A STUDY ON FIRE HAZARD AND SMOKE CONTROL IN LARGE RAILWAY INTERCHANGE STATIONS

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A Study on Fire Hazard and Smoke Control in Large Railway Interchange Stations

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CERTIFICATE OF ORIGINALITY

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ABSTRACT

In a busy city like Hong Kong, railway interchange stations are obliged to cope with the growing population and the expansion of the railway network. As of now, a number of new railway lines are, or will soon be, in operation. Within the integrated railway network, the design of the new railway stations with smoke control via a smoke management system is becoming more and more complicated. Likewise, a timeline analysis of the Available Safe Egress Time (ASET)/Required Safe Egress Time (RSET) and a fire hazard assessment based on the architectural design and smoke management system must consider the effects of different fire scenarios, fire loads, and occupancy factors.

Complicated station designs and the integration of the railway stations with other transport facilities, including Public Transport Interchanges, can produce problems in the evacuation of passengers in the event of fire. Due to complicated station designs, the standard prescriptive code on fire safety cannot be directly applied to all stations. Clearly, the station configuration built nowadays is commonly very complicated in terms of the building size, building height, and method of construction. In order to

justify that the railway station is safe for use, it is necessary to adopt the performance-based fire engineering approach to work out a solution.

In the design and planning of the railway station, especially one with a Public Transport Interchange, a fire evacuation strategy has to be developed based on the consideration of a number of important factors. As a general rule and design requirement, passengers within the fire incident place should be able to leave the place before becoming unduly affected by the fire and smoke; passengers in an area remote from the fire should be given sufficient and clear information to enable them to react according to the instructions from the station staff or clear announcements broadcast in the station.

The prescriptive building codes deal with the provisions for escape based on the lengths of escape routes, width and number of exits, the time for evacuation, and the evacuation path. By using the Fire Dynamics Simulator (FDS), a Computational Fluid Dynamics (CFD) software simulation model, and the data obtained from experimental results, the fire hazards in relation to the smoke control system in the large railway stations can be assessed, and the ASET can be determined. The railway stations with complicated architectural layouts and evacuation route arrangements can be justified by the performance-based fire engineering approach of analysis.

A smoke management system is a method of controlling the smoke generated by fires in railway stations. The objective of the smoke control system is to keep the smoke at high levels, thus facilitating the fire-fighting process and passenger evacuation. In this study, the smoke layer height and the ASET will be estimated via FDS simulation. With sufficient data collected from the CFD simulation results and experimental results from the scale model of a tilted enclosed space, the CFD simulation results can be compared, and the ASET from the CFD model by FDS can be validated. A fire safety management plan based on the validated results can then be developed to accommodate the railway station design.

In large railway interchange stations, the main concourse areas are often connected to horizontal passenger subways, slightly tilted passenger corridors, and even tunnels for trains due to a construction alignment. In order to study fire characteristics in large railway interchange stations, a scale fire model of an enclosed space similar to the configuration of a tunnel, with the ratio of 1:40 and angles of 0^o, 2^o, 4^o, and 6^o to the horizontal, is created and studied. The fire source is modelled by the use of containers in different sizes in the 1:40 scale model of an enclosed space. A 37-mm-diameter pool fire is created to represent the Heat Release Rate (HRR) of 5 MW from a bulk of burning luggage. It is conventional in Hong Kong and many countries worldwide to adopt the convective heat flow as the steady-state design fire for smoke control calculations. The experimental results indicate that the flame-bending angle increases while the flame height decreases with an increase in the inclination angle of the enclosed space, as additional force is acting along the longitudinal direction with the gravitational force. It is also observed that the flame colour is independent of the tilted angle. Flame colour remains yellow at different tilted angles due to the supply of oxygen maintaining the reaction of the emissions of small carbon-based particles. Different tilted angles produce fires with different characteristics involving the flame pattern, gas temperature, and flame height. Fire engineers should take these factors into consideration in the design of fire and smoke control systems in large railway interchange stations.

The use of timeline analysis in the performance-based fire engineering approach should be reviewed by fire engineers with knowledge in fire dynamics. In terms of railway station designs, exit arrangements should be carefully reviewed with the aid of a predictive evacuation model. Further systematic studies on human behaviour including a proper interpretation of fire and evacuation predictive models with the RSET data supported by the field measurements of crowd movements are recommended.

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ABBREVIATIONS

BD	Buildings Department
BS	British Standard
BSI	British Standards Institution
CFD	Computational Fluid Dynamics
CIBSE	Chartered Institution of Building Services Engineers
CoP	Code of Practice
FDS	Fire Dynamics Simulator
FRP	Fire Resistance Period
FSD	Fire Services Department
FSI	Code of Practice for Minimum Fire Service Installations and Equipment and Inspection, Testing and Maintenance of Installations and Equipment
HRR	Heat Release Rate
LES	Large Eddy Simulations
NFPA	National Fire Protection Association
NIST	National Institute of Standards and Technology
PNAP	Practice Note for Authorised Persons

SFPE	Society of Fire Protection Engineers
TD	Transport Department

NOMENCLATURE

A	area (m^2)
ASET	available safe egress time (s)
C_p	specific heat of air (J/g K)
D	passenger density (person/m^2)
D*	characteristic fire diameter (m)
δ_x	nominal size of mesh cell (m)
F_c	calculated flow rate (person/s)
Fr	Froude number
F_s	specific flow (person/m/s)
g	gravitational acceleration (m/s^2)
H_f	flame height (m)
HRR	heat release rate (MW)
$\dot{m}$	burning rate (kg/m^2/s)
m_r	mass loss rate (kg/s)
N	number of passengers (person)
$\dot{Q}$	fire power (kW)
q	volumetric flow rate per unit width (m^2/s)

ρ	air density (kg/m^3)
RSET	required safe egress time (s)
SI	safety index
SM	safety margin
t_{marg}	safety margin
t	time (s)
t_{ASET}	available safe egress time (s)
t_{RSET}	required safe egress time (s)
T	temperature (^{o}C)
TET	total evacuation time (s)
V	smoke velocity (m/s)
W_e	effective width of door/exit (m)

CHAPTER 1 INTRODUCTION

1.1 Background of the Study

Local fire safety codes are considered as prescriptive requirements. In Hong Kong, the code requirements are taken care of by the Buildings Department (2011) and Fire Services Department (2012). Due to complicated railway station configuration built nowadays, a proper fire evacuation design and hazard analysis should apply a performance-based fire engineering approach (Chow, 2012a). With the expansion of railway networks to accommodate growing populations, millions of people use the railway service as a means of transport every day (Transport Department, 2015). It is thus important to have a sophisticated and detailed analysis of the fire safety strategies of heavily populated facilities that considers both passive and active measures. Among the different passive measures in place, the design of an evacuation path (Fong and Ma, 2004) is one important aspect in the design of railway stations and must be thoroughly reviewed. In terms of fire evacuation designs (Fruin, 1971), various factors contribute to the performance of fire evacuations (Fridolf, 2010). This includes the railway station configuration, evacuation procedures, environmental factors, and human behaviour. To study evacuation performance, the station configuration factor can be analysed with sufficient, available data gathered from the passenger load, station layout, number of exits available, exit width, travel distance, common path of travel, exit capacity, and number of dead-end paths. All these parameters can be used to study the total evacuation time (Ng and Chow, 2006) from the railway station.

In terms of commercial building designs, the escape route design in Hong Kong is based on the Code of Practice for the Fire Safety in Buildings (BD, 2011). As guidance for the purpose of design, a set of factors representing the usable floor area for different types of buildings is given in the code to determine the maximum population within a building. This occupancy factor is often presented in the form of square metre per person (m^2 per person). Another set of guidance is given based on the measurements of staircases or escalators; as an example, the different widths of staircases and escalators with corresponding discharge values or capacities are given for different buildings with varying stories and heights. Based on the calculated maximum population rate, the number of staircases with proper widths can be assigned to the building in the early stage of the design. Following other international standards (BS 9999, 2008) is another option for consideration when designing fire evacuations.

Railway system is a key transportation means in dense urban areas in the pacific region. Particularly in Hong Kong, most railway stations are often crowded with passengers being squeezed into train carriages during rush hour (Cheung, 2014). As reported in the newspaper in Hong Kong (SCMP, 2014b), after the maximum passenger capacity in the train carriage changed from six passengers per square meter to four, the capacity became 70% full during rush hour. However, the train capacity can still be over 90% of a full loading as observed in the event of a delay or an interruption in train operation due to many reasons (Chow, 2011b). Despite the train carriage capacity, railway stations have become more crowded with an average weekday patronage of over 5 million passengers (Cheung, 2014).

Railway stations in Hong Kong are mostly located at the basement or ground levels (Qu, 2013) connected to commercial shopping centres or commercial or residential buildings in the town centre. The occupancy density of train passengers can be much higher than usual during the days of special events (The Sun, 2016; Apple Daily, 2014) such as fireworks or festival events. In the event of an emergency with high occupancy, therefore, evacuation time from the railway stations can be prolonged. With the platform screen doors (Qu and Chow, 2012) in place at most of the railway station platforms, the evacuation can become even more complicated. Complicated station designs (Tam, 2014) and the integration of the railway stations with other transport facilities, including public transport interchanges (Qu, 2013), can trigger problems in the evacuation of passengers in the event of fire. To gain a better understanding of the safety issue in large railway interchange stations, the evacuation times in different situations will be compared and studied.

‘Timeline analysis’ (CIBSE Guide E, 2010) has been applied in performance-based designs for many railway projects that encounter difficulties in complying with prescriptive fire safety codes. The ASET is simulated by fire models by referring to reported data on the tenability criteria on thermal exposure and smoke (Cooper and Stroup, 1982). The RSET is estimated with evacuation software. Both the ASET and the RSET are estimated and compared. To assure that the railway station is considered as safe in the event of fire evacuation, passengers in the railway station that are required to evacuate must be able to reach a place of safety within the timeframe. In other words, the RSET should be less than the ASET. To demonstrate that the ASET is greater than the RSET with a margin of safety (Chow, 2011b), the margin of safety and the safety index in different scenarios will be analysed in this study.

Smoke management system (Luo and Wong, 2007) is a method of controlling the smoke generated by the fire in a railway station. The objective of the smoke control system is to keep the smoke at high levels, thereby facilitating the evacuation of people and fire-fighting processes. To study the fire characteristics and smoke movement in enclosed spaces, including horizontal passenger subways and slightly tilted passenger corridors, scale modelling experiments will be carried out. With sufficient data collected from the CFD simulation results and the data collected from the experimental results from the scale model of a tilted enclosed space, the data can be analysed.

1.2 Objectives of the Study

The objectives of this research project are to study the fire hazard and smoke control of the large railway interchange stations in Hong Kong by means of fire risk analysis and the use of computational fluid model and evacuation models. The major scope of the study is focused on the large railway interchange stations in Hong Kong. Since most of the architectural features and building materials used in the railway stations are very similar to those of new railway stations in other countries in the Far East, including Beijing and Shanghai, the study can be further applied to other railway stations in the rest of the world.

Fire and safety hazard aspects of large railway interchange stations will be studied in this research project with the following objectives:

- To identify fire and safety hazards and their consequences.
- To evaluate the evacuation situation under different designs of fire and occupant loading with the use of predictive evacuation models.
- To investigate the fire and smoke movements in horizontal and tilted enclosed spaces with the use of scale modelling and CFD.

1.3 Methodologies Adopted in the Study

This research study focuses on large railway interchange stations. A CFD fire model and experiments in the form of scale models and predictive evacuation models are applied in this research study. Literature review and surveys are conducted with an in-depth investigation into the relationship between the ASET and RSET with different occupant loading, fire loads, and smoke control systems in the event of a fire evacuation.

Numerical studies using the Fire Dynamics Simulator (Version 5) are used as the fire model to study the fire and smoke development, including the determination of the ASET when conditions become untenable due to a fire in the assessment of safe evacuations. An evacuation model constructed by the software SIMULEX (IES, 2015) is used to determine the RSET to predict the evacuation time.

1.4 Outline of the Thesis

A flowchart showing the organisation of this study is shown in Fig. 1.1. The following is the breakdown of the thesis by chapter:

Chapter 1 discusses the background and nature of the problems associated with the large railway interchange stations under review and evaluation.

Chapter 2 provides an overview of the research process and the fire engineering design management aspects.

Chapter 3 discusses the background of the research and the fire hazards of large railway stations with a review of geometry, fire risk, occupant behaviour, and evacuation time, and the information gathered on the current code requirements for an evacuation design.

Chapter 4 discusses the fire safety concerns related to the design fire, fire safety provisions, smoke management system, and evacuation strategies.

Chapter 5 focuses on and describes the timeline analysis of the ASET and RSET and the simulation by the predictive fire and evacuation modelling. A CFD fire model by the FDS is used to simulate the heat and smoke propagation phenomena in large railway interchange stations.

Chapter 6 discusses the results from the scale tilted model experiments and the phenomena supported by the CFD fire model.

Chapter 7 discusses the development of the predictive evacuation modelling, the limitations that dictate the modelling process, and the requirements and output of the predictive modelling programme.

Chapter 8 gives an overall account of the research study and provides a conclusion based on the experimental data gathered with a comparison of the results from the simulation programme obtained from the fire and predictive evacuation modelling. It also presents recommendations for improving the safety level of large railway interchange stations.

