805.8	265.775	0.25	0.25	0.25	0	250.401	540.025
215	417	296.975	0.35	0.25	0.35	0	256.931	120.025
216	519.35	309.325	0.65	0.25	0.65	0	259.489	210.025
217		0	0	0	0	0	0	
218	801.35	261.325	0.25	0.25	0.25	0	240.325	540.025
219	393.35	303.325	0.475	0.25	0.475	0	253.523	90.025
220	686.575	266.55	1.375	0.2	1.25	0.125	248.981	420.025
221		0	0	0	0	0	0	
222	847.775	247.75	0.25	0.25	0.25	0	238.081	600.025
223	417.9	297.875	0.425	0.25	0.425	0	264.834	120.025
224	802.8	262.775	0.25	0.25	0.25	0	249.139	540.025
225	783	242.975	0.25	0.25	0.25	0	232.187	540.025
226	694.5	274.475	0.525	0.25	0.475	0.05	245.732	420.025
227	452.575	242.55	0.325	0.25	0.325	0	224.645	210.025
228	832.15	232.125	0.25	0.25	0.25	0	222.549	600.025
229	551.475	251.45	1.7	0.65	1.6	0.1	232.095	300.025
230	433.25	253.225	0.525	0.25	0.525	0	224.657	180.025
231	501.45	261.425	1.075	0.3	1.075	0	238.554	240.025
232	580.55	220.525	1.2	0.125	1.075	0.125	275.162	360.025
233		0	0	0	0	0	0	
234	457.5	247.475	0.4	0.25	0.4	0	231.538	210.025
235	788.525	308.5	0.575	0.25	0.575	0	263.96	480.025
236	554.725	224.7	0.25	0.25	0.25	0	215.236	330.025
237	729.675	249.65	0.25	0.25	0.25	0	228.554	480.025
238	394.775	274.75	0.675	0.25	0.675	0	237.751	120.025
239	251.65	221.625	0.25	0.25	0.25	0	212.646	30.025
240		0	0	0	0	0	0	
241	302.35	212.325	0.25	0.25	0.25	0	202.794	90.025
242	396.525	276.5	0.325	0.325	0.325	0	202.596	120.025
243	573.5	213.475	0.275	0.15	0.275	0	249.542	360.025
244		0	0	0	0	0	0	
245	551.625	221.6	0.625	0.25	0.625	0	209.025	330.025
246	554.9	224.875	0.325	0.25	0.325	0	214.364	330.025

247	539.6	209.575	0.425	0.175	0.275	0.15	235.262	330.025
248		0	0	0	0	0	0	
249	340.175	220.15	0.25	0.25	0.25	0	213.545	120.025
250	617.6	257.575	0.375	0.25	0.375	0	227.419	360.025
251	685.875	265.85	0.325	0.325	0.325	0	195.071	420.025
252	449.85	239.825	0.25	0.25	0.25	0	216.409	210.025
253	454.4	244.375	0.275	0.25	0.275	0	226.243	210.025
254	748.25	208.225	0.35	0.2	0.35	0	222.481	540.025
255	269.75	209.725	0.25	0.25	0.25	0	202.829	60.025
256	751.625	211.6	0.2	0.2	0.2	0	218.259	540.025
257	539.325	209.3	0.4	0.175	0.4	0	230.661	330.025
258	790.55	250.525	1.175	0.65	1.175	0	223.106	540.025
259	239.1	209.075	0.25	0.25	0.25	0	202.273	30.025
260	273.5	213.475	0.25	0.25	0.25	0	206.823	60.025
261	274.475	214.45	0.25	0.25	0.25	0	208.232	60.025
262	336.2	246.175	0.75	0.25	0.55	0.2	215.729	90.025
263	504.75	204.725	0.325	0.25	0.275	0.05	190.953	300.025
264	559.725	199.7	0.25	0.25	0.25	0	190.604	360.025
265	542.45	212.425	0.9	0.2	0.9	0	219.667	330.025
266	536.4	236.375	0.475	0.25	0.475	0	206.59	300.025
267	681.325	201.3	0.25	0.25	0.25	0	194.601	480.025
268	546.8	216.775	0.275	0.25	0.275	0	202.686	330.025
269	532.15	232.125	0.525	0.2	0.525	0	219.682	300.025
270	456.7	216.675	0.55	0.25	0.55	0	201.724	240.025
271	234.05	204.025	0.275	0.25	0.275	0	197.757	30.025
272	683.3	203.275	0.25	0.25	0.25	0	196.477	480.025
273	435.35	255.325	1.375	0.375	1.375	0	212.681	180.025
274	613.35	193.325	0.25	0.25	0.25	0	187.511	420.025
275	669.3	189.275	0.25	0.25	0.25	0	182.964	480.025
276	789.475	248.925	0.375	0.25	0.375	0	215.34	540.55
277	543.475	213.45	0.775	0.45	0.775	0	199.958	330.025
278	264.2	204.175	0.25	0.25	0.25	0	200.524	60.025
279	383.275	203.25	1.775	0.45	1.6	0.175	202.12	180.025
280	611.35	191.325	0.225	0.225	0.225	0	184.979	420.025
281	260.725	200.7	0.25	0.25	0.25	0	196.186	60.025
282	339.25	249.225	0.325	0.325	0.325	0	186.554	90.025
283	787	186.975	0.25	0.25	0.25	0	181.403	600.025
284	500.4	170.375	0.475	0.15	0.35	0.125	198.648	330.025
285	216.05	186.025	0.25	0.25	0.25	0	180.888	30.025
286	208.325	178.3	0.225	0.225	0.225	0	189.99	30.025
287	626.45	206.425	0.525	0.25	0.525	0	184.675	420.025
288	212.15	182.125	0.25	0.25	0.25	0	175.483	30.025
289	451.2	211.175	0.4	0.25	0.4	0	189.38	240.025

290	647.5	167.475	0.225	0.225	0.225	0	163.014	480.025
291	550.15	190.125	0.55	0.25	0.55	0	180.309	360.025
292	325.95	205.925	0.425	0.15	0.25	0.175	202.487	120.025
293	416.075	206.05	1.6	0.3	1.425	0.175	215.831	210.025
294	495.35	195.325	0.35	0.225	0.25	0.1	182.546	300.025
295	536.9	206.875	0.25	0.25	0.25	0	182.603	330.025
296	692.85	212.825	0.525	0.25	0.525	0	185.403	480.025
297	341.875	161.85	0.25	0.25	0.25	0	156.123	180.025
298	411.025	231	0.325	0.325	0.325	0	173.72	180.025
299	352.85	172.825	0.25	0.25	0.25	0	169.543	180.025
300	455.75	155.725	0.225	0.2	0.225	0	174.109	300.025
301	594.675	174.65	0.425	0.25	0.425	0	168.9	420.025
302	539.225	179.2	0.75	0.2	0.75	0	176.069	360.025
303	419.15	209.125	1.175	0.4	1.175	0	179.478	210.025
304	624.8	204.775	0.5	0.25	0.5	0	181.556	420.025
305	405.65	195.625	0.25	0.25	0.25	0	176.28	210.025
306		0	0	0	0	0	0	
307	527.15	167.125	0.625	0.15	0.6	0.025	173.007	360.025
308	209.275	149.25	0.2	0.2	0.2	0	165.878	60.025
309	397.45	187.425	1.225	0.25	1.225	0	157.803	210.025
310	196.15	166.125	0.225	0.225	0.225	0	170.506	30.025
311	276.425	156.4	0.25	0.25	0.25	0	152.526	120.025
312	764.45	164.425	0.25	0.25	0.25	0	161.802	600.025
313	258.6	168.575	0.25	0.25	0.25	0	166.857	90.025
314	530.925	200.9	0.975	0.45	0.925	0.05	169.157	330.025
315	762.45	162.425	0.3	0.225	0.3	0	157.392	600.025
316	734.875	194.325	0.325	0.325	0.325	0	144.645	540.55
317	191.45	161.425	0.275	0.25	0.275	0	159.469	30.025
318	259.85	139.825	0.225	0.225	0.225	0	135.877	120.025
319	529.45	199.425	3.2	0.9	2.725	0.475	170.546	330.025
320	347.15	167.125	0.3	0.25	0.3	0	159.529	180.025
321		0	0	0	0	0	0	
322	677.825	137.8	0.175	0.175	0.175	0	163.422	540.025
323	241.2	151.175	0.25	0.25	0.25	0	147.191	90.025
324	278.675	158.65	0.25	0.25	0.25	0	156.46	120.025
325	570.975	150.95	0.25	0.25	0.25	0	146.284	420.025
326	271.4	151.375	0.25	0.25	0.25	0	148.482	120.025
327	406.8	166.775	0.675	0.25	0.675	0	149.051	240.025
328		0	0	0	0	0	0	
329	543.3	183.275	0.325	0.325	0.325	0	135.505	360.025
330	341.75	161.725	1.625	0.425	1.625	0	145.138	180.025
331	343.25	133.225	0.35	0.15	0.35	0	173.377	210.025
332	564.975	144.95	0.25	0.25	0.25	0	142.628	420.025

333	677.2	137.175	0.25	0.25	0.25	0	133.572	540.025
334	453.45	153.425	0.225	0.225	0.225	0	143.537	300.025
335	420.125	180.1	1.15	0.225	1.15	0	159.339	240.025
336	743.45	143.425	0.25	0.25	0.25	0	140.881	600.025
337	679.375	139.35	0.225	0.225	0.225	0	135.126	540.025
338	457.025	157	0.5	0.25	0.5	0	150.529	300.025
339	637.4	157.375	0.275	0.25	0.275	0	153.175	480.025
340	232.875	142.85	0.275	0.25	0.275	0	139.433	90.025
341	360.75	150.725	0.25	0.25	0.25	0	149.799	210.025
342	327.975	147.95	0.25	0.25	0.25	0	146.221	180.025
343		0	0	0	0	0	0	
344	180.475	150.45	0.25	0.25	0.25	0	147.617	30.025
345	222.875	132.85	0.275	0.25	0.275	0	130.102	90.025
346	788.175	188.15	0.575	0.325	0.575	0	141.459	600.025
347	701.725	101.7	0.325	0.15	0.325	0	147.645	600.025
348	371.05	131.025	0.25	0.25	0.25	0	130.302	240.025
349	351.45	141.425	0.25	0.25	0.25	0	140.172	210.025
350	533.475	173.45	1.95	0.575	1.95	0	144.334	360.025
351	236.625	146.6	0.525	0.25	0.525	0	143.63	90.025
352	184.5	124.475	0.225	0.225	0.225	0	120.925	60.025
353	348.875	138.85	0.25	0.25	0.25	0	134.591	210.025
354	561.8	141.775	0.25	0.25	0.25	0	141.229	420.025
355	508.425	148.4	0.4	0.25	0.35	0.05	140.066	360.025
356	616.575	136.55	0.25	0.25	0.25	0	134.839	480.025
357	553.15	133.125	0.25	0.25	0.25	0	132.733	420.025
358	513.675	153.65	0.25	0.25	0.25	0	134.439	360.025
359	500.475	170.45	0.325	0.325	0.325	0	129.826	330.025
360	110.6	80.575	0.15	0.15	0.15	0	122.724	30.025
361		0	0	0	0	0	0	
362	343.525	163.5	1.15	0.25	1.15	0	145.051	180.025
363		0	0	0	0	0	0	
364	193.55	133.525	0.25	0.25	0.25	0	132.799	60.025
365	521.625	161.6	0.775	0.25	0.775	0	143.781	360.025
366	463.725	133.7	0.25	0.25	0.25	0	133.784	330.025
367	526.25	166.225	0.425	0.25	0.275	0.15	146.295	360.025
368	459.1	129.075	0.35	0.225	0.35	0	126.538	330.025
369	344.625	134.6	0.25	0.25	0.25	0	134.516	210.025
370	366.55	126.525	0.25	0.25	0.25	0	127.614	240.025
371		0	0	0	0	0	0	
372	502.35	142.325	0.25	0.25	0.25	0	133.258	360.025
373	188.475	128.45	0.25	0.25	0.25	0	128.899	60.025
374		0	0	0	0	0	0	
375		0	0	0	0	0	0	