CHAPTER 2 FRAMEWORK OF THE RESEARCH STUDY

2.1 Research Process

The research process is developed through the following steps:

(a) *Identification and understanding of the current large railway interchange stations and configuration of enclosed spaces*. The first step to gaining an understanding of the current practice adopted by railway operators in Hong Kong and the relevant overseas practices is by conducting a literature review. This is considered to be the groundwork for the identification of issues and concerns.

(b) *Analysis of the issues*. Upon completion of the identification of issues and concerns related to the current railway system design in Hong Kong, individual elements can be analysed critically such that appropriate evaluations with solutions for the identified issues can be subsequently conducted.

(c) *Evaluations and discussion of the issues*. The third step is to use the findings of the identified issues and concerns and resolve them appropriately by evaluating the current design, reviewing the available research findings, and evaluating the technical parts to create recommendations to be discussed in the conclusion.

Following the above steps as part of the research study framework development, a literature review is carried out to gain an understanding of the current railway stations in Hong Kong and their current development. The analysis and evaluation of a selected large railway interchange station are presented in the subsequent chapters.

2.2 Fire Engineering Design Management Aspects

Due to the complex nature of the railway stations, railway tunnels, adjacent buildings, and transport interchange facilities, it has been acknowledged by the authorities (BD, 1998) that some of the existing codes and regulations (BD, 2011) pertaining to the fire safety standards for commercial buildings may not be appropriate. As they deal with general and standard building designs, prescriptive codes and regulations cannot be applied directly in an effective way to complex large railway stations and transport interchange facilities. A performance-based fire engineering approach has been developed and adopted in current practices in Hong Kong.

A performance-based fire engineering design provides a flexible alternative for building owners to comply with the requirements when it is impracticable to follow the prescriptive provisions in the codes or standards, especially when it comes to special or large and complex buildings, railway stations, or alterations and additional works in existing buildings. The aim of a performance-based fire engineering design is to provide an overall level of safety that is equivalent to that which will result if fire safety (Malhotra, 1987) is achieved through complete compliance with the prescriptive provisions of the relevant codes of practice and standards. A performance-based fire engineering design provides a framework for fire engineers to demonstrate that the performance requirements of legislations are met, or even exceeded, although some of the design solutions adopted are not mentioned in or fall outside of the prescriptive provisions in the codes, with fire safety measures added to compensate for the deviation or shortfall.

The most important concept in the adoption of a performance-based fire engineering approach (Zhao, 2001) is to achieve a level of safety equivalent to the level necessitated by the minimum prescriptive provisions (BD, 2011). The process of the performance-based fire engineering design and arrangements consists of two major parts: preliminary analysis and quantitative analysis. The objective of the preliminary analysis is to review and come to an agreement with the concerned parties upon the scope of the design proposal, identify potential fire hazards, define performance criteria, and specify the various representative fire scenarios that are appropriate for detailed analysis and quantification.

The objective of the quantitative analysis is to demonstrate, using standard tools and methodologies, that the performance-based fire engineering design meets the performance criteria agreed to in the preliminary analysis. The quantitative analysis should be based on both probabilistic and deterministic methods (ABS, 2010), including fire engineering calculations, computer fire modelling, failure mode analysis, event tree analysis, and scientific fire tests.

Under the performance-based fire engineering design process, the design team is to be set up to:

(a) Appoint a fire engineering design team leader serving as the contact point.

(b) Communicate with the railway operator management for advice on the acceptability of the engineering analysis of the alternative fire engineering design and arrangements throughout the entire design process.

(c) Determine the safety margin adopted at the outset of the design process and review and amend it as necessary during the whole process of the analysis.

(d) Conduct a preliminary analysis to develop the conceptual fire engineering design in qualitative terms. This includes a clear definition of the scope of the alternative fire engineering design and arrangements for the railway station, and the code requirements that affect the engineering design; a clear understanding of the objectives and functional requirements of the codes and regulations; the development of fire scenarios and alternative trial designs. This part of the process should be documented in the form of an interim report that is reviewed and agreed upon by all interested parties and submitted to the railway operator management before the quantitative portion of the analysis is started.

(e) Conduct a quantitative analysis to evaluate possible alternative trial engineering designs using quantitative engineering analysis. This consists of the fire load specification of design fires, development of performance criteria based on the performance of an acceptable prescriptive engineering design, and evaluation of the alternative trial designs against the agreed performance criteria. From this point, the final alternative engineering design and arrangements are selected and the entire quantitative analysis is documented in the interim reports.

(f) Prepare documentation, specification, and a life-cycle maintenance programme for the facilities at the railway stations. The alternative engineering design and arrangements should be clearly documented and approved by the management of the railway operator, and a comprehensive report describing the alternative fire engineering design and arrangements and required maintenance programme should be kept by the railway operators and the operation staff working at the railway stations. An operation and maintenance manual should be developed for this purpose. The manual should include an outline of the design conditions of the fire service installations that should be maintained over the life of the railway development.

2.3 Fire Engineering Design Approach

In the adoption of a fire engineering design approach, it is important to design a building to achieve a level of safety equivalent to the level necessitated by the minimum prescriptive provisions (BD, 2011). The objectives of the performance requirements of the fire engineering design are to identify all risks of fire or fire propagation. When a fire occurs, the fire and smoke should be contained within the fire incident place. In order to allow the fire-fighting personnel to gain access to the building through a proper route without risk, the building should be designed with a safe structure, including the integrity of the building and that of the building's adjacent property. During fire evacuations, the building occupants or the staff should be able to evacuate with sufficient time from the fire incident place.

The fundamental element of a fire engineering design approach is an assessment of the actual fire risks and hazards in the building and the adoption of a realistic design fire as the basis of the fire engineering design of active fire-fighting systems (FSD, 2012).

CHAPTER 3 FIRE HAZARDS IN LARGE RAILWAY INTERCHANGE STATIONS

3.1 Geometry of Large Railway Interchange Stations

Standard or prescriptive fire safety regulations often cannot be directly applied to the complex geometry of large railway stations with complicated routes and circulation areas. With the performance-based fire safety engineering design of railway stations developed from comprehensive experience, the railway operator can justify the fire engineering issues on all railway stations and tunnels (Ho, Chow and Li, 2009) that do not conform to the existing regulations and conventional practices on fire safety matters commonly adopted for commercial buildings. A performance-based fire engineering concept (CIBSE Guide E, 2010) is therefore adopted and developed to optimise the fire safety design performance and cost (Law, 1996).

With the construction of new railway lines over the years, more and more large railway interchange stations are being built (Qu, 2013) to cope with the increasing transport demand. These interchange stations are often built with other transport interchange facilities such as the Public Transport Interchanges (PTIs), as shown in Table 3.1. Typical PTIs are often located at focal points to facilitate passengers' transfers between different railways lines, bus services, taxis, or private cars at the same station concourse level or at different concourse levels, from underground to ground levels, with lifts or escalators provided. There are a few large railway interchange stations in the Far East, including Hong Kong (TD, 2015), Shanghai, and Beijing in recent years. In some cases, railway terminuses and PTIs are integrated together with large commercial shopping centres.

Large railway interchange stations often accommodate a large amount of passengers whenever they are in transit across the railway lines or via the stations to the PTIs or commercial shopping centres. Concourses and platforms typically have fire safety provisions that are different from those of other commercial buildings. Public circulation spaces along the platforms are provided to allow passengers to transit or move onto the next platform or concourse level. There are island and side platforms for the passengers to stand or move around on. The public circulation space should be able to hold under the maximum occupant loading of passengers (BD, 2011). The exits and entrances should be effectively positioned to allow smooth passenger flow.

In Hong Kong, large railway interchange stations are integrated with either PTIs and/or commercial shopping malls. Examples are the Admiralty Station, Central Station, Kowloon Tong Station, Hung Hom Station, Yuen Long Station, and Tai Wai Station.

The general characteristics of the large railway interchange stations are very similar. They are located in the town centre of the region and integrated with other transport facilities. The whole complex of the buildings is confined or semi-confined, requiring longer travelling time for passengers to reach the exits.

3.2 Fire Risk in the Stations

Nowadays, there are many commercial business activities such as exhibition showcases or display boards inside large railway station concourses and atrium halls (Hung, 2001) that may obstruct the evacuation path (Ku and Chow, 2012). Arson fire cases that occurred in Hong Kong and South Korea (Chow, 2004a) have shown the importance of fire safety management. With increasing business connections between Hong Kong and mainland China, it has been observed that most railway passengers carry lots of luggage (Chow and Li, 2000) when crossing the boundary, which poses a fire risk at railway stations. When the luggage carried (Ku, 2012) by the passenger is on fire, it would generate a considerable amount of smoke depending on the nature of the substances inside the luggage (Chow, 2012a). The visibility of the egress route is another factor contributing to the time for completing an emergency evacuation. The clearance of smoke would primarily rely on the effectiveness of the smoke management system (NFPA 92, 2012). A clear and visible signage installation for the emergency escape route (Chow, 2012b) and the geometric configuration of the railway station would be defining factors of the RSET.

Field surveys have shown that luggage and equipment (Ho, Ku and Chow, 2016), brought to the railway station by parallel traders, contribute to the fire load (Fong and Chow, 2011) and may increase the development of fire. With the increase of commercial businesses in railway operation, a number of free newspaper booths and paper recycling bins are situated within railway stations, thereby contributing to the fire load and fire risks of railway stations. In some cases, passengers are also allowed to carry bikes and trolley bags, which may not lead to larger fire loads (Chow 2012a), but are nevertheless factors influencing the evacuation situation (Ku, 2012) in the event of a fire.

3.3 Occupant Behaviour

During an emergency situation, occupants will not behave in the same way as they normally would. As people develop, their life experiences and educational backgrounds shape their decision-making processes and abilities. How occupants perform during an emergency situation is the direct result of their behavioural and decision-making processes (Babrauskas, Fleming, and Russell, 2010). They do not act or react randomly to changes in an environment. In a previous study (Proulx, Kaufman, and Pineau, 1996), a decision model was created to incorporate the effect of different levels of stress on the choices made during the selection of an option. The study showed that occupants will first fear the unknown danger of an emergency situation before they start to worry.

The occupant behaviour during an emergency includes both their pre-evacuation activities (BS 7974, 2001) and their actions during the movement phase of the evacuation. Pre-evacuation movement behaviour is that which occurs before a fire alarm is sounded. This includes the actions that occur between the fire alarm and the occupant's initiation of movement towards an exit.

The ultimate goal to improve the life safety of occupants in the event of a fire in performance-based fire engineering is to develop a comprehensive theory of human response. The theory of human behaviour (Pauls, 1995) toward fires is complex. The response can be classified into two main periods: the pre-evacuation period and the movement period (Pauls, 1987). The pre-evacuation and movement periods (Proulx and Fahy, 1997) consist of the pre-alarm phase that is the time between the point when a fire is ignited and the point when the fire alarm is initiated. The evacuation decision-making period is the point when the occupants are exposed to the fire and decide to protect themselves and evacuate from the incident place. The protective action also includes the collection of personal belongings or the assistance of others in preparing for the fire evacuation (Proulx, 2002).

3.4 Evacuation Time

It is important that the estimated number of the total railway station occupant loading (Chow, 2012a) is determined by traffic parameters or by using the railway station circulation areas as the basis of the evaluation of evacuation time. The occupant loading calculation should include the scenario in which the railway train is fully loaded in its maximum carrying capacity of passengers (Fong and Ma, 2004) and the passengers boarding to the trains, which are gathered by the railway operator based on statistical data. Considering that the passengers missing the trains would result in extra passenger load in the station, a conservative and reasonable station occupant loading should be used for modelling the event of fire evacuation.

Generally, due to the complexity of large railway interchange stations, the maximum travel distance to the exits in these railway stations often exceeds those specified in Hong Kong's prescriptive codes (BD, 2011) or overseas standards (NFPA 130, 2010). To justify the tenability of the design in the face of longer travel distances in the event of fire, the smoke extraction system and evacuation time calculations should be used to demonstrate that the evacuation time (Ng and Chow, 2006) would be safe even for a longer period, with the smoke layer above the head height of the evacuees, thereby not affecting them during the evacuation movement. The critical evacuation time of 4.5 minutes is often specified by the railway operator in Hong Kong. During this timeframe, the evacuees would safely make their way from the fire incident zone to a place of safety with the aid of a smoke management system and emergency announcements using an automatic voice system supplemented by flashing exit signs to initiate the evacuation at railway stations.

NFPA (NPFA 130, 2010) includes recommendations for maximum occupancy levels within train stations. It states that the maximum occupant loading for a train station should be based on the simultaneous arrivals of trains to each platform of a station plus the simultaneous arrivals of individuals to the station for each train during peak times.

CHAPTER 4 FIRE SAFETY CONCERNS IN LARGE RAILWAY INTERCHANGE STATIONS

4.1 Design Fire

The design fire size (Kim and Milke, 1998) is the basis of fire engineering analysis. The fire size and burning source (Thauvoye, Zhao, Klein and Fontana, 2008) also dictate the smoke production rate, which in turn determines the required smoke handling capacity of the smoke management system (Klote and Milke, 1992). The design fire (Maevski, 2012) is also the factor contributing to the available time for safe passenger evacuation. Some passengers who use the railway stations as a means of transport everyday might be familiar with the geometry of the stations. In normal situations, passengers know the direction or the way to go up or down in the railway station through normal routes or points of access. In the event of a fire, passengers might also use the most familiar routes or exits to evacuate (Luo and Wong, 2007). Clear instructions or a broadcasting system should be provided to guide the passengers in using the evacuation route or emergency exits.