376	360.925	120.9	0.25	0.25	0.25	0	120.996	240.025
377	441.1	141.075	0.45	0.25	0.45	0	126.881	300.025
378	153	122.975	0.25	0.25	0.25	0	123.474	30.025
379	447.15	147.125	0.25	0.25	0.25	0	127.556	300.025
380	544	123.975	0.25	0.25	0.25	0	115.184	420.025
381	730.85	130.825	0.25	0.25	0.25	0	126.992	600.025
382	654.05	114.025	0.25	0.25	0.25	0	114.836	540.025
383	205.8	115.775	0.25	0.25	0.25	0	116.795	90.025
384	185.35	125.325	0.3	0.3	0.3	0	93.723	60.025
385	618.8	138.775	0.25	0.25	0.25	0	125.511	480.025
386	202.5	112.475	0.25	0.25	0.25	0	113.091	90.025
387	268.025	88	0.325	0.15	0.325	0	130.22	180.025
388	436.475	136.45	1.7	0.425	1.7	0	120.315	300.025
389	654.275	113.725	0.25	0.25	0.25	0	113.957	540.55
390	322.175	112.15	0.275	0.225	0.275	0	119.3	210.025
391	229.7	109.675	0.25	0.25	0.25	0	109.891	120.025
392	358.9	118.875	0.25	0.25	0.25	0	120.637	240.025
393	548.425	128.4	0.25	0.25	0.25	0	122.429	420.025
394	430.275	130.25	0.5	0.25	0.5	0	116.864	300.025
395	325.95	115.925	0.25	0.25	0.25	0	117.037	210.025
396	186.475	96.45	0.25	0.25	0.25	0	94.74	90.025
397	584.8	104.775	0.25	0.25	0.25	0	105.878	480.025
398	446.8	116.775	0.25	0.25	0.25	0	110.073	330.025
399	436.15	106.125	0.425	0.15	0.425	0	120.432	330.025
400	645.5	105.475	0.25	0.25	0.25	0	106.158	540.025
401	283.775	103.75	0.25	0.25	0.25	0	104.961	180.025
402		0	0	0	0	0	0	
403	704.35	104.325	0.25	0.25	0.25	0	97.697	600.025
404	332.25	92.225	0.225	0.225	0.225	0	91.48	240.025
405	639.175	98.625	0.25	0.25	0.25	0	100.848	540.55
406	300.4	90.375	0.25	0.25	0.25	0	90.827	210.025
407	334.375	94.35	0.25	0.25	0.25	0	95.82	240.025
408	409.725	109.7	0.275	0.25	0.275	0	103.026	300.025
409	460.925	100.9	0.25	0.25	0.25	0	103.612	360.025
410		0	0	0	0	0	0	
411	579.175	99.15	0.25	0.25	0.25	0	100.19	480.025
412	276.575	96.55	0.325	0.25	0.325	0	97.013	180.025
413		0	0	0	0	0	0	
414	702.875	102.85	0.375	0.25	0.375	0	96.284	600.025
415	153.85	93.825	0.25	0.25	0.25	0	95.178	60.025
416	207.8	87.775	0.225	0.225	0.225	0	87.535	120.025
417	408.1	108.075	0.25	0.25	0.25	0	101.847	300.025
418	640.7	100.675	0.25	0.25	0.25	0	103.278	540.025

419	306.675	96.65	0.25	0.25	0.25	0	98.372	210.025
420	321.575	81.55	0.25	0.25	0.25	0	81.764	240.025
421	267.775	87.75	0.25	0.25	0.25	0	90.295	180.025
422	632.15	92.125	0.25	0.25	0.25	0	95.487	540.025
423	149.05	89.025	0.25	0.25	0.25	0	91.756	60.025
424	114.25	84.225	0.25	0.25	0.25	0	85.755	30.025
425	146.5	86.475	0.25	0.25	0.25	0	88.734	60.025
426		0	0	0	0	0	0	
427	558.1	78.075	0.25	0.25	0.25	0	77.015	480.025
428	342.4	102.375	0.275	0.2	0.275	0	103.613	240.025
429		0	0	0	0	0	0	
430	509.975	89.95	0.3	0.25	0.3	0	87.015	420.025
431	296.55	86.525	0.25	0.25	0.25	0	88.689	210.025
432	573.05	93.025	0.25	0.25	0.25	0	95.854	480.025
433		0	0	0	0	0	0	
434	339.025	99	0.4	0.25	0.4	0	91.641	240.025
435	455.7	95.675	0.275	0.25	0.275	0	91.088	360.025
436	632.85	92.825	0.25	0.25	0.25	0	89.96	540.025
437	689.25	89.225	0.8	0.25	0.625	0.175	79.076	600.025
438	266.35	86.325	0.25	0.25	0.25	0	90.635	180.025
439	614.825	74.275	0.2	0.2	0.2	0	86.264	540.55
440	104.75	74.725	0.225	0.225	0.225	0	82.665	30.025
441	304.375	64.35	0.35	0.25	0.35	0	65.745	240.025
442		0	0	0	0	0	0	
443	92.15	62.125	0.225	0.225	0.225	0	63.571	30.025
444	664.65	64.625	0.25	0.25	0.25	0	66.823	600.025
445	556.45	76.425	0.25	0.25	0.25	0	80.122	480.025
446	195.575	75.55	0.25	0.25	0.25	0	78.937	120.025
447	185.65	65.625	0.25	0.25	0.25	0	67.827	120.025
448		0	0	0	0	0	0	
449	104.15	74.125	0.25	0.25	0.25	0	78.468	30.025
450	681.55	81.525	0.3	0.25	0.3	0	76.132	600.025
451	279.4	69.375	0.25	0.25	0.25	0	72.517	210.025
452	411.075	81.05	0.375	0.25	0.375	0	81.399	330.025
453	542.625	62.6	0.225	0.225	0.225	0	55.762	480.025
454	547.15	67.125	0.325	0.25	0.325	0	65.33	480.025
455	396.1	66.075	0.425	0.25	0.425	0	61.953	330.025
456	398.5	68.475	0.375	0.25	0.375	0	66.595	330.025
457	174.3	54.275	0.225	0.225	0.225	0	56.648	120.025
458		0	0	0	0	0	0	
459	310.9	70.875	0.25	0.25	0.25	0	76.649	240.025
460	488.8	68.775	0.25	0.25	0.25	0	74.108	420.025
461	437.025	77	0.825	0.475	0.825	0	69.967	360.025

462	432.35	72.325	0.3	0.25	0.3	0	69.629	360.025
463	592.85	52.825	0.225	0.225	0.225	0	57.065	540.025
464	652.275	52.25	0.25	0.25	0.25	0	56.613	600.025
465	272.25	62.225	0.25	0.25	0.25	0	68.602	210.025
466	71.05	41.025	0.25	0.25	0.25	0	43.655	30.025
467	169.5	49.475	0.225	0.225	0.225	0	52.816	120.025
468	167.65	47.625	0.25	0.25	0.25	0	51.25	120.025
469	234.775	54.75	0.425	0.25	0.425	0	57.569	180.025
470	424.375	64.35	0.3	0.25	0.3	0	63.927	360.025
471		0	0	0	0	0	0	
472	137.8	47.775	0.25	0.25	0.25	0	53.354	90.025
473	81.5	51.475	0.25	0.25	0.25	0	58.034	30.025
474	139.2	49.175	0.25	0.25	0.25	0	55.333	90.025
475		0	0	0	0	0	0	
476		0	0	0	0	0	0	
477	237.025	27	0.175	0.175	0.175	0	44.194	210.025
478	586.6	46.575	0.25	0.25	0.25	0	51.995	540.025
479	222.125	42.1	0.225	0.225	0.225	0	48.208	180.025
480	367.3	37.275	0.225	0.225	0.225	0	40.622	330.025
481		0	0	0	0	0	0	
482	592.8	52.25	0.25	0.25	0.25	0	57.904	540.55
483	517.775	37.75	0.225	0.225	0.225	0	41.698	480.025
484		0	0	0	0	0	0	
485	122.25	32.225	0.25	0.25	0.25	0	37.575	90.025
486	515.225	35.2	0.25	0.25	0.25	0	40.952	480.025