As smoking is not allowed in railway stations or indoor spaces anywhere in Hong Kong, it is more likely that a fire will begin from the station's retail shop areas. Other than the retail shop areas, passengers carrying small liquefied petroleum gas (LPG) cylinders for domestic gas cookers or bottles of flammable liquid fuel for construction work such as kerosene may pose a hazard and contribute to the fire load of the railway stations.

Since the amount of combustible baggage carried by passengers is restricted, the heat release rate (Chow, 2003b) might not be too high in normal circumstances. Without the data from a full-scale burning test on the baggage or combustible materials carried by passengers, it would be difficult to estimate the heat release rate. To limit contributions to the fire load at railway stations, the control of baggage and combustible materials by the frontline railway operation staff would be more effective.

In the development of the performance-based fire engineering design, most of the design assumptions require the knowledge of the size of the fire (Yuen and Chow, 2005). The design fire has an influence on the design of the smoke management system of railway stations. In most cases, the design fire would be estimated by the baggage likely to be carried by passengers. Even though the heat release rates for some combustible materials are known, it is difficult to accurately estimate the fire load of an unknown quantity of combustible materials. Based on the individuals, the heat release rate is a function of all of the materials carried by the individual.

There are a number of factors in the development of a fire. These include the quantity and amount of combustible materials and the arrangement of fuel. The development of a fire also depends on the availability of a fire detection device and smoke management system (Kang, 2007). The design fire adopted by most fire engineers is generally based on the statistics or historical data of occupancy types.

Nowadays, some of the railway stations in Hong Kong, especially those in the airport railway line, provide a quick beverage service to the passengers. Fire control based on the cabin design (Beever 1991; Law 1990) of the retail shop areas is of concern. The fire risk will be high if gas cookers and LPG cylinders are used in the retail shop areas. Due to upgrades to the retail shop areas, some of the renovation works inside the railway station might involve the flame cutting of construction materials, which may pose another fire hazard at railway stations.

The amount of combustible materials in railway stations would pose a considerable fire hazard (Chow, 2015). Fire load density (FLD, in MJm^{-2}) is a key factor in the development of a fire. Basically, the FLD consists of two parts: movable fire load and fixed fire load (Chow, 2003b). The upper limit of FLD for most commercial buildings adopted in the local prescriptive fire codes (FSD, 2012) is 1,135 MJm^{-2}, or else a dynamic or smoke management system is required. As shown in the present field survey, baggage can accumulate in the concourse area of large railway interchange stations while cross-border passengers wait for others or decide on their next move. The FLD is also related to the anticipated number of passengers, N_{max}, in a railway station and the amount of baggage, H_{per}, carried by the passengers:

$$\text{FLD} = \frac{N_{max}\ \ H_{per}}{Floor\ \ Area} \tag{4.1}$$

where

FLD = Fire load density (MJm^{-2});

N_{max} = Anticipated number of passengers;

H_{per} = Weight of contents (kg) x Calorific value of contents ($MJkg^{-2}$).

The fire load of the baggage carried by passengers depends on the individuals. In a previous study, a full-scale burning test on a passenger train car was conducted (Luo and Wong, 2007) to show that the peak heat release rate of the passenger train car was over 12 MW.

The size of the design fire is represented by the heat release rate (Chow, 2012a). The design fire is the basic and fundamental element of a performance-based fire engineering design (Babrauskas 2002; Morgan and Gardner 1999). The parameters for estimating the heat release rate are an indication of the size of the fire (Chow, 2011b) and the rate of the fire growth in terms of the amount of smoke and toxic gas released. The handling capacity of the fire management system is related to the design fire and thus the time available for escape (Togawa, 1955).

The following heat release rates of specific design fires are often adopted by the railway operator (KCRC, 2007) in Hong Kong.

Platform Fire	2 MW
Concourse Fire	2 MW
Baggage Fire	2 MW
Sprinklered Retail Fire (Cabin Concept)	2 MW
Train Fire	5 MW to 17 MW

4.2 Fire Safety Provisions

In terms of passive fire control, a fire resistance construction is necessary to ensure that the combustible materials are burnt out and contained within the confined areas. To confine the fire from spreading to other areas of the railway stations, the fire resistance period should be longer than the duration of the fire. Generally, the fire resistance period of walls or floors in the railway stations in Hong Kong is governed by requirements in the prescriptive codes, including the Code of Practice for Fire Safety in Buildings (BD, 2011), while a performance-based fire engineering design by active and passive means (Chow 2003b) is adopted for the design of railway stations.

In terms of active fire control systems, a variety of systems are adopted for railway stations. The following fire service installations were observed in the present study on a large railway interchange station in Hong Kong:

- Sprinkler heads were found in the retail shop areas on the concourse level.
- Fire hose reels, fire hydrants, portable fire extinguishers, and break glass units were found on the concourse and platform levels near 'EXIT' signs.

- Smoke detectors were found on the concourse and platform levels.
- Emergency lighting was found on the concourse and platform levels.
- An audio/visual advisory broadcasting system was installed to direct the flow of passengers in the event of a fire evacuation.
- A smoke management system was installed in the retail shop areas, on the concourse and platform levels.

It has been observed that the cabin concept is applied to retail shop areas within the railway station along the corridor of the concourse areas. Since the retail shop areas are identified as the areas of higher fire load and fire risk, compared to the circulation areas of the other parts of the railway station, the design of the cabin concept (Luo and Wong, 2007) can provide a higher level of fire protection by using a combination of smoke detection, sprinklers, and a dedicated smoke management system.

Depending on the baggage carried by passengers, the fire loads in the railway station areas are considered to be low. The cabin concept is a system designed to protect the retail shop areas within the railway stations that are of higher fire loads. The cabin concept relies on an effective combination of fire detection, sprinklers, and a dedicated smoke extraction system. The smoke bulkhead in the retail shop areas is used to form a smoke reservoir immediately over the protected area. A smoke management system should be designed to have a smoke extraction rate based on the design fire load that represents the worst scenario. Smoke generated by a fire incident should not be allowed to spread to the low fire load areas such as the adjacent circulation areas of the railway station.

The survey conducted on 24 Dec 2011 observed that a number of retail shop areas had a common smoke reservoir with the following fire service provisions within the cabin:

- fire detectors and alarms.
- fire-rated smoke bulkhead and barrier to contain smoke inside the shop areas.
- combined smoke extraction and normal ventilation systems.
- sprinkler system with the use of fast-response sprinkler heads.

4.3 Smoke Management System

It is difficult to separate the railway station's functional requirements into the fire compartment's maximum volume of 28,000 m^3, as specified in Hong Kong's prescriptive fire codes (FSD, 2012). However, full justification based on the station design, fire spread calculations, and passenger or occupant characteristics is required to allow the adoption of a larger fire compartment for the public areas of a station (BD, 1998). According to the findings of another research study (Chow and Ng, 2008), the most effective way to evacuate passengers in railway stations is to utilise the normal access routes that allow clarity and ease of passenger flow (Hankin and Wright, 1958). It is thus neither practical nor desirable to fully compartmentalise, such as by fire shutters, and to separate the public areas being used as escape routes in large railway interchange stations.

For large railway interchange stations, in terms of the smoke and fire spread analysis, limiting the compartment size to 28,000 m^3 is considered difficult due to the complexity of the building structure. The high fire risk area, such as the retail shop areas, is comparably small with respect to the railway station area; thus, the fire and smoke can be controlled by a dedicated smoke management system (Luo and Wong, 2007) to limit the fire spread to adjacent circulation areas. With the adoption of the cabin concept in the relatively high fire risk retail shop areas of the railway station, fire is controlled by the use of fast-response sprinkler heads and a dedicated smoke management system.

Under the prescriptive fire codes (FSD, 2012), the dynamic smoke control system should prevent the smoke from travelling more than 30 m before entering the nearest point of inlet to the extraction system, and at least one extraction point should be provided every 500 square metres of floor area.

In order to maintain a smoke-clear height for safe evacuation in the event of fire, a minimum of 2 m should be achieved (NFPA 92, 2012). If there are open connections between the smoke control zones, passive or active smoke control measures in the form of smoke barriers or smoke curtains should be provided such that the risk of smoke flowing from the fire incident area to the adjacent safe passage can be reduced. The smoke reservoirs containing smoke within the smoke control zones are to be maintained to allow the smoke extraction system to remove effectively the smoke from the fire incident area. Smoke barriers or smoke curtains should be installed to separate the smoke control zones from the lifts, escalators, stairs, and other voids to prevent the smoke from flowing from the fire incident area to the public circulation area.

In the event of a fire identified on a train, the platform screen doors (Qu and Chow, 2012) should be opened to allow passengers from within the train carriage to escape to a safe place away from the platform. The platform and the track should be considered as a combined smoke reservoir. The smoke extraction system for a train fire should consist of a combination of over-track exhaust system for the train fire and over-platform exhaust system to handle the smoke spillage from the train fire onto the nearby platform.

In order to allow the smoke management extraction system to operate effectively (Qu, 2013), it is necessary to have an adequate supply of make-up air. In terms of the areas adjacent to the fire, the adjacent ventilation systems should be changed into the supply air mode to allow sufficient air to compensate for the volume of smoke being extracted from the fire incident area. The make-up air should also provide a flow of fresh air into the fire incident area as the evacuees escape outwards or upwards. In the case of a train fire, fresh air can flow in naturally or by mechanical means via the tunnels that should be able to maintain sufficient make-up air to compensate for the extraction of smoke by the smoke extraction fan.

Smoke movement can be managed by proper compartmentalisation, airflow control, pressurisation, dilution, or buoyancy. Defined by NFPA (NFPA 92, 2012), a smoke control system is an engineered system that uses mechanical fans to produce pressure differences across smoke barriers to inhibit smoke movement. Air pressurisation produced by mechanical fans is referred to as smoke control (Ho, 2008). NFPA (NFPA 92, 2012) also provides guidelines to implement the smoke control system by using pressure differentials to achieve one or more of the following functions:

- reduce or control the migration of smoke from the fire incident area.
- maintain a tenable condition in the exit routes during the fire evacuation.
- assist the emergency response or fire-fighting personnel in conducting search and rescue operations and locating the source of fire.
- protect life and reduce property loss.

The mechanical smoke control system is considered to be an important element in maintaining the smoke control and fire safety of large railway interchange stations. According to the NFPA 130 requirements (NFPA 130, 2010), the mechanical emergency ventilation system should make provisions for the protection of passengers, operation staff, and emergency rescue and fire-fighting personnel from fire and smoke during the emergency of a fire incident (TD, 2014) and should be designed to maintain the required air flow rates for at least an hour more, but not less than, the anticipated evacuation time. In Hong Kong and other countries worldwide, there is the practice of integrating the normal mechanical ventilation system with the smoke extraction system by a common ductwork for the safe evacuation of passengers during a fire. The normal mechanical ventilation system in the tunnels (Chow, Qu and Pang, 2011) and the platform's over-track exhaust system may also be in operation in the event of a fire evacuation. For large railway interchange stations, tenability should be maintained for an extended period of time due to the higher occupant loading and the complexity in the station evacuation routes.

4.4 Evacuation Strategy

Evacuation strategy (Lo et al., 2004) is an important aspect related to the fire safety of large railway stations. As for the behaviour of passengers, research studies (Proulx, 2002) have shown that most railway passengers tend to use familiar routes, particularly in an emergency such as when a fire occurs. To ensure a timely fire evacuation, railway station emergency evacuation procedures (Ku, Fong and Chow, 2013) should be developed in the form of an evacuation strategy to facilitate the fire evacuation. The fire-fighting equipment and other facilities should be maintained in proper operating modes.

When escalators are used for fire evacuation (Luo and Wong, 2007), those that run in the same direction as the evacuation should continue to operate in the event of a fire as a means for the evacuees to leave the station, whilst those running counter to the direction of the evacuation should be stopped and used as stairs to aid the flow of the evacuation. Although most international practices and guides (NFPA 130, 2010) allow escalators in the railway stations to be used as a means of egress, the statistical data on the reliability of escalators and escalator specifications should be carefully reviewed in terms of their suitability for safe evacuations.

Due to the complex geometry and nature of railway stations, fire evacuation procedures and the evacuation strategy should be established for each railway station, including the day-to-day inspection and maintenance of fire service installations, housekeeping procedures to remove fire hazards, limitation of combustible materials in passengers' baggage, security and vigilance by the railway station staff to limit the risks of deliberate fires, and staff training for fire drills, gaining incident handling skills, using handy fire-fighting means, and emergency communication and evacuation procedures. Further education of the general public to increase the awareness of fire hazards, the risk of deliberate fire ignition, reporting a fire incident, and things to do in the event of a fire will be helpful through the implementation of safety campaigns as part of the comprehensive fire safety strategy.

CHAPTER 5 NUMERICAL STUDIES ON THE PERFORMANCE OF THE SMOKE MANAGEMENT SYSTEM

5.1 Fire Dynamics Simulator

The railway facilities are built to provide a means of transportation for passengers. The railway station environment is quite different from that of other commercial buildings. Even if a small fire occurs, the large quantity of smoke generated might pose a hazard to the passengers if the environment becomes untenable due to the fire incident. Passengers are exposed to high risks during evacuation. A smoke control system (NFPA 92, 2012) is therefore necessary to provide a clear evacuation route when the fire occurs. To ensure that the smoke control system is effective for maintaining a clear evacuation route, the technique of CFD (Chow, 1999) is to be adopted.