Daytime – Doors

time(s)	Remaining (Total)	Exited (Total)	Door00	Door00 width(m)	Door00 total boundary(m)	Stair01 door 1	Stair01 door 1 width(m)
0	487	0	0	2	0	0	1.219
1	487	0	0	2	0	0	1.219
2	487	0	0	2	0	0	1.219
3	487	0	0	2	0	0	1.219
4	487	0	0	2	0	0	1.219
5	487	0	0	2	0	0	1.219
6	487	0	0	2	0	0	1.219
7	487	0	0	2	0	0	1.219
8	487	0	0	2	0	0	1.219
9	487	0	0	2	0	0	1.219
10	487	0	0	2	0	0	1.219
11	487	0	0	2	0	0	1.219
12	487	0	0	2	0	0	1.219
13	487	0	0	2	0	0	1.219
14	487	0	0	2	0	0	1.219
15	487	0	0	2	0	0	1.219
16	487	0	0	2	0	0	1.219
17	487	0	0	2	0	0	1.219
18	487	0	0	2	0	0	1.219
19	487	0	0	2	0	0	1.219
20	487	0	0	2	0	0	1.219
21	487	0	0	2	0	0	1.219
22	487	0	0	2	0	0	1.219
23	487	0	0	2	0	0	1.219
24	487	0	0	2	0	0	1.219
25	487	0	0	2	0	0	1.219
26	487	0	0	2	0	0	1.219
27	487	0	0	2	0	0	1.219
28	487	0	0	2	0	0	1.219
29	487	0	0	2	0	0	1.219
30	487	0	0	2	0	0	1.219
31	487	0	0	2	0	0	1.219
32	487	0	0	2	0	0	1.219
33	487	0	0	2	0	0	1.219
34	487	0	0	2	0	1	1.219
35	487	0	0	2	0	0	1.219
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38	487	0	0	2	0	0	1.219

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42	487	0	0	2	0	0	1.219
43	487	0	0	2	0	0	1.219
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45	487	0	0	2	0	0	1.219
46	487	0	0	2	0	0	1.219
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71	487	0	0	2	0	0	1.219
72	486	1	1	2	0	0	1.219
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79	486	1	0	2	0	0	1.219
80	486	1	0	2	0	0	1.219
81	486	1	0	2	0	0	1.219

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85	485	2	0	2	0	0	1.219
86	485	2	0	2	0	0	1.219
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89	485	2	0	2	0	0	1.219
90	485	2	0	2	0	0	1.219
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92	485	2	0	2	0	0	1.219
93	484	3	1	2	0	0	1.219
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122	480	7	0	2	0	0	1.219
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136	479	8	0	2	0	0	1.219
137	479	8	0	2	0	1	1.219
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141	477	10	0	2	0	0	1.219
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144	477	10	0	2	0	0	1.219
145	477	10	0	2	0	0	1.219
146	477	10	0	2	0	0	1.219
147	476	11	1	2	0	1	1.219
148	476	11	0	2	0	0	1.219
149	476	11	0	2	0	1	1.219
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154	473	14	2	2	0	0	1.219
155	473	14	0	2	0	1	1.219
156	473	14	0	2	0	0	1.219
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166	473	14	0	2	0	0	1.219
167	473	14	0	2	0	0	1.219

168	472	15	1	2	0	0	1.219
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170	471	16	1	2	0	0	1.219
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175	470	17	1	2	0	1	1.219
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181	469	18	1	2	0	0	1.219
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184	469	18	0	2	0	0	1.219
185	468	19	1	2	0	0	1.219
186	466	21	2	2	0	1	1.219
187	465	22	1	2	0	0	1.219
188	465	22	0	2	0	0	1.219
189	464	23	1	2	0	0	1.219
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191	464	23	0	2	0	0	1.219
192	463	24	1	2	0	0	1.219
193	463	24	0	2	0	0	1.219
194	462	25	1	2	0	0	1.219
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196	461	26	1	2	0	1	1.219
197	460	27	1	2	0	0	1.219
198	460	27	0	2	0	1	1.219
199	460	27	0	2	0	1	1.219
200	460	27	0	2	0	0	1.219
201	460	27	0	2	0	0	1.219
202	460	27	0	2	0	0	1.219
203	459	28	1	2	0	0	1.219
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205	459	28	0	2	0	0	1.219
206	458	29	1	2	0	0	1.219
207	458	29	0	2	0	0	1.219
208	457	30	1	2	0	0	1.219
209	456	31	1	2	0	0	1.219
210	455	32	1	2	0	0	1.219

211	455	32	0	2	0	0	1.219
212	455	32	0	2	0	0	1.219
213	454	33	1	2	0	0	1.219
214	454	33	0	2	0	0	1.219
215	454	33	0	2	0	1	1.219
216	454	33	0	2	0	0	1.219
217	453	34	1	2	0	0	1.219
218	453	34	0	2	0	0	1.219
219	453	34	0	2	0	0	1.219
220	453	34	0	2	0	0	1.219
221	453	34	0	2	0	0	1.219
222	453	34	0	2	0	0	1.219
223	451	36	2	2	0	1	1.219
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225	451	36	0	2	0	0	1.219
226	451	36	0	2	0	0	1.219
227	451	36	0	2	0	0	1.219
228	451	36	0	2	0	0	1.219
229	451	36	0	2	0	0	1.219
230	450	37	1	2	0	0	1.219
231	450	37	0	2	0	1	1.219
232	450	37	0	2	0	0	1.219
233	449	38	1	2	0	1	1.219
234	449	38	0	2	0	0	1.219
235	447	40	2	2	0	1	1.219
236	447	40	0	2	0	0	1.219
237	446	41	1	2	0	0	1.219
238	445	42	1	2	0	1	1.219
239	445	42	0	2	0	0	1.219
240	444	43	1	2	0	1	1.219
241	444	43	0	2	0	0	1.219
242	443	44	1	2	0	1	1.219
243	443	44	0	2	0	0	1.219
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249	443	44	0	2	0	0	1.219
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252	442	45	1	2	0	0	1.219
253	442	45	0	2	0	0	1.219