The CFD techniques have been used for many years in the fire engineering analysis (Chow, 1999) of the ventilation system under fire scenarios. The FDS (McGrattan et al., 2010) developed by the National Institute of Standards and Technology in the

USA has been used to study fires in large halls (Chow, 2007a), car parks (Lin et al., 2008), and subway stations (Roh et al., 2009). Different fire scenarios like enclosed-space fires and fires under ventilation, among others, have been studied by other researchers (Morgan and Gardner, 1999). In this study, the performance of the smoke control system in the railway station in Hong Kong is investigated by simulating heat and smoke propagation phenomena in the railway station.

The FDS is a CFD model of fire-driven fluid flow (McGrattan et al., 2010). It numerically solves a form of the Navier-Stokes equations appropriate for low-speed, thermally-driven flow with an emphasis on the smoke and heat transfer from fires. The partial derivatives of the conservation equations of mass, momentum, and energy are approximately finite differences, and the solution is updated in time on a three-dimensional, rectilinear grid. Thermal radiation is computed using a finite volume technique on the same grid as the flow solver. Lagrangian particles are used to simulate smoke movement, sprinkler discharge, and fuel sprays.

Smokeview is a companion programme to FDS that produces useful images and animations of the computational results. In this sense, Smokeview, via its technique of three-dimensional renderings, is now an integral part of the physical smoke model, as it allows the user to assess the visibility within a fire compartment in ways that ordinary scientific visualisation software cannot.

Throughout its fire and smoke development, FDS has been aimed at solving many practical fire problems in fire protection engineering, while providing, at the same time, a very powerful tool for studying fundamental fire dynamics and combustion. FDS can be used to model the following phenomena:

(a) Low-speed transport of heat and combustion products from the fire

(b) Convective and radiative heat transfer between the gas and solid surfaces

(c) Pyrolysis

(d) Flame spread and fire growth

(e) Heat detector, smoke detector, and sprinkler activation

(f) Sprinkler sprays and fire suppression by water

Although FDS is designed specifically for fire simulations, it can also be used for other low-speed fluid flow simulations that do not necessarily include thermal or fire effects. Most of the applications of the model have been for the design of smoke control systems, sprinklers activation studies, and smoke detector activation studies.

The rest of the applications have been for residential and industrial fire reconstructions.

The FDS includes the following major model components:

Hydrodynamic Model: FDS numerically solves a form of the Navier-Stokes equations appropriate for low-speed, thermally-driven flow with an emphasis on the heat and smoke transport from fires. The main algorithm is an explicit predictor-corrector scheme that is second-order accurate in space and time. Turbulence is treated by means of the Smagorinsky form of the Large Eddy Simulation (LES). It is also possible to perform a Direct Numerical Simulation (DNS) if the underlying numerical grid is relatively fine. The LES is set to be the default mode of operation.

Combustion Model: For most fire engineering applications, FDS uses a combustion model based on the mixture fraction principle. The mixture fraction is a conserved scalar quantity that is defined as the fraction of gas at a given point in the flow field that originates as fuel. Unlike in the versions of FDS prior to 5, the reaction of fuel and oxygen is not necessarily instantaneous and complete, and there are several options of schemes for selection that are designed to predict the extent of combustion in under-ventilated spaces. The mass fractions of all of the major reactants and products are derived from the mixture fraction by means of ‘state relations,’ expressions arrived at by a combination of simplified analysis and measurement.

Radiation Transport: Radiative heat transfer is included in the model by using the solution of the radiation transport equation for a grey gas. In some cases, a wide band model is used in place of the grey gas model to provide better spectral accuracy. The radiation equation is solved by a technique similar to the finite volume method for convective transport; thus, its name is the Finite Volume Method (FVM). With approximately 100 discrete angles, the finite volume solver requires about 20% of the total CPU calculation time, a modest cost given the complexity of radiation heat transfer. As water droplets absorb and scatter thermal radiation, the solution is important in cases involving water mist sprinklers, but also plays a role in all other sprinkler cases. The absorption and scattering coefficients are based on the Mie Theory. The scattering from gaseous species and soot is excluded from the model.

Geometry: FDS approximates the governing equations on one or more rectilinear grids. The user prescribes rectangular obstructions that are forced to conform to the underlying, defined grid cell. All solid surfaces are assigned thermal boundary conditions, including information about the burning behaviour of the material. Generally, material properties are stored in a database and invoked by name. Heat and mass transfer to and from solid surfaces is typically handled with empirical correlations, although the heat and mass transfer can also be computed by performing a DNS.

Output Parameters: FDS computes the temperature, density, pressure, velocity, and chemical composition within each defined, numerical grid cell at each discrete time step. There are typically hundreds of thousands to millions of grid cells and thousands to hundreds of thousands of time steps. In addition, FDS also computes at solid surfaces the temperature, heat flux, mass loss rate, and various other quantities. Understanding the parameters is essential for a careful selection of the data to save in designing a model for an actual experiment. Even though only a small fraction of the computed information can be solved, the output typically consists of large data files. The typical output quantities for the gas phase are as follows:

(a) Gas temperature

(b) Gas velocity

(c) Gas species concentration (water vapour, CO_2, CO, N_2)

(d) Smoke concentration and visibility estimates

(e) Pressure

(f) Heat release rate per unit volume

(g) Mixture fraction (or air/fuel ratio)

(h) Gas density

(i) Water droplet mass per unit volume

In terms of solid surfaces, FDS predicts additional quantities associated with the energy balance between the gas and solid phases. These include:

(a) Surface and interior temperature

(b) Heat flux, both radiative and convective

(c) Burning rate

(d) Water droplet mass per unit area

Other than the above, global quantities recorded by the programme include:

(a) Total heat release rate

(b) Sprinkler and detector activation times

(c) Mass and energy fluxes through openings or solids

Various quantities at a single point in space or global quantities like the heat release rate of the fire are saved by the time histories in simple, comma-delimited text files that can be plotted by using any spread sheet software. However, most of the field data or surface data are visualised with a programme called Smokeview, a tool specifically designed to analyse numerous data generated by the FDS. The FDS and Smokeview are used together to model and visualise fire phenomena. Smokeview performs this visualisation by showing animated tracer particle flow, animated contour slices of computed gas variables, and animated surface data. Smokeview also presents contours and vector graphs or plots of static data anywhere within a specific scene at a fixed time.

Smoke, fire, and sprinkler spray can be displayed realistically by using a series of partially transparent planes. The smoke transparencies are determined by using the smoke densities generated by the FDS. The fire and sprinkler spray transparencies are determined by using a heuristic based on the heat release rate and water density data, again generated by the FDS. Dynamic data are visualised by animating particle flow showing the location and values of tracer particles, as well as 2D contour slices both within the control domain and on solid surfaces and 3D isosurfaces. 2D contour slices can also be generated and drawn with vectors in different colours that use velocity data flow direction, speed, and value. Static data are visualised similarly by generating 2D contours, vector plots, and 3D surfaces.

Smoke Visibility: The model evaluates smoke visibility based on the line of sight. The importance of the visibility function as a line integral has been reported and demonstrated in a compartment fire under natural ventilation (Lin, Chuah, and Liu, 2008) and an underground railway station fire under both natural ventilation and mechanical ventilation conditions (Kang 2007). The smoke model offers an evaluation tool for a direct comparison of numerical and experimental results (Li, Li, and Chow 2012).

Smoke spread in the modelled large railway interchange station under this study is investigated by using transient visibility because visibility is the most important factor in estimating the time of reaching an untenable condition. Visibility of the exit route in the smoke control zone is investigated via the CFD model.

5.2 Timeline Analysis of the ASET/RSET

The fundamental concept in the assessment of passenger safety in large railway interchange stations under fire conditions is the determination of the time required (Stahl, 1982) for passengers to egress (Tubbs and Meacham, 2007) from the fire incident area to a place of safety before it becomes an untenable environment. In the study of fire evacuations in buildings, the timeline approach or time-based system (Hinks, 1985) are commonly applied to large railway stations, shopping malls, and PTIs. The ASET refers to the time between ignition and the moment when the environment becomes untenable to evacuees (Hinks, 1985). It can be estimated (CIBSE Guide E, 2010; Shields, Silcock, and Dunlop, 1992) by comparing the published data on tenability criteria. The RSET is estimated in the Far East by empirical equations and evacuation software developed overseas (IES, 2015). For any specific set of ASET and RSET calculations (ISO/TR 16738, 2009), the margin of safety (t_{marg}) is represented by the difference between the ASET (t_{ASET}) and the RSET (t_{RSET}) as given by:

$$t_{marg} = t_{ASET} - t_{RSET} \tag{5.1}$$

where

t_{marg} = margin of safety, or SM;

t_{ASET} = available safe egress time, or ASET;

t_{RSET} = required safe egress time, or RSET.

Evacuees should reach a place of safety before the fire environment in the building exceeds tenability limits (Shields, Silcock, and Dunlop, 1992). The building design is considered to be safe if the ASET is longer than the RSET, whereas the margin of safety, SM, should be at least 0 second or greater. It is essential to identify the SM to ensure life safety (Shields, Silcock, and Dunlop, 1992), as occupants are evacuated in a safe condition without causing serious injuries or deaths. A safety index (SI) can be derived from the SM and the RSET:

$$SI = \frac{SM}{RSET} \tag{5.2}$$

where

SI = safety index;

RSET = required safe egress time.

SI is used as a benchmark to evaluate the safety level of occupants in a building. Higher values of SI indicate increased levels of safety, while increased levels of risk are indicated by negative values of SI. Results predicted by such a fire engineering tool for local buildings with high occupant loading have not been adequately verified. No studies supported by full-scale burning tests have been conducted; nor are current studies in the Far East based on large-scale field tests of emergency fire evacuations in buildings with high occupant loading. The ASET has been commonly estimated (Chow, 2011a) by fire models (McGrattan et al., 2010) with a relatively small design fire size and lower values of tenability limits.

For an evaluation of the safety conditions in fire evacuations, the ASET/RSET analysis has become widespread and is now commonly used in the performance-based fire engineering design. However, the concept has been criticised (Babrauskas, Fleming, and Russell, 2010) for ignoring the wide variations in the capabilities and physical conditions of evacuees involved in a fire incident. It is based on an implicit assumption that, after a briefing where they assess the situation and mobilise themselves, evacuees will then proceed to the nearest exit in a robotic manner. The current codes or guidelines lack clear acceptance criteria for the value of the margin of safety under the ASET/RSET analysis (Chow, 2013a) in terms of the safety factors that should be applied.

Predictive evacuation simulation software (Lo et al., 2004; IES, 2015) can be used to predict the flow of the evacuation pattern. No predictive evacuation software (Chow, 2011b) applicable to Hong Kong has been discussed in advanced science journals. Such software should not only include the instantaneous positions of the persons staying inside a building, but also take into account any psychological factors. No systematic studies on human behaviours during an accidental fire in Hong Kong have been carried out. Detailed research involving human subjects (Chow, 2013a) should be carefully planned and funded by local authorities, as well as be supported by the public sector, which includes railway operators.

5.3 The Selected Interchange Railway Station

The large interchange railway station selected for this detailed study is a crowded interchange station consisting of a concourse level and a platform level, as shown in Fig. 5.1 and Fig. 5.2. The station serves a cross-border railway line and an urban railway line in Hong Kong. It is a typically large railway interchange station with a projected increase in passenger loading demand due to the residential developments at the top of the railway station and the nearby railway depot structure. Apart from the interchange railway station, there is an adjacent PTI providing other modes of transportation including mini buses, buses, taxis, and private coach buses at the same horizontal level as the railway concourse.

The selected interchange station has basically two major levels with a mezzanine level serving as the plant room areas, as shown in the sectional view in Fig. 5.3. The approximate dimensions of the major concourse level are about 230 m (Length) x 80 m (Width) with an atrium of about 22 m (Height). There are two railway tracks on each platform of the railway line: the cross-border railway line is about 230 m (Length) x 18 m (Width) x 6 m (Height) and the urban railway line is about 150 m (Length) x 20 m (Width) x 4 m (Height). The platforms of the two railway lines are connected by walkways. While the urban railway line platform is a fully enclosed structure, the cross-border railway line platform is a semi-open structure without a cover over the two railway tracks. The total floor areas of the principal concourse level and platform level are about 18,400 m^2 and 7,140 m^2, respectively.

On the principal concourse level, there are four passenger exits with one connected to the adjacent PTI. There are also emergency exit doors that become unlocked during an emergency situation.

On the platform level of the cross-border railway line, there are a total of 15 passenger exits either in the form of escalators or stairs. On the platform level of the urban railway line, there are a total of 10 passenger exits either in the form of escalators or stairs. There are a total of four passenger lifts serving each of the railway tracks between the concourse level and the platform level.

5.4 Fire Model for Estimating the ASET

Estimating the ASET via fire models (Chow, 1999) is commonly adopted in the performance-based fire engineering design. The use of CFD techniques has been widely adopted for many years in the fire engineering analysis (Chow and Fong, 2012) of the smoke management system in fire scenarios. The results will be used to determine whether the fire safety provisions are adequate under the agreed fire scenarios for large railway stations (Qu and Chow, 2012). FDS version 5.5.3 is used (McGrattan et al., 2010) in this detailed study to predict the ASET in the selected interchange railway station. It numerically solves a form of the Navier-Stokes equations appropriate for low-speed, thermally-driven flow with an emphasis on the smoke and heat transfer from fires. A baggage fire at the concourse level is considered in this detailed study.

To estimate the ASET, the tenability limits adopted by most fire engineers in Hong Kong include the temperature and visibility effects. The common tenability limits (Chow, 2011a) on life safety for the occupants and fire-fighting personnel are as follows, where the lower values are partly stated (CIBSE Guide E, 2010; NFPA 101-2009; Babrauskas, Fleming and Russell, 2010):

- Smoke layer interface height: 2.5 m
- Smoke layer temperature: 120 ^{o}C
- Radiative heat flux: 2.5 kWm^{-2}
- Carbon monoxide concentration: 6000 to 8000 ppm, 5-minute exposure

In this detailed study, the large interchange railway station selected is a large building structure. Due to the large, open-circulation space, the smoke toxicity will not have a significant effect on the evacuees. The heights of the two railway line platforms are not the same, and the cross-border railway platform is particularly low. The smoke temperature due to the fire may affect the evacuees throughout the evacuation routes. Considering these factors, the temperature and visibility based on the smoke-clear height are used to estimate the ASET of each scenario. Other factors such as psychological factors and the toxicity of the smoke gas rising from the fire are not considered in this detailed study, even though these factors would contribute to the total evacuation time of the passengers.

To study the tenability of the fire scenarios in the fire incident place, a CFD model by the FDS (McGrattan et al., 2010) is developed to simulate the effect of the fire within a smoke control zone on the concourse level. The location of the fire source on the concourse level and the isometric view of the CFD model are shown in Fig. 5.4 and Fig. 5.5, respectively. The CFD results (scenarios F1, F2, F3, and F4) are shown in Figs. 5.7 to 5.22.

In this large railway interchange station, tenable conditions should be maintained in an adjacent place with safe passage for a period of time in order to facilitate the evacuation from the station and the rescue by fire-fighting personnel in the event of fire. The purpose of this detailed study via CFD simulation is to estimate the ASET and find out whether the smoke generated from the fire source can be contained within the designated smoke control zone to allow the safe evacuation of passengers.

Based on the smoke control principle (NFPA 92, 2012), tenable conditions for railway passengers in the public circulation areas of railway stations should be maintained primarily through the use of a smoke extraction system. In this detailed study, a smoke extraction system is employed to minimise the evacuees' exposure to undue hazards (Milke, 2000) as a result of smoke accumulation, loss of visibility, or intolerable conditions due to fire or radiation. In this study, tenability of the station environment for evacuation mainly involves the following two factors:

a) Temperature – In order to maintain tenable conditions for the evacuation of passengers and for fire-fighting purposes, the smoke generated from the fire source should be controlled to maintain a minimum smoke-clear height of 2.5 m above the finished floor level, according to the codes (FSD, 2013). Basically, thermal burns to the respiratory tract can occur upon the inhalation of air above 60^{o} C that is saturated with water vapour. In consideration of this condition, the temperature of 60^{o} C is used as the criterion for tenability in this study as a conservative approach for the temperature threshold.

b) Visibility – For the purpose of a smooth passenger evacuation under tenable conditions, visibility of at least 10 m of the evacuation path should be maintained.

Other than the temperature and visibility limits (Roh et al., 2009), air velocity, radiation, and carbon monoxide concentrations are also important factors for the evaluation of the tenability of the evacuation path. Since the selected railway interchange station is relatively large in terms of station volume and the floor space for circulation, evacuees can easily move away from the fire source; therefore, the amount of carbon monoxide generated from the fire source will not accumulate to a high concentration, leading to an endangerment of the life of the evacuees. As the effects of radiation and carbon monoxide in the large railway station will not be major concerns, the assessments of the changes to the temperature and visibility level will be used instead as the basis of the formation of the ASET.

In the current practices adopted by the railway operator, the heat release rate of 2 MW is assumed by the performance-based fire engineering calculations to be the fire size. This rate is the basis of the development of the fire strategy report submitted and endorsed by the government authorities in Hong Kong. Four fire sizes of 2 MW, 2.5 MW, 5 MW, and 10 MW are chosen to assess the inter-related effect on the ASET and to represent different types of fire sources. For the simulation involving buoyant plumes, a measure of how well the flow field is resolved is given by the non-dimensional expression, D^*/δ_x, where D^* is a characteristic fire diameter. The nominal size of the mesh cell, δ_x, and the characteristic fire diameter, D^*, given by fire power, $\dot{Q}$, air density, ρ_∞, temperature, T_∞, specific heat of air, c_p, and gravitational acceleration, g, is $D^* = \left(\frac{\dot{Q}}{\rho_\infty c_p T_\infty \sqrt{g}}\right)^{2/5}$. A reference within the FDS user guide (verification and validation of selected fire models for nuclear power plant applications, NUREG 1824, United States Nuclear Regulatory Commission [NUREG-1824, 2007f]) using a D^* / δ_x ratio between 4 and 16 is considered to accurately resolve fires in various applications. All the fire scenarios are simulated with the same CFD grid system. A grid system with 1,406,250 cells with the grid size of 0.2 x 0.2 x 0.2 m is used to cover the whole computational domain and is applied to all four fire sizes and four passenger loading scenarios. The non-dimensional expression, D^* / δ_x, with the grid size of 0.2 x 0.2 x 0.2 m for the four fire sizes, is within the recommended ratio.

In the above fire scenarios, the fire source is assumed to be a baggage on fire with a peak heat release rate of 2 MW, 2.5 MW, 5 MW, and 10 MW. Under the normal fire incident of baggage fire, the fire will grow in the initial stage and then maintain to a constant stage for a certain period. The fire source will decay when the fuel for the burning baggage (Thauvoye et al., 2008) is used up. In the FDS simulation, the fire is assumed to be a t-squared fast-growing type until it reaches the peak heat release rate of 2 MW at about 210 s, as shown in Fig. 5.6. Based on the typical fire instance in the experimental result as adopted by the railway operator, the fire will grow in the initial stage as assumed and then decay at the stated period due to fuel consumption. After reaching the peak, the fire will be under a steady state for a certain period until 390 s. After 390 s, the heat release rate of the fire will decay from the peak to 0 MW at 600 s.

In this detailed study, the major parameters of the CFD input are as follows:

Duration of Simulation Time: 600 s

Ambient Temperature: 32^0 C

Smoke Extraction Rate: 4.2 m^3/s

Make-Up Air: Naturally from the adjacent concourse area

Smoke Soot Yield: 0.035 kg/kg

Peak Heat Release Rate: 2 MW, 2.5 MW, 5 MW, and 10 MW

Heat Release Rate per unit area: 500 kW/m^2

Visibility Factor: 3

Fire Location: Concourse C1, Concourse C2, Passenger Link Zone

5.5 Evacuation Model for Estimating the RSET

It is very difficult to estimate the evacuation time required for all passengers to reach a place of safety during real fires. Therefore, the RSET is often calculated by a predictive evacuation software model (Thompson and Marchant, 1995) with reference to the occupant loading under local conditions, though the assumption of robotic motion has always been criticised (Babrauskas, 2010). The predictive evacuation software model assumes that passengers begin the evacuation as soon as the fire occurs. The predictive evacuation tool used to estimate the RSET in this detailed study is SIMULEX (IES, 2015).

SIMULEX is a computer package that simulates the escape movement of people from a very large or geometrically complex building. SIMULEX allows the user to produce a 3-D model of the building by using the computer-aided design (CAD) with building floors connected by staircases. The user can define the final external exits outside of the building, and SIMULEX will calculate the travel distances and routes throughout the evacuation process. Once the building layout and the population are defined by the user, the simulation can be carried out in the computer. The software has been widely used as a consultancy and analysis tool (Chow, 1999) for simulating the physical aspects of evacuation movements around the world. It has also been used to simulate evacuations in buildings with high occupant loadings, such as railway stations. The user can assign the type of occupancy, whether individual or in a group. The percentage distribution of passengers as defined in this detailed study is 30% average, 30% male, 30% female, and 10% child by SIMULEX (IES, 2015).

Since the maximum passenger loading allowed of transport facilities like railway stations or bus terminuses is not specified clearly in Hong Kong's local codes (BD, 2011), the value specified in the codes is based on the area of the actual design layout (BD, 2011). However, 0.5 m^2/person is commonly used in areas accessible to the public, such as places of public entertainment like cinemas, sports stadia, banking halls, and galleries. The number of passengers based on the 0.5 m^2/person passenger load is shown in Table 5.2. The design's occupant loading in crowded railway stations during train incidents (Chow, 2011a) is far below the maximum number of 0.5 m^2/person in the building codes.

In this detailed study, fire evacuation from the concourse level is considered. The four fire scenarios of 2 MW, 2.5 MW, 5 MW, and 10 MW are labelled as F1, F2, F3, and F4 with different occupant loadings of 0.5, 1.0, 2.0, and 4.0 m^2/person representing the different operation hours of the interchange railway station.

5.6 Simulation Results

It is observed from the results of the predictive evacuation model created by SIMULEX that slow movement and congestion occurred around the fire incident area within the smoke control zone on the concourse level at the start of the evacuation. Congestion and slow movement will prolong the RSET under crowded conditions and lead to issues in the event of fire. Smoke will also affect the evacuation of passengers clustered at the emergency exit doors in the smoke control zone on the concourse level. It will affect how they find their way out of the station. Although the predicted results indicate that the spread of smoke and fire is not too fast within the smoke control zone, they also show that the smoke intermittently drops below the smoke-clear height of 2.5 m (FSD, 2013) along the edges or corners of the smoke control zone. The smoke-clear heights of Zone C1 under the four scenarios are shown in Figs. 5.7 to 5.22, along with the visibility and temperature contours in both X-direction and Y-direction. The numbers of passengers leaving the fire incident zone in the evacuation scenarios are shown in Table 5.2. It is observed that the temperature and visibility decrease as one gets closer to the fire incident area. Comparing the results with those from the CFD fire simulation model, it is observed that the fire size has an obvious effect on and contribution to the development of the smoke layer and the temperature rise. Smoke is likely to affect the passengers' evacuation from the railway station if the passengers stay near the fire source, even though the selected railway interchange station is relatively large in terms of station volume and the floor space for circulation. Evacuees may be able to move away from the fire source quickly to a place of safety.

The results of the predicted ASET and RSET in the four fire scenarios and different occupant loadings are summarised in Tables 5.1 to 5.3. The vicinity area near the fire source on the concourse level is easily affected by smoke and temperature. The ASET under all fire scenarios is not long. The results can be used as a reference to describe the evacuation conditions under different operation hours, which would occur in each of the fire scenarios.

The ASET/RSET analysis of this detailed study illustrates that a full evacuation for the entire railway station would take longer than the evacuation of passengers from an affected smoke control zone. Even for a small fire incident, the RSET in cases of high occupant loading scenario is longer than the ASET. The value of the ASET can be higher than the RSET for the evacuees to leave the smoke control zone, depending on the fire size and the occupant loading as shown in Tables 5.1 to 5.3. With a small fire size of 2 MW, the ASET is rather long in terms of a fire evacuation. The simulation results from the predictive evacuation model can be used as a reference by fire engineers and fire safety management (Lui and Chow, 2000) to formulate an evacuation strategy.

5.7 Margin of Safety

Since its introduction for assessments of fire safety, the ASET/RSET analysis has been applied to performance-based fire engineering designs. When human factors involve uncertainty, the margin of safety (Sime, 1986) plays an important role in fire safety. The acceptance criterion for the margin of safety adopted by fire engineers is highly simplistic (Babrauskas, Fleming and Russell, 2010). Under the current building codes (BD, 2011) or guidelines, no clear requirements or recommendations exist to appoint the appropriate margin of safety to be applied. As pointed out by Babrauskas, Fleming, and Russell (2010), this lack of clarity ignores the possibility of wide variations in fire scenarios. Although the same building or fire safety provisions can be evaluated, both the ASET and the RSET can change drastically, depending on the fire scenarios or evacuation scenarios adopted. The consequence of using the ASET/RSET analysis (Poon, 2014) for performance-based fire engineering designs without clear acceptance criteria for the margin of safety is that injuries or even deaths, which can be prevented, will continue to occur due to fire incidents.

The ASET is commonly estimated by CFD fire models based on the time when the fire environment becomes untenable. Very few experimental data are available to verify the results for large spaces such as railway stations. In this study, the ASET/RSET results under different fire and occupant loading scenarios with varying margin of safety are shown in Figs. 5.23 to 5.25. When the ASET is equal to the RSET, the SI will become 0. The SI values on both positive and negative sides indicate whether the fire scenarios are safe or unsafe. The ASET/RSET results demonstrate that most of the fire scenarios under the occupant loading of 0.5 m^2/person are in the unsafe region and will pose significant fire hazards to evacuees.

5.8 Potential Risks

A comparison between the RSET, the time required for the fire evacuation, and the ASET, the time available for egress before the fire environment becomes untenable, is often used as the basis of a fire safety assessment (Chow, 2013a). The RSET depends upon the time from the ignition to the detection of fire and the time from the detection of fire to the start of the fire evacuation warning for evacuees.

The evaluation of both the ASET and the RSET, as quantitative variables, is very subjective (Babrauskas, Fleming and Russell, 2010) and sometimes misleading if not carefully interpreted. To estimate the ASET, fire engineers have to quantify the fire conditions as well as the time when the evacuees will not be able to move safely from the fire environment via the exit routes to the place of safety or other protected smoke control zones. Tenability criteria and the use of the fire modelling technique for assessments are not clearly delineated in the codes (BD, 2011) or guidelines. The ASET has been criticised as ill-defined and lacking in objectivity, criticisms that are equally applicable to the RSET. The basis of the evaluation of the RSET by the predictive evacuation model is that human beings act like robots and will proceed to the exit route in a linear and straightforward manner. In fact, humans do not have robotic reactions to the environment under fire conditions; it is sometimes observed that evacuees will adopt a manner that may be counterproductive to the fire evacuation process. It is rather dangerous to use a low margin of safety (Chow, 2013a) in the ASET/RSET analysis with different fire scenarios considered in the assessment.