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257	442	45	0	2	0	0	1.219
258	442	45	0	2	0	0	1.219
259	441	46	1	2	0	0	1.219
260	440	47	1	2	0	1	1.219
261	439	48	1	2	0	0	1.219
262	439	48	0	2	0	0	1.219
263	439	48	0	2	0	0	1.219
264	439	48	0	2	0	0	1.219
265	438	49	1	2	0	1	1.219
266	438	49	0	2	0	0	1.219
267	437	50	1	2	0	0	1.219
268	436	51	1	2	0	1	1.219
269	435	52	1	2	0	0	1.219
270	434	53	1	2	0	1	1.219
271	434	53	0	2	0	0	1.219
272	433	54	1	2	0	0	1.219
273	432	55	1	2	0	0	1.219
274	431	56	1	2	0	0	1.219
275	430	57	1	2	0	0	1.219
276	430	57	0	2	0	0	1.219
277	428	59	2	2	0	0	1.219
278	428	59	0	2	0	0	1.219
279	427	60	1	2	0	0	1.219
280	426	61	1	2	0	0	1.219
281	426	61	0	2	0	0	1.219
282	426	61	0	2	0	1	1.219
283	426	61	0	2	0	1	1.219
284	425	62	1	2	0	0	1.219
285	425	62	0	2	0	1	1.219
286	425	62	0	2	0	1	1.219
287	425	62	0	2	0	0	1.219
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293	425	62	0	2	0	1	1.219
294	424	63	1	2	0	0	1.219
295	424	63	0	2	0	1	1.219
296	424	63	0	2	0	0	1.219

297	423	64	1	2	0	0	1.219
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301	422	65	1	2	0	1	1.219
302	422	65	0	2	0	0	1.219
303	421	66	1	2	0	1	1.219
304	421	66	0	2	0	0	1.219
305	420	67	1	2	0	1	1.219
306	420	67	0	2	0	0	1.219
307	419	68	1	2	0	0	1.219
308	419	68	0	2	0	1	1.219
309	419	68	0	2	0	0	1.219
310	419	68	0	2	0	1	1.219
311	418	69	1	2	0	0	1.219
312	417	70	1	2	0	0	1.219
313	417	70	0	2	0	0	1.219
314	417	70	0	2	0	0	1.219
315	417	70	0	2	0	0	1.219
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317	417	70	0	2	0	0	1.219
318	417	70	0	2	0	0	1.219
319	416	71	1	2	0	0	1.219
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321	416	71	0	2	0	0	1.219
322	415	72	1	2	0	0	1.219
323	414	73	1	2	0	0	1.219
324	414	73	0	2	0	1	1.219
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326	412	75	2	2	0	0	1.219
327	412	75	0	2	0	0	1.219
328	411	76	1	2	0	0	1.219
329	411	76	0	2	0	0	1.219
330	410	77	1	2	0	1	1.219
331	410	77	0	2	0	0	1.219
332	410	77	0	2	0	0	1.219
333	409	78	1	2	0	0	1.219
334	409	78	0	2	0	1	1.219
335	407	80	2	2	0	0	1.219
336	407	80	0	2	0	0	1.219
337	405	82	2	2	0	0	1.219
338	403	84	2	2	0	0	1.219
339	403	84	0	2	0	0	1.219

340	401	86	2	2	0	0	1.219
341	399	88	2	2	0	0	1.219
342	397	90	2	2	0	0	1.219
343	396	91	1	2	0	0	1.219
344	394	93	2	2	0	0	1.219
345	393	94	1	2	0	0	1.219
346	392	95	1	2	0	0	1.219
347	391	96	1	2	0	0	1.219
348	390	97	1	2	0	0	1.219
349	389	98	1	2	0	0	1.219
350	389	98	0	2	0	0	1.219
351	389	98	0	2	0	0	1.219
352	388	99	1	2	0	0	1.219
353	387	100	1	2	0	0	1.219
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356	387	100	0	2	0	0	1.219
357	387	100	0	2	0	0	1.219
358	387	100	0	2	0	0	1.219
359	386	101	1	2	0	0	1.219
360	386	101	0	2	0	0	1.219
361	384	103	2	2	0	0	1.219
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363	384	103	0	2	0	0	1.219
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366	384	103	0	2	0	0	1.219
367	383	104	1	2	0	0	1.219
368	382	105	1	2	0	0	1.219
369	382	105	0	2	0	0	1.219
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371	382	105	0	2	0	1	1.219
372	381	106	1	2	0	1	1.219
373	381	106	0	2	0	0	1.219
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381	381	106	0	2	0	1	1.219
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383	381	106	0	2	0	1	1.219
384	380	107	1	2	0	0	1.219
385	380	107	0	2	0	1	1.219
386	380	107	0	2	0	1	1.219
387	380	107	0	2	0	1	1.219
388	379	108	1	2	0	0	1.219
389	379	108	0	2	0	1	1.219
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391	379	108	0	2	0	1	1.219
392	379	108	0	2	0	0	1.219
393	379	108	0	2	0	1	1.219
394	378	109	1	2	0	1	1.219
395	377	110	1	2	0	0	1.219
396	377	110	0	2	0	1	1.219
397	375	112	2	2	0	1	1.219
398	374	113	1	2	0	0	1.219
399	373	114	1	2	0	1	1.219
400	373	114	0	2	0	1	1.219
401	373	114	0	2	0	0	1.219
402	373	114	0	2	0	1	1.219
403	373	114	0	2	0	1	1.219
404	373	114	0	2	0	1	1.219
405	373	114	0	2	0	0	1.219
406	372	115	1	2	0	1	1.219
407	371	116	1	2	0	0	1.219
408	371	116	0	2	0	1	1.219
409	370	117	1	2	0	0	1.219
410	369	118	1	2	0	1	1.219
411	369	118	0	2	0	1	1.219
412	367	120	2	2	0	0	1.219
413	367	120	0	2	0	1	1.219
414	366	121	1	2	0	1	1.219
415	365	122	1	2	0	1	1.219
416	364	123	1	2	0	0	1.219
417	363	124	1	2	0	1	1.219
418	361	126	2	2	0	0	1.219
419	361	126	0	2	0	1	1.219
420	360	127	1	2	0	1	1.219
421	358	129	2	2	0	0	1.219
422	357	130	1	2	0	1	1.219
423	357	130	0	2	0	0	1.219
424	356	131	1	2	0	0	1.219
425	354	133	2	2	0	0	1.219

426	354	133	0	2	0	0	1.219
427	352	135	2	2	0	0	1.219
428	351	136	1	2	0	0	1.219
429	350	137	1	2	0	0	1.219
430	348	139	2	2	0	0	1.219
431	345	142	3	2	0	0	1.219
432	344	143	1	2	0	0	1.219
433	343	144	1	2	0	0	1.219
434	341	146	2	2	0	0	1.219
435	340	147	1	2	0	0	1.219
436	339	148	1	2	0	0	1.219
437	337	150	2	2	0	0	1.219
438	335	152	2	2	0	0	1.219
439	334	153	1	2	0	0	1.219
440	332	155	2	2	0	0	1.219
441	332	155	0	2	0	0	1.219
442	330	157	2	2	0	0	1.219
443	329	158	1	2	0	0	1.219
444	328	159	1	2	0	0	1.219
445	327	160	1	2	0	0	1.219
446	325	162	2	2	0	0	1.219
447	324	163	1	2	0	0	1.219
448	323	164	1	2	0	0	1.219
449	321	166	2	2	0	0	1.219
450	320	167	1	2	0	0	1.219
451	319	168	1	2	0	1	1.219
452	317	170	2	2	0	0	1.219
453	316	171	1	2	0	1	1.219
454	314	173	2	2	0	0	1.219
455	312	175	2	2	0	1	1.219
456	310	177	2	2	0	0	1.219
457	309	178	1	2	0	1	1.219
458	307	180	2	2	0	1	1.219
459	306	181	1	2	0	0	1.219
460	305	182	1	2	0	1	1.219
461	304	183	1	2	0	0	1.219
462	304	183	0	2	0	1	1.219
463	304	183	0	2	0	1	1.219
464	303	184	1	2	0	0	1.219
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472	303	184	0	2	0	0	1.219
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496	300	187	2	2	0	1	1.219
497	300	187	0	2	0	0	1.219
498	300	187	0	2	0	1	1.219
499	299	188	1	2	0	1	1.219
500	298	189	1	2	0	1	1.219
501	296	191	2	2	0	1	1.219
502	295	192	1	2	0	1	1.219
503	294	193	1	2	0	0	1.219
504	294	193	0	2	0	1	1.219
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507	291	196	1	2	0	1	1.219
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511	289	198	0	2	0	1	1.219

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514	288	199	1	2	0	1	1.219
515	287	200	1	2	0	0	1.219
516	286	201	1	2	0	0	1.219
517	285	202	1	2	0	0	1.219
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521	280	207	1	2	0	0	1.219
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526	277	210	0	2	0	1	1.219
527	276	211	1	2	0	0	1.219
528	274	213	2	2	0	1	1.219
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532	272	215	0	2	0	1	1.219
533	270	217	2	2	0	0	1.219
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537	267	220	2	2	0	0	1.219
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539	265	222	2	2	0	0	1.219
540	262	225	3	2	0	1	1.219
541	260	227	2	2	0	0	1.219
542	260	227	0	2	0	1	1.219
543	258	229	2	2	0	0	1.219
544	256	231	2	2	0	1	1.219
545	254	233	2	2	0	0	1.219
546	253	234	1	2	0	0	1.219
547	252	235	1	2	0	1	1.219
548	251	236	1	2	0	0	1.219
549	249	238	2	2	0	0	1.219
550	248	239	1	2	0	0	1.219
551	247	240	1	2	0	1	1.219
552	245	242	2	2	0	0	1.219
553	245	242	0	2	0	1	1.219
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559	239	248	1	2	0	0	1.219
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562	236	251	2	2	0	0	1.219
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571	231	256	1	2	0	0	1.219
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578	227	260	1	2	0	0	1.219
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580	226	261	1	2	0	1	1.219
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584	225	262	0	2	0	1	1.219
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593	218	269	2	2	0	0	1.219
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627	200	287	1	2	0	0	1.219
628	199	288	1	2	0	1	1.219
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630	198	289	1	2	0	0	1.219
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632	197	290	1	2	0	0	1.219
633	195	292	2	2	0	0	1.219
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635	194	293	1	2	0	0	1.219
636	193	294	1	2	0	1	1.219
637	193	294	0	2	0	0	1.219
638	192	295	1	2	0	1	1.219
639	192	295	0	2	0	1	1.219
640	190	297	2	2	0	0	1.219

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646	187	300	1	2	0	0	1.219
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674	178	309	1	2	0	0	1.219
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679	176	311	0	2	0	0	1.219
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687	166	321	2	2	0	0	1.219
688	165	322	1	2	0	0	1.219
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690	162	325	2	2	0	0	1.219
691	160	327	2	2	0	0	1.219
692	160	327	0	2	0	0	1.219
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695	157	330	1	2	0	0	1.219
696	156	331	1	2	0	0	1.219
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700	154	333	1	2	0	0	1.219
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705	150	337	1	2	0	0	1.219
706	150	337	0	2	0	0	1.219
707	149	338	1	2	0	1	1.219
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725	148	339	0	2	0	0	1.219
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729	148	339	0	2	0	0	1.219
730	147	340	1	2	0	0	1.219
731	146	341	1	2	0	0	1.219
732	146	341	0	2	0	0	1.219
733	146	341	0	2	0	0	1.219
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735	145	342	1	2	0	0	1.219
736	145	342	0	2	0	0	1.219
737	145	342	0	2	0	0	1.219
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744	144	343	1	2	0	1	1.219
745	144	343	0	2	0	0	1.219
746	143	344	1	2	0	1	1.219
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749	141	346	2	2	0	0	1.219
750	140	347	1	2	0	1	1.219
751	140	347	0	2	0	0	1.219
752	138	349	2	2	0	1	1.219
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757	137	350	1	2	0	0	1.219
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763	134	353	2	2	0	0	1.219
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765	132	355	2	2	0	0	1.219
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768	131	356	1	2	0	0	1.219
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774	130	357	0	2	0	0	1.219
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776	129	358	0	2	0	0	1.219
777	127	360	2	2	0	0	1.219
778	126	361	1	2	0	1	1.219
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781	125	362	1	2	0	0	1.219
782	125	362	0	2	0	0	1.219
783	124	363	1	2	0	0	1.219
784	123	364	1	2	0	0	1.219
785	121	366	2	2	0	0	1.219
786	120	367	1	2	0	0	1.219
787	119	368	1	2	0	1	1.219
788	118	369	1	2	0	0	1.219
789	116	371	2	2	0	0	1.219
790	114	373	2	2	0	0	1.219
791	113	374	1	2	0	0	1.219
792	112	375	1	2	0	0	1.219
793	111	376	1	2	0	1	1.219
794	109	378	2	2	0	0	1.219
795	109	378	0	2	0	1	1.219
796	107	380	2	2	0	0	1.219
797	106	381	1	2	0	0	1.219
798	105	382	1	2	0	0	1.219
799	104	383	1	2	0	0	1.219
800	103	384	1	2	0	0	1.219
801	103	384	0	2	0	0	1.219
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803	101	386	1	2	0	0	1.219
804	101	386	0	2	0	0	1.219
805	100	387	1	2	0	0	1.219
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807	98	389	1	2	0	0	1.219
808	97	390	1	2	0	0	1.219
809	96	391	1	2	0	1	1.219
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811	96	391	0	2	0	1	1.219
812	96	391	0	2	0	0	1.219