The passenger loading in railway stations, particularly large railway interchange stations, is approximately 0.5 m^2/person under crowded conditions in the event of train incidents or during festival days. The safety index in most fire scenarios with a passenger loading of 0.5 m^2/person is of a negative value ranging from -0.4 to -0.04, indicating that the occupants are unsafe in the event of a fire evacuation.

CHAPTER 6 FIRE AND SMOKE MOVEMENTS IN TILTED ENCLOSED SPACES

6.1 Fire Spread and Smoke Movement in Enclosed Spaces

Air movement and the combustion process in enclosed spaces with a configuration similar to a tunnel are complicated, particularly when they are near the fire source (Chow et al., 2016). The buoyancy of the smoke layer in an enclosed space and the smoke velocity distribution should be carefully studied. Fires in enclosed spaces or tunnel fires have been extensively studied in the literature. Previous works have mainly focused on observing smoke movement in horizontal enclosed spaces or tunnels (Fedkiw, Stam, and Jensen, 2001) with the formulation of empirical equations (Chow, 2013b) or studying the effect of the enclosed space or tunnel opening on smoke spread, the critical wind speed of a longitudinal ventilation system, and the effect of the presence of vehicles or other objects inside the enclosed space or tunnel on smoke spread (Morgan, Vanhove, and DeSmedt, 2004). A previous study (Chow et al., 2016) reported that the smoke temperature decay rate in a horizontal enclosed space or tunnel along the longitudinal axis can be described by an exponential function. For an enclosed space or tunnel with a tilted angle, the smoke temperature can decay with different exponential functions on two sides of the fire. The smoke velocity along the longitudinal axis is not symmetric with regards to the fire source.

In some complex railway stations, the main concourse area is often connected to horizontal or slightly tilted passenger subways due to construction alignment. In some cases, for aesthetic reasons or other functional purposes, tilted ceilings or roof structures are utilised. Fire and smoke movements along these enclosed spaces or areas with tilted ceilings or roofs should be studied to tackle possible fire incidents with the proper design and operation of a smoke management system.

The characteristics of a fire spread in an enclosed space or tunnel are important; they are considered to be fundamental elements for gaining an understanding of the propagation of fire and smoke. Understanding the complexity of a fire spread in an enclosed space or tunnel helps rescue or fire-fighting personnel to handle the situation as the fire develops.

The Heat Release Rate (HRR) of a fire is considered to be a major contributing factor to the severity of a fire (SCMP, 2014a). Other factors to consider include the composition of the fire source, air flow conditions, and geometry of the enclosed space. The fire size in the enclosed space is expected to be significantly greater than the size of a similar fire in an open space because of the effect of the enclosure (Tso and Chow, 2012).

To understand the fire development in enclosed spaces, it is necessary to evaluate how these fires ignite and grow. In terms of fire accidents in large enclosed spaces, sometimes two or multiple luggage contribute to the fire spreading to adjacent luggage via radiation from the flames and hot smoke. The fire will spread from one luggage to another luggage in an enclosed space when it reaches a high temperature to the point of spontaneous ignition reaches on another luggage, according to the slope of the enclosed space and air flow direction.

Important elements to consider regarding the fire spread in an enclosed space or tunnel (Atkinson, Drysdale, and Wu, 1995; NFPA 502, 2011) include the heat feedback from the surrounding environment and the effect of natural ventilation on the fire. When it comes to a fire in an enclosed space, the heat feedback to the fire source is governed by the flame volume, enclosure lining, cross-sectional area, as well as the effect of natural ventilation.

For combustion, oxygen is needed to sustain the burning. The burning conditions will develop to either a fuel-controlled condition where unreacted air bypasses the burning source or a ventilation-controlled condition that gives rise to certain large amounts of toxic fumed and products of incomplete combustion. The fire developed in an enclosed space interacts with the ventilation airflow and will generate air flow patterns and turbulence in the close vicinity of the fire source. The heat generated by the fire will warm up the surrounding air, and when the enclosed space is tilted to the horizontal, buoyancy forces (Tajadura, Morros, and Marigorta, 2006) will be created along the tilted enclosed space and govern the smoke movement and air flow inside the tilted enclosed space. This will lead to substantial changes in the ventilation flow pattern (Morgan, Vanhove, and Desmedt, 2004) within the entire enclosed area. If the longitudinal air flow velocity is not high enough, a reserve flow of hot smoke near the ceiling, known as back-layering, will be created (Hu, Huo, and Chow, 2008). The main concerns with the natural ventilation in enclosed spaces involve the enclosed space geometry, the size and location of the fire source governing the flow of hot smoke in the enclosed space, and the atmospheric conditions at the two ends of the enclosed space.

It is difficult for rescue and fire-fighting personnel, who are required to deal with the situation while the fire is developing, to understand what is happening with the fire inside an enclosed space. The smoke generated from the fire can be seen from the two ends of the enclosed space. Effects of the fire on the natural ventilation inside the enclosed space, such as a rapid propagation of toxic gas fumes far from the fire, will complicate fire-fighting efforts and pose higher hazards to the life of the people present (Ingason, 2007). There may be sudden changes in the air flow due to pressure changes between the inside and the outside of the enclosed space, unless a mechanical ventilation system, such as a smoke management system, is applied.

For the fires within enclosed spaces, the size of the fire, the location of the fire source within the enclosed space, the angle tilted to the horizontal, the cross-sectional area of the fire incident place, and the total length of the enclosed space are the major parameters that govern the natural ventilation within the enclosed space. At a short distance from the point where the fire plume impinges on the ceiling of the enclosed space, the smoke flow will move longitudinally in the enclosed space. The stratification of the smoke gradually disperses. This is governed by the heat loss in the surrounding walls and by the turbulent mixing between the buoyant smoke layer and the opposite moving cold layer. The characteristics of the smoke spread are very dependent on the air velocity and the location of the fire source in the enclosed space (Chow, 2007b).

6.2 Scale Modelling Experiments

Fire and flame spread in an enclosed space is fundamental to gaining an understanding of the characteristics of fire. In order to study the spread of smoke and flames, an experiment with a tilted scale model is carried out to examine the effect of the location of the fire source on the flame shape pattern, flame colour, flame spread, gas temperature, and flame height under different inclined angles.

According to a previous study (Tso and Chow, 2012), longitudinal ventilation systems are commonly installed in new tunnels in big cities in the Far East, including Mainland China, Hong Kong, and Taiwan. Many tunnels and enclosed spaces are found in these cities by the present study, and some of them are inclined at an angle to the horizontal. However, smoke movement in these tilted enclosed spaces (Chow, Wong, and Chung 2010) remains partially understood.

Smoke control systems are specified in the new generation of fire codes in many countries. Longitudinal ventilation systems are commonly installed in modern tunnels in advanced cities such as Hong Kong. As a result, longitudinal ventilation in some enclosed spaces or tunnels has been designed based on a presumption of smoke movement patterns without a clear demonstration or verification via experimental studies. This approach might have even been applied to passenger subways (Ip and Luo, 2005).

Previous studies in the literature, such as those by Zukoski (1995) in the USA and that by Atkinson, Drysdale, and Wu (1995) on the trench effect after the King's Cross fires in the UK, have shown that the phenomena can be quite different. Smoke movement in a tilted enclosed space or tunnel, including numerical simulations via CFD, has been analysed and discussed in previous studies (Atkinson and Wu, 1996; Wu, Xing, and Atkinson, 2000; Tajadura, Moros, and Marigorta, 2006). An example is the work of Tajadura, Moros, and Marigorta (2006) on a passenger corridor with a 2% tilt along an upward slope. However, these previous studies simulated hot air from an inclined heat source.

In Hong Kong, railway interchange stations are heavily used; thus, a fire safety strategy should be carefully developed. There are many enclosed passenger subways that are tilted to the horizontal. According to a previous study (Chow, 1998), smoke patterns at various inclination angles were observed to flow upwards towards the enclosed space. Air was entrained horizontally from the ambient. The buoyant jet grew in thickness while it moved up. Heat transfer and skin friction at the wall and air entrainment from the ambient affected the development of the plume. A smoke layer eventually formed below the ceiling. Initially, a clear zone was observed below the smoke layer. However, the space was eventually filled up by smoke to create a thicker smoke layer. The upper part of the sloped enclosed space was filled up by smoke.

In order to understand the large fire characteristics in tilted enclosed spaces, an enclosed space scale model is created by the scale modelling technique with a ratio of 1:40 and further analysed. A fire burning the bulk of some luggage in an enclosed space is simulated by using a propanol pool fire, in order to study the characteristics of large fires, such as the flame shape pattern, flame height, flame colour, hot gas temperature, and flame spread rate, in a tilted enclosed space under different inclination angles. The fire spread to adjacent luggage is simulated by wood cribs. The test is conducted at different tilted angles including 0^{o}, 2^{o}, 4^{o}, and 6^{o} to the horizontal to study the effect of the variation of tilted angles on the characteristics of the large fire. The tests are recorded in video for subsequent evaluation.

6.3 Scaling Factors

In this study, the scale modelling technique is considered to be the appropriate method for gaining an understanding of the smoke movement and flame spread that occur during a real fire. Conducting full-scale fire tests is expensive and time-consuming for data collection and report compilation. It is also difficult to reproduce and repeat the same full-scale building tests. The Froude number modelling technique for simulating smoke movement with appropriate scaling factors is adopted in this study. According to a previous study (Quintiere, 1989), the scale models with appropriate scaling factors are suitable for studying smoke movement and post-flashover room fire. The scale model used (Quintiere, 2012) in this experiment can also be repeated and reproduced. To validate the data obtained from the experimental results, the CFD model using FDS is also adopted in this study.

The Froude scaling technique is used for scaling the model to a full-sized enclosed space (Ingason 2007). The influence of the material thermal inertia and radiation effects on the fire spread (Ingason, 1994) is neglected.

$$Q_F = Q_M \left(\frac{L_F}{L_M} \right)^{\frac{5}{2}} \tag{6.1}$$

$$m_F = m_M \left(\frac{L_F}{L_M} \right)^3 \quad (6.2)$$

$$Q = m_r \ \Delta H_{c,eff} \quad (6.3)$$

where Q is the HRR in W, m is the total mass of fuel in kg, L is the character length, m_r is the mass loss rate in kg/s, $\Delta H_{c,eff}$ is the effective heat of combustion in kJ/g, and index M and index F denote model and full scales, respectively.

6.4 Experimental Results

The flame-bending angle is related to the inclination angle of the enclosed space (Zukoski, 1995). The flame colour is independent of the tilted angle. The characteristic yellow luminosity is the result of the emissions from small carbon-based particles formed within the flame (Beard and Carvel, 2012). During the burning process, the hydrocarbon reacts with O_2 and produces CO_2. If there is sufficient O_2, the reaction can be maintained and the yellow flame is produced. The flame height can be expressed as a function of the pool diameter (D). The classical correlation provided by Thomas is used to estimate the flame height of a fire under natural ventilation conditions, as shown in Fig 6.3 (Thomas, 1963). Researchers have defined the flame height as the height at which the flame is observed at least 50 per cent of the time.

$$\frac{\mathrm{H}_f}{D} = 42 \left(\frac{\dot{m}}{\rho_0 (gD)^{0.5}} \right)^{0.61} \qquad (6.4)$$

where H_f is the flame height in m, g is the gravitational acceleration in m/s^2, $\dot{m}$ is the burning rate in kg/m^2/s, and D is the propanol pool diameter.

Studies (Atkinson, Drysdale, and Wu, 1995) on the flame spread on inclined surfaces have been carried out. Different inclined angles result in various lengths of fire plume attachment, which is defined as the length starting from the burner's front edge to where the hot flow detaches from the surface (Wu, Xing, and Atkinson, 2000). The longer the plume attachment length, the greater the convective heat transfer from the fire plume to the surface (Heskestad, 1984), which results in a faster flame spread. A previous study (Wu, Xing, and Atkinson, 2000) conducted experiments on the effect of a slope in an enclosed space on the hot gas temperature surrounding an inclined fire. The results showed that the gas temperature decays faster along the ceiling in enclosed spaces with higher slopes (Hu, Chen, and Wu, 2013). When the tilted angle of the enclosed space increases, the buoyancy induces entrainment due to the increase of the gravitational force, such that the decay of the gas temperature becomes faster with distance.

The methodology of the experiment uses the scaling ratio of 1:40. The dimensions of the model are 1700 mm (L) x 187.5 mm (W) x 140 mm (H). One side of the model is made by 6-mm tempered glass and the remaining part is constructed by 3-mm non-combustible steel, as shown in Fig. 6.4.

Propanol is used in the experiment as it produces fewer pollutants when it is burnt. It is poured in a container, and the test is performed on a thermally isolated strain gauge, as shown in Fig. 6.5.

6.4.1 Mass Loss Rate Method

The HRR of 5 MW for burning a bulk of luggage with the 1:40 enclosed space model in this study is calculated by applying the Froude formula. The mass of propanol is measured by a strain gauge, while the mass loss rate of propanol is obtained in the slope of the propanol mass loss against time. The effective heat of the combustion of propanol is 30.11 kJ/g. The mass loss rate can be used to calculate the HRR of the scale model by using Equation 6.2.

6.4.2 Test of the Flame Spread Rate

The fire load of the adjacent luggage is simulated by wood cribs, as shown in Fig 6.5. All parts of the enclosed space are made of non-combustible steel and glass. Therefore, the only fire loads in these experiments are from the wood cribs. The time during which the fire spreads from the fire source to the wood cribs is recorded.

6.4.3 Measurement of the Hot Gas Temperature

A K-type thermocouple made with Nickel-Chromium and Nickel is used with a temperature range of 0^{o} C to 1250^{o} C with a standard tolerance of $\pm 2.2^{o}$ C or ±75%. Thermocouples connected with a data logger are placed at the centre line with an interval of 100 mm between one another on the upper layer of the enclosed space to measure the horizontal temperature distribution of the hot gas.

6.4.4 Heat Release Rate

Different sizes of containers are used to find a suitable size for simulating the HRR (Babrauskas and Grayson, 1992) of burning luggage, as shown in Table 6.1. The mass loss over time is recorded in Fig 6.6. The mass loss rate of burning propanol in a 37-mm-diameter container is 0.0166 g/s from the slope of mass loss against time. The effective heat of the combustion of propanol is 30.11 kJ/g. The HRR of the model, which is 0.5 kW, is determined by Equation 6.1. The HRR of burning a bulk of luggage is calculated by Equation 6.3 as 5.06 MW.

6.5 Flame Spread in Tilted Enclosed Spaces

When the enclosed space has a slope, there is an additional force, $g(\rho-\rho_0)\sin\theta$, along the longitudinal direction due to the gravitational force, as shown in Fig. 6.7. The experimental results show that the flame-bending angle increases and the flame height decreases with the increasing slope of the enclosed space, as shown in Fig. 6.9 and Table 6.2. This result is similar to those of the experiments carried out by Zukoski (1995). Yellow flame is observed at different tilted angles, as shown in Fig. 6.9. The flame colour is found to be independent of the tilted angle because there is sufficient O_2 maintaining the reaction of the emissions of small carbon-based particles.

The clear spacing, (S), stack thickness, (D), and crib height, (hc), of the wood crib are 8 mm, 4 mm, and 24 mm, respectively, as shown in Fig. 6.10. The dimensions of the wood crib are determined by using the mass loss rate method to simulate the HRR of burning a bulk of luggage or a passenger car. No flame spread is found from the fire source to the wood cribs at tilted angles of 0^o and 2^o. The flame spread time increases from tilted angles of 4^o to 6^o, as shown in Table 6.3. The flame spread shown in Figs. 6.11 to 6.14 at 50 s indicates the direction of the heat flux. As much of the heat flux is directed to the wood cribs at 4^{o} and 6^{o} tilted angles, flame spread occurs from the fire source at 4^{o} and 6^{o} tilted angles rather than at 0^{o} and 2^{o} tilted angles. The results are similar to those of the study by Atkinson, Drysdale, and Wu (1995), which showed that the flame spread rate increases when the tilted angle increases (Wu, Xing, and Atkinson, 2000).

As shown from the graphs in Fig. 6.15, no peak temperature is measured at 0^{o} and 2^{o} tilted angles, as there is no flame spread from the fire source to the wood cribs at these angles. However, a peak of about 450^{o}C in hot gas temperature is found at 4^{o} and 6^{o} tilted angles, as the flame spread to the wood cribs increases the fire load. The peak occurs for the two tilted angles at the fire spread times of 129 s and 107 s, respectively. The induced hot gas temperature measured between CH15 and CH11 at the 6^{o} tilted angle is the highest among the temperatures measured at other tilted angles because the flame-bending angle is the greatest at the 6^{o} tilted angle.

This study investigates the characteristics of a fire in a tilted enclosed space. Experiments using tilted angles of 0^{o}, 2^{o}, 4^{o}, and 6^{o} to the horizontal are performed with a 1:40 scale model. Different sizes of containers are used for testing and a 37-mm-diameter container is found to be suitable for simulating the HRR of 5 MW for burning a bulk of luggage. The experimental results show that the flame-bending angle increases and the flame height decreases with the increasing slope of the enclosed space, as additional force, $g(\rho-\rho_0) \sin\theta$, is acting along the longitudinal direction due to the gravitational force. The flame colour is independent of the tilted angle. Yellow flame is observed at different tilted angles as sufficient O_2 maintains the reaction of the emissions of small carbon-based particles. Moreover, flame spread occurs at the 4^o and 6^o tilted angles, but not at the 0^o and 2^o tilted angles. The flame spread rate increases when the tilted angle increases. A peak temperature of about 450^o C occurs at the 4^o and 6^o tilted angles at the time of the flame spread to the wood cribs, which increases the fire load.

Different tilted angles of the enclosed space lead to different fire characteristics. Fire characteristics such as the flame pattern, flame height, and hot gas temperature are important for fire safety engineers when designing a suitable fire detection system, fire suppression system, and the fire protection of buildings. The fire spread rate can be reduced by restricting the tilted angle, so that people can evacuate before the fire spreads in an enclosed space.

6.6 Critical Angle

The experiments show that the effect of the flame spread is higher with increasing angles to the horizontal in a tilted enclosed space. The hot smoke will move up and accelerate along the longitudinal axis due to the gravitational force. In designing the smoke control system, the acceleration of the smoke movement should be taken into consideration. The smoke movement pattern (Ip and Luo, 2005), whether in tilted enclosed spaces or long corridors, should be investigated via experiments or scale modelling tests. Most research studies (Quintiere, 2012) have focused on smoke movement in horizontal enclosed spaces rather than in tilted enclosed spaces. It is important to understand the effect of the flame spread in tilted enclosed spaces.

Numerical studies (Tajadura, Morros, and Marigorta, 2006) on tilted tunnels have suggested that the tilted angle and the ceiling height are the major factors dominating the smoke movement along tunnels. In this study, the experimental results show that the flame spread rate increases when the tilted angle in the enclosed space increases from the angle of 4^{o} and upwards. Similar observations have been reported (Atkinson, Drysdale, and Wu, 1995).

6.7 Comparison of Results from the Experiment with the CFD Model

Numerical studies on the fire environment in tilted enclosed spaces have provided insight into the fire characteristics and how fire and smoke spread in an enclosed space with or without angles tilted to the horizontal under a natural ventilation condition. The temperature field induced by fire is an important factor for evaluating whether or not the evacuees are able to escape safely from the enclosed space. Hot smoke will spread to the top portal with the help of the stack effect much faster in a tilted enclosed space than in a horizontal enclosed space.

The experiments show that smoke moves up as a plume due to buoyancy effects from air entrained horizontally from the ambient. A ceiling jet is formed at the early stage below the ceiling and then grows while moving up. It has been reported (Zukoski, 1995) that heat transfer, skin friction at the wall, and air entrainment from the ambient air will affect the development of the fire plume. A thick ceiling jet is formed when smoke moves to the upstream of the enclosed space.

Based on the observations from the experiments, the shape of the buoyant plume depends on the tilted angle of the enclosed space. The smoke plume will bend towards the upstream of the enclosed space at different tilted angles.

The CFD simulation model by the FDS is used to evaluate the results, as shown in Figs. 6.16 to 6.17. The data collected from the experimental results and the FDS-predicted results are observed to be in good agreement, as shown in Figs 6.18 to 6.19.

The experimental results show that there is a difference between the smoke movement in horizontal enclosed spaces and tilted enclosed spaces due to the additional driving force, $g(\rho - \rho_0)\sin\theta$, along the longitudinal direction. The accelerated smoke movement will have a greater momentum when moving upstream of the tilted enclosed space.

CHAPTER 7 DISCUSSION

7.1 Fire Model

Fire is a dynamic process involving the interactions of physics and chemical reactions. Fire phenomena include a relatively large range of temporal and spatial scales. The fundamental conservation equations for fire dynamics include the governing equations of fluid dynamics, heat transfer, and combustion. Significant progress has been made in the development of numerical solutions for fluid and thermal applications. The simplest methods to predict fire phenomena are the basic algebraic equations developed wholly or in part from the correlation of experimental data. They produce, at best, some levels of significant uncertainty. Yet, under the proper use and certain circumstances, fire modelling has been demonstrated to provide accurate and useful results for analysis.

Generally, there are two fundamentally different approaches to fire modelling: (1) probabilistic and (2) deterministic. The probabilistic or stochastic approach involves the assessment of probable fire risks in a compartment or an enclosure by associating finite probabilities with all fire-influencing parameters, such as distributions of the fuel source, number of natural vents and intake air openings, and human behaviour, etc. Little to no physics are included in the basic probabilistic models. This approach, while useful in demonstrating the likelihood of a fire in a given compartment space, offers little to no information about the distribution of the fire production, temperature profile, and smoke and fire propagation.

In deterministic models, a complete set of differential equations based on the laws of physics and chemical reactions can compute the conditions produced by the fire source at a given time in a specified volume of air in a well-defined physical fire scenario. Deterministic fire models can also be in a range from a simple linear correlation to very complex fire models. The more complex fire models are typically divided into two classes: (1) zone models and (2) field models, based on the fire strategy used to solve the equations representing the physical processes associated with the fire.

7.2 Field Model

In analysing the effect of fire, the field model or CFD model is very often used for railway projects. It allows a deterministic analysis. The approach is based on the conservation of physical quantities including mass, energy, and momentum. There are many fire engineering problems that are simulated by CFD models. The CFD model is therefore often used in railway design projects, although it is limited to certain aspects and processes involved in fire safety engineering. For railway station designs, the FDS software is sometimes used to model fire-driven air flow conditions. The FDS software numerically solves an LES form of the Navier-Stokes equations appropriate for low-speed, thermally-driven flow, with an emphasis on the smoke and heat transport from fires.

7.3 Fire Modelling Technique

While field models provide more details than zone models, they do have certain limitations in terms of their use for fire safety engineering. The most significant limitations of the field model are the cost and computation time. Unlike conventional CFD models, a pyrolysis or combustion model requires sophistication as the chemistry and physics of the combustion process are rather complicated. The field models that predict fire scenarios are thus significantly more expensive than a conventional CFD model. Although the involved costs continue to limit the widespread use of field models in fire safety engineering applications, the advanced development of computer technology and computational techniques will certainly enhance the usability of field models.

Some limitations of field models come from the theoretical approximations of CFD models and chemical combustion. Except for some limited cases, the fire sources must be prescribed and inputted into the programme by the user. Other major phenomena that can only be approximated include turbulence, particularly large eddies associated with strong plumes and flames, and thermal radiation interchanges between soot, gases, and solid surfaces. In some cases, the fuel and air oxidiser are initially separate and the combustion process occurs in the zone where they mix together. Field models do not have a direct simulation of turbulent diffusion flames as well. Some field models even yield incorrect results for relatively small fires in a large space (Chow and Lo, 2008) or big fires in a relatively small space. As the development and application of field models continue, it is foreseeable that these limitations can be gradually eliminated with progressive improvements.

In addition, the application of field models requires a great deal of user knowledge of fire engineering and the user sophistication to specify the fire problem and interpret the generated results. Training is necessary and significant for fire engineers to learn how to implement field models effectively. It requires the users of the fire model to develop a thorough understanding of the physics and chemical processes behind the fire dynamic models.

7.4 Evacuation Modelling Technique

Evacuation models such as SIMULEX predict the time that the occupants of a structure take to evacuate from a large space, such as in a railway station. Evacuation models are often used in performance-based fire engineering design analysis as an alternative method for acquiring design code compliance and determining where the congestion areas will be during a fire evacuation.

SIMULEX is an evacuation programme capable of simulating the evacuation of large populations from a large complex building, such as a railway station. It allows the user to create a layout that includes multiple floor plans connected by stairs, directly from the commercially available CAD drawing programmes in the form of 'DXF' files as an input for the building. The number of occupants can be added either one by one or as groups at any location on the 2D floor plans.

SIMULEX is quite a sophisticated ball-bearing model that uses the fine network approach. As a result, it requires a large amount of CPU time to compute the results. One of the best features of the model is a visual display of the evacuation in the form of an animation movie. The user is able to view the movements of all individuals at any location during the evacuation process. Therefore, the user is able to see the occupants overtaking, sidestepping, and queuing during the evacuation. It helps the user to identify any bottleneck areas and problems encountered during the evacuation simulation, such as evacuees being stuck at intersections or in certain spaces.

The principal assumptions made by SIMULEX about the geometry of escape and the methods of individual movements are as follows:

(a) Each person is assigned to have a normal, unimpeded walking speed

(b) Walking speeds are reduced as people get closer together during the evacuation

(c) Each person heads towards the nearest exit by taking a direction that is at right angles of the contours shown on the chosen distance map

(d) Body rotation, overtaking, sidestepping, and small degrees of back-stepping are accommodated in the simulation

7.5 Evacuation Time by the Hydraulic and Predictive Models

To study the evacuation time from the platform to a place of safety, the hydraulic model and the predictive evacuation software, SIMULEX, are used to simulate the evacuation. The results of the predicted evacuation time from the railway platforms of the selected railway interchange station and the changes in the evacuation time in different crowded conditions are then analysed. The selected railway station is a complex interchange station between two railway lines. It is also one of the most crowded stations in Hong Kong with a high occupancy density.

Evacuation Performance by the Hydraulic Model - Different scenarios are considered to simulate the evacuation from Station A. Evacuation times from the railway stations in different scenarios are analysed by the use of the hydraulic model calculations (Proulx, 2002; Nelson and Mowrer, 2002).

Evacuation Requirements under the Code - The stations in railway systems are primarily used for the purpose of passenger transit as specified in the local codes (BD, 2011; FSD, 2012). Passengers normally stay on a railway concourse or platform for a period of time that is no longer than that necessary to wait for the train and board a departing train or exit the railway station on arrival of the destination.