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814	95	392	1	2	0	0	1.219
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816	94	393	0	2	0	0	1.219
817	93	394	1	2	0	0	1.219
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820	92	395	0	2	0	0	1.219
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825	91	396	0	2	0	0	1.219
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830	90	397	1	2	0	1	1.219
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832	89	398	0	2	0	0	1.219
833	87	400	2	2	0	0	1.219
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838	87	400	0	2	0	0	1.219
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841	87	400	0	2	0	1	1.219
842	86	401	1	2	0	0	1.219
843	86	401	0	2	0	0	1.219
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846	85	402	1	2	0	0	1.219
847	85	402	0	2	0	0	1.219
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850	83	404	1	2	0	0	1.219
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861	81	406	1	2	0	0	1.219
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863	79	408	1	2	0	0	1.219
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870	77	410	0	2	0	0	1.219
871	77	410	0	2	0	0	1.219
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879	74	413	2	2	0	0	1.219
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883	72	415	1	2	0	0	1.219
884	72	415	0	2	0	0	1.219
885	71	416	1	2	0	0	1.219
886	71	416	0	2	0	0	1.219
887	71	416	0	2	0	0	1.219
888	71	416	0	2	0	0	1.219
889	71	416	0	2	0	0	1.219
890	71	416	0	2	0	0	1.219
891	71	416	0	2	0	0	1.219
892	70	417	1	2	0	0	1.219
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896	70	417	0	2	0	0	1.219
897	69	418	1	2	0	0	1.219
898	69	418	0	2	0	0	1.219

899	69	418	0	2	0	0	1.219
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915	67	420	0	2	0	0	1.219
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925	64	423	0	2	0	0	1.219
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935	63	424	0	2	0	0	1.219
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938	63	424	0	2	0	0	1.219
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940	63	424	0	2	0	0	1.219
941	62	425	1	2	0	0	1.219

942	62	425	0	2	0	0	1.219
943	62	425	0	2	0	0	1.219
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1019	57	430	0	2	0	0	1.219
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1067	56	431	0	2	0	0	1.219
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1071	56	431	0	2	0	0	1.219
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1079	56	431	0	2	0	0	1.219
1080	56	431	0	2	0	0	1.219
1081	56	431	0	2	0	0	1.219
1082	56	431	0	2	0	0	1.219
1083	56	431	0	2	0	0	1.219
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1089	56	431	0	2	0	0	1.219
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1091	56	431	0	2	0	0	1.219
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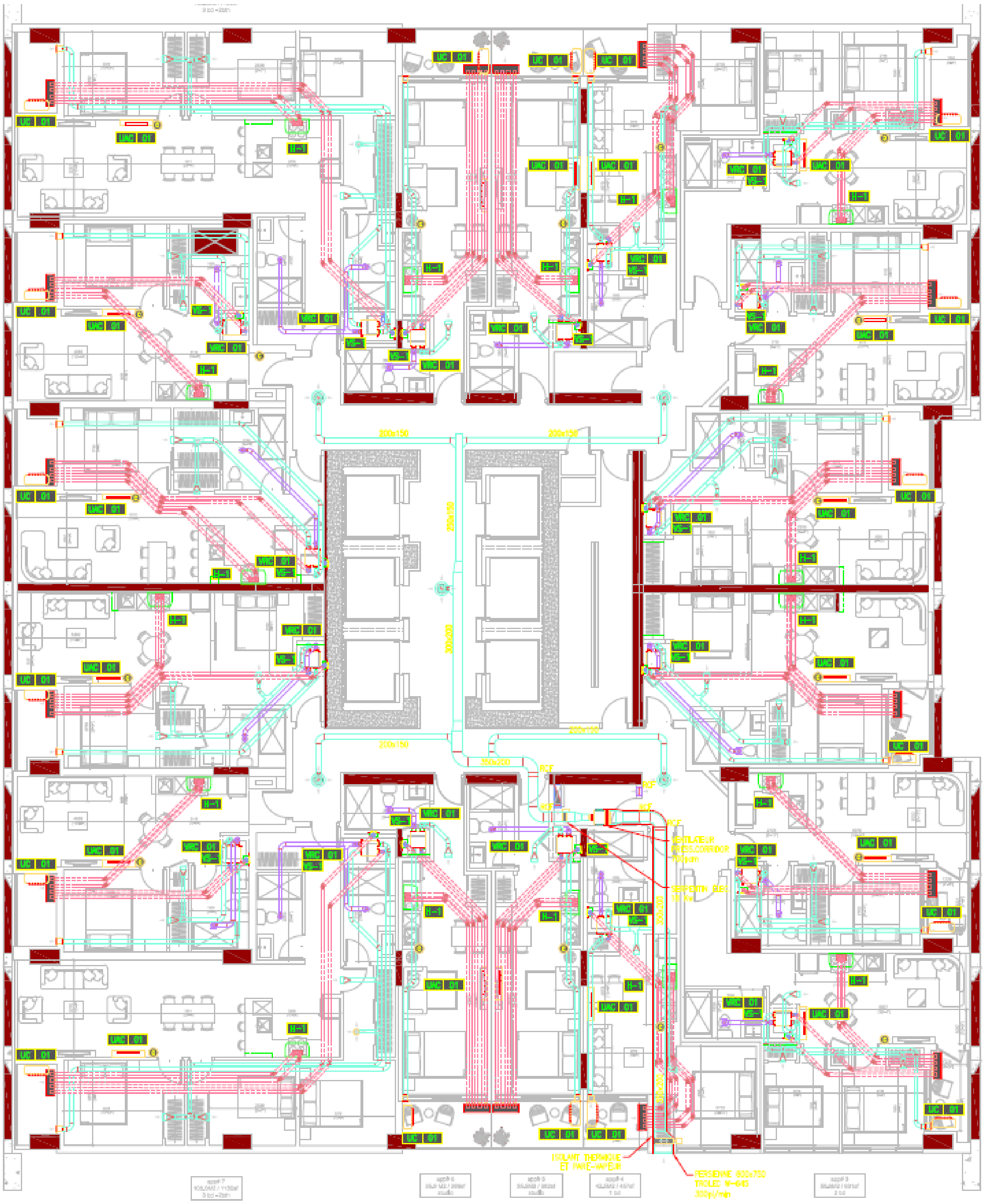
1094	56	431	0	2	0	0	1.219
1095	56	431	0	2	0	0	1.219
1096	56	431	0	2	0	0	1.219
1097	56	431	0	2	0	0	1.219
1098	56	431	0	2	0	0	1.219
1099	56	431	0	2	0	0	1.219
1100	56	431	0	2	0	0	1.219
1101	56	431	0	2	0	0	1.219
1102	56	431	0	2	0	0	1.219
1103	56	431	0	2	0	0	1.219
1103.275	55	432	1	2	0	0	1.219

APPENDIX E – Ventilation plans



APPENDIX F – Fire incident report samples

For the purpose of this study, twenty-seven fire incidents in Montreal were studied. The detail information of these reports is not provided due to the confidentiality of the information. However, few sample reports for fire incidents are presented below to provide an understanding of the information reviewed for each case. See the following pages for the samples.

Sample 1:

Sample form for your own use (not for reporting to WorkSafe).

ACCIDENT/INCIDENT REPORT FORM **Record No:**_______

Personal details

Name:

Occupation:

Section/Dept: Date of report: / /

Accident/incident details

Date: Time: Date reported: / /

Location: Witness:

Reported to whom:

Full accident/incident details – what happened, or in the case of a near miss, what could have happened

Injury – Nature of Injury

☐ Contusion/crush	☐ Burn	☐ Dislocation	☐ Amputation
☐ Laceration/open wound	☐ Superficial injury	☐ Foreign body	☐ Internal injury
☐ Concussion	☐ Sprain/strain	☐ Fracture	☐ Dermatitis

Location of Injury

☐ Head/face	☐ Eye	☐ Internal organs
☐ Hand/fingers	☐ Shoulder/arms	☐ Trunk (other than back)
☐ Hip/leg	☐ Foot/toes	☐ Back
☐ Other (state)		

Results of accident

Lost time injury Y / N No. of days: _____ days Workers' compensation Y / N

Treatment received: ☐ First aid ☐ Doctor ☐ Hospital

Damage to equipment/buildings/vehicles etc.

What was damaged?

Extent of damage:

Contributing factors

What were the contributing factors (if any)?

Corrective actions

Immediate actions

What controls can be put in place to prevent this from happening again?

Recommendations for action

Who is to implement these controls/corrective actions?

Date by which action is to be taken / /

Signatures

Officer: HS Rep: Manager:

Director: Investigating officer:

Actions completed: Date: / / Manager:

Sample 2:

CRITICAL AND EMERGENCY INCIDENT REPORT FORM

The Critical Incident Standard determined by the Minister for Education in accordance with s.159(1)(i) of the *School Education Act 1999* requires the principal to notify the chair of the governing body and the Director General, Department of Education Services, about any critical and emergency incidents as soon as practicable and, in any event, within 48 hours of the incident.

This form should be completed as soon as practicable and, in any event, within 48 hours of the incident, saved for your records and sent to:

Assistant Director, Non-Government Schools
Telephone: (08) 9441 1900 Facsimile: (08) 9441 1901
Email: criticalincidents@des.wa.gov.au
Postal address: PO Box 1766, OSBORNE PARK DC WA 6017

INCIDENT TYPE

Please indicate the type of critical or emergency incident by ticking one or more of the boxes below.

- ☐ Death, or life-threatening injury, of a student or staff member at school, or following an incident that occurred at the school or through a related school-based activity or circumstance;
- ☐ Circumstances that pose a critical risk to the health, safety or well-being of one or more students or staff;
  A circumstance posing a *critical risk* is one which would, if action had not been taken or the risk otherwise averted, have resulted in death, life-threatening illness orlife-threatening injury to one or more students and/or staff.
- ☐ Receipt of an allegation of child abuse, including but not limited to sexual abuse, against a student by a staff member or student or other person, whether the abuse is alleged to have occurred recently or in the past;
- ☐ Issuing a formal warning to a staff member or ceasing the employment of a staff member for a breach of the Staff Code of Conduct suspected to be grooming behaviour;
- ☐ Incidents requiring school closure, lockdown, or reduction of number of students or staff attending.

If you cannot tick one of these boxes, the incident may not need to be reported to DES as a critical incident. If in doubt, please contact the Assistant Director, Non-Government Schools, for clarification.

SCHOOL DETAILS

School:	Campus:
Chair of Governing Body:	Principal:
Telephone (business):	Telephone (mobile):
Email:	

INCIDENT

Date of Incident:	Time of Incident:
Location of Incident:	
Date Principal first notified of incident and by whom:	
Date Chair of Governing Body notified:	
Date Parents/Caregivers notified (if applicable):	

PERSON(S) INVOLVED (tick all applicable)

☐ Whole School ☐ Student(s) – Year level(s): ________ ☐ Teaching Staff ☐ Support Staff
☐ Volunteer ☐ Former student ☐ Student from another school ☐ Other (please specify): ________

DESCRIPTION OF THE INCIDENT (detail what happened, who was affected and whose actions caused the incident)

AGENCIES NOTIFIED OF INCIDENT (by governing body, principal or staff members – when applicable and known to the Critical Incident Reporter)		
☐ WA Police notified	Date:	Report No:
☐ DCPFS notified (Mandatory report)	Date:	Receipt No:
☐ DCPFS notified (child protection concern)	Date:	
☐ DEFS notified	Date:	
☐ TRBWA notified	Date:	
☐ WorkSafe notified	Date:	
☐ Other:	Date:	

ACTION(S) TAKEN TO RESOLVE THE INCIDENT (by governing body, principal or staff members)	
☐ Suspension/exclusion of student(s)	Period of time:
☐ Expulsion of student(s)	Date:
☐ School closure	Date:
☐ School lockdown	Date:
☐ Reduction in students or staff attending	Date:
☐ Counselling sought/provided	Date:
☐ Health and safety services advice sought	Date:
☐ Staff Code of Conduct breach warning issued	Date:
☐ Staff disciplinary action taken (please specify):	Details:
☐ School policies/procedures followed (including School Critical and Emergency Incident Policy)	Details:
☐ Other action(s) taken (please specify):	Details:

DESCRIPTION OF ACTION TAKEN TO RESOLVE THE INCIDENT

HOW ARE ANY ONGOING RISKS TO STUDENTS AND/OR STAFF BEING MANAGED?

Who is responsible for management of these risks? ___________

LODGED BY AUTHORISED CRITICAL INCIDENT REPORTER	Date:
Name:	Position:

Thank you for completing the Critical Incident Report.

The Department may contact you at a later date to obtain further information.

DES INTERNAL USE ONLY	
Incident Number:	Related RM8 References:
DES Staff Name:	Position:
Date Received:	Time Received:

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