Evacuation Time Predicted by the Hydraulic Model - As summarised in a time chart by Ng and Chow (2006), the evacuation effectiveness from a crowded station and the evacuation time from when the fire occurs are functions of the sequence of occupant response to fire. The movement time is only a small part of the evacuation process as passengers are not expected to react effectively to emergency situations without appropriate notification by the railway operator of the fire safety management (Proulx, 2002). The hydraulic model calculations can be applied to study the egress time under different population densities.

The evacuation time with various passenger loadings can be calculated by the hydraulic model (Nelson and Mowrer, 2002). The total evacuation time (TET) comprises of the human response time, t_{resp}, travel time, t_{tra}, and waiting time, t_{wait} :

$$TET = t_{resp} + t_{tra} + t_{wait} \qquad (7.1)$$

Time delay (Proulx, Kaufman, and Pineau, 1996; Proulx and Fahy, 1997) to start evacuation is a concern. The waiting time (Ng and Chow, 2006) should be considered carefully in the result of the TET, as some passengers may encounter a jam if some passengers resist evacuation at the same time. It is impossible for passengers or small groups of passengers to move under a high population density. The waiting time (Chow, 2007a), during which passengers wait to escape from the fire incident place, will be extended. As no systematic studies on human behaviour and clinical psychology in Hong Kong have been conducted (Chow, 2012a; 2015), response time values adopted elsewhere are to be used in Hong Kong.

Nelson and Mowrer (2002) developed the following equation for the relationship between the speed, S (in m/s), along the line of travel, and the density between the limits of 0.54 person/m^2 and 3.8 person/m^2:

$$S = k - akD \tag{7.2}$$

where

S = speed along the line of travel in s

k = 1.4 for horizontal travel

a = 0.266

D = density in person/m^2

The travel velocity can be derived from the population density. People will reach the maximum travel speed when a threshold distance from the preceding person is achieved.

(Nelson and Mowrer, 2002) derived the equation for the relationship between the speed along the line of horizontal travel and the density between the limits of 0.54 person/m^2 and 3.8 person/m^2. When the density is 0.54 person/m^2, the threshold distance can be achieved and the movement of people is optimized. The maximum travel speed of the person in optimum condition is 1.19 m/s with the density of 0.54 person/m^2.

Below the maximum flow capacity, flow rates depend on the passenger density and their travel speeds. The calculated flow rate, F_c, is the specific flow rate multiplied by the effective width, W_e (in m), and the specific flow, F_s, that is, the number of persons evacuating past a point per metre of effective width per second as follows:

$$F_c = F_s W_e = SDW_e \qquad (7.3)$$

where

S = speed in s

D = the density in person/m^2

F_s = specific flow in person/m/s

W_e = effective width in m

F_c = calculated flow rate in person/s

Time for egress, t_p , the time for a group of persons to pass a point in an exit route, expressed in minutes, is given by:

$$t_p = \frac{P}{F_c} \qquad (7.4)$$

where

P = population in the number of persons

F_c = flow rate in person/min

From the above, the specific flow, F_s, is calculated as follows:

$$F_s = SD = (1 - 0.266D)kD \tag{7.5}$$

Therefore, the maximum specific flow, F_s, in optimum condition is when D is 1.9. The flow rate will be reduced when the density is above or below the optimum condition.

The queuing time, t_{wait}, during which the passengers queue at the exit along the horizontal line of travel, is defined based on the maximum specific flow, F_s, as follows:

$$t_{wait} = \frac{P}{1.32\ W_e} \tag{7.6}$$

Under any conditions, the travel time, t_{tra}, along the horizontal line of travel is as follows:

$$t_{tra} = \frac{L}{V} \tag{7.7}$$

where

L = length of travel in m

V = travel speed in m/s

As defined earlier, the travel speed of the person in optimum condition is 1.19 m/s with the density of 0.54 person/m^2.

Evacuation Time Predicted by SIMULEX – SIMULEX is a computer package that simulates the escape movement of people from a very large or geometrically complex building. SIMULEX allows the user to produce a 3-D model of the building by using the computer-aided design (CAD) with building floors connected by staircases. The user can define the final external exits outside of the building, and SIMULEX will calculate the travel distances and routes throughout the evacuation process. Once the building layout and the population are defined by the user, the simulation can be carried out in the computer. The software has been widely used as a consultancy and analysis tool (Chow, 1999) for simulating the physical aspects of evacuation movements around the world. It has also been used to simulate evacuations in buildings with high occupant loadings, such as railway stations. The user can assign the type of occupancy, whether individual or in a group.

Evacuation Time Analysis and Results - The train passenger capacity in the selected railway interchange station is observed to be very high in the field survey during peak hours. Passengers are usually queued up on the platform area waiting for the next train. There are four railway platforms, namely, Platform 1, Platform 2, Platform 3, and Platform 4, in the entire interchange station, as shown in Fig. 5.1 and Fig. 5.2. The most critical cases under fire conditions are the evacuations from Platforms 2 and 3, where passengers are arriving from two remote areas to the city centre where the railway interchange station is situated, as shown in Fig. 7.5. Therefore, four scenarios for these platform evacuations under fire conditions are studied.

Scenario P1: Evacuation of a full load in the trains from Platforms 2 and 3

Scenario P2: Evacuation of 80% of a full load in the trains from Platforms 2 and 3 with passengers waiting at both Platforms 2 and 3

Scenario P3: Evacuation of a full load in the trains from Platforms 2 and 3 with four exits relocated

Scenario P4: Evacuation of 80% of a full load in the trains from Platforms 2 and 3 with passengers waiting at both Platforms 2 and 3 with four exits relocated

In studying the crowd movements on railway platforms, the maximum passenger capacity and 80% of a full load with waiting passengers on the platforms are assumed for scenarios P1 and P2 to evaluate the longest evacuation time required. The maximum train capacity based on the 4 person/m^2 criteria is approximately 220 per train carriage. Two other scenarios, P3 and P4, are used to evaluate improvements to the evacuation time when four exits are relocated.

The evacuation times from Station A under these four scenarios are analysed with both the hydraulic calculations and the use of the evacuation software, SIMULEX.

Predicted Evacuation Time - The passenger capacity of a full load in a train carriage is approximately 220 based on the 4 person/m^2 criteria. There are 12 train carriages on Platform 2 travelling from remote areas via Station A and the total number of passengers inside the train carriages is around 2,600. The total number of passengers inside four other train carriages on Platform 3 coming from other remote areas via the selected railway interchange station is around 880.

There are seven exits on Platform 2 with an effective exit width ranging from 1 m to 3 m, and three exits on Platform 3 with an effective exit width ranging from 1 m to 2 m.

7.5.1 Analysis of the Predictive Results (Scenario P1)

In terms of scenario P1, when fire occurs in a train carriage, all passengers will leave the trains from Platforms 2 and 3 via the platform areas to a place of safety. Based on the simulation created by SIMULEX, the passenger flow through each of the seven exits will be adopted similarly in the hydraulic calculations for a direct comparison of the results from the hydraulic calculations and SIMULEX. The number of passengers passing through the exits is not evenly distributed since the evacuees in the SIMULEX simulation tend to choose the shortest distance from the point where the evacuation starts.

Results are summarised in Table 7.1. As shown in Table 7.1, the TET of the last passenger leaving Platform 2 via Exit no. 12, as predicted by the hydraulic calculations, is 358 s (around 5.96 mins), while the TET from the same platform, as predicted by SIMULEX, is 300 s (around 5 mins) with the last passenger leaving Platform 2 via Exit no. 10. Apart from the differences in the overall evacuation times predicted by the two methods, the predicted evacuation times via the other exits are also different by about 1 to 3 mins.

The TET of the last passenger leaving Platform 3 via Exit no. 16, as predicted by the hydraulic calculations, is 267 s (around 4.46 mins), while the TET from the same platform, as predicted by SIMULEX, is 300 s (around 5 mins) with the last passenger leaving Platform 3 via Exits no. 9 and 19. Even though the overall evacuation times predicted by the two methods are more consistent, there remain differences of about 2 to 3 mins in the evacuation times predicted by the two methods for the other exits.

7.5.2 Analysis of the Predictive Results (Scenario P2)

In terms of scenario P2, when fire occurs in a train carriage with 80% of a full load, all passengers together with the waiting passengers that are equivalent to 20% of a full load will leave the trains from Platforms 2 and 3 via the platform areas to a place of safety. Based on the simulation created by SIMULEX, the passenger flow through each of the seven exits will be adopted similarly in the hydraulic calculations for a direct comparison of the results from the hydraulic calculations and SIMULEX. The number of passengers passing through the exits is not evenly distributed since the evacuees in the SIMULEX simulation tend to choose the shortest distance from the point where the evacuation starts.

Results are summarised in Table 7.2. As shown in Table 7.2, the TET of the last passenger leaving Platform 2 via Exit no. 12, as predicted by the hydraulic calculations, is 336 s (around 5.6 mins), while the TET from the same platform, as predicted by SIMULEX, is 295 s (around 4.92 mins) with the last passenger leaving Platform 2 via Exit no. 10. Apart from the differences in the overall evacuation times predicted by the two methods, the predicted evacuation times via the other exits are also different by about 1 to 3 mins.

The TET of the last passenger leaving Platform 3 via Exit no. 16, as predicted by the hydraulic calculations, is 258 s (around 4.29 mins), while the TET from the same platform, as predicted by SIMULEX, is 270 s (around 4.5 mins) with the last passenger leaving Platform 3 via Exits no. 9 and 19. Even though the overall evacuation times predicted by the two methods are more consistent, there remain differences of about 1 to 2 mins in the evacuation times predicted by the two methods for the other exits.

7.5.3 Analysis of the Predictive Results (Scenario P3)

Similar to scenario P1, scenario P3 shows that when fire occurs in a train carriage, all passengers will leave the trains from Platforms 2 and 3 via the platform areas to a place of safety. To improve the evacuation flow rate, four exits comprising three exits at Platform 2 and one exit at Platform 3 are relocated. Based on the simulation created by SIMULEX, the passenger flow through each of the seven exits will be adopted similarly in the hydraulic calculations for a direct comparison of the results from the hydraulic calculations and SIMULEX. The number of passengers passing through the exits is not evenly distributed since the evacuees in the SIMULEX simulation tend to choose the shortest distance from the point where the evacuation starts.

Results are summarised in Table 7.3. As shown in Table 7.3, the TET of the last passenger leaving Platform 2 via Exit no. 12, as predicted by the hydraulic calculations, is 321 s (around 5.34 mins), while the TET from the same platform, as predicted by SIMULEX, is 270 s (around 4.5 mins) with the last passenger leaving Platform 2 via Exit no. 8. Apart from the differences in the overall evacuation times predicted by the two methods, the predicted evacuation times via the other exits are also different by about 1 to 2 mins.

The TET of the last passenger leaving Platform 3 via Exit no. 16, as predicted by the hydraulic calculations, is 361 s (around 6.02 mins), while the TET from the same platform, as predicted by SIMULEX, is 170 s (around 2.83 mins) with the last passenger leaving Platform 3 via Exit no. 24. Apart from the differences in the overall evacuation times predicted by the two methods, the predicted evacuation times via the other exits are also different by about 1 to 4 mins.

7.5.4 Analysis of the Predictive Results (Scenario P4)

Similar to scenario P2, scenario P4 shows that when fire occurs in a train carriage with 80% of a full load, all passengers together with the waiting passengers that are equivalent to 20% of a full load will leave the trains from Platforms 2 and 3 via the platform areas to a place of safety. Based on the simulation created by SIMULEX, the passenger flow through each of the seven exits will be adopted similarly in the hydraulic calculations for a direct comparison of the results from the hydraulic calculations and SIMULEX. The number of passengers passing through the exits is not evenly distributed since the evacuees in the SIMULEX simulation tend to choose the shortest distance from the point where the evacuation starts.

Results are summarised in Table 7.4. As shown in Table 7.4, the TET of the last passenger leaving Platform 2 via Exit no. 12, as predicted by the hydraulic calculations, is 294 s (around 4.9 mins), while the TET from the same platform, as predicted by SIMULEX, is 280 s (around 4.67 mins) with the last passenger leaving Platform 2 via Exit no. 8. Apart from the differences in the overall evacuation times predicted by the two methods, the predicted evacuation times via the other exits are also different by about 1 to 2 mins.

The TET of the last passenger leaving Platform 3 via Exit no. 16, as predicted by the hydraulic calculations, is 362 s (around 6.03 mins), while the TET from the same platform, as predicted by SIMULEX, is 160 s (around 2.67 mins) with the last passenger leaving Platform 3 via Exits no. 16 and 24. Apart from the differences in the overall evacuation times predicted by the two methods, the predicted evacuation times for the other exits are also different by about 1 to 4 mins.

7.6 Comparison of the Predictive Evacuation Results

Results of the predictive evacuation simulations from SIMULEX for the selected railway interchange station are analysed, and evacuation strategies are also evaluated. The main observations are as follows:

(a) A platform evacuation can generally be completed within the specified time in cases of emergency; safe evacuation may be difficult to achieve in special cases of emergency, such as those that include a blockage of exits or escape paths from the platform. Passengers cannot completely evacuate in 4.5 minutes, which is very often specified in most fire strategy reports compiled by railway operators. Bottlenecks during the evacuation are also observed in some special circumstances.

(b) The opening or closing of an evacuation route depends on where the fire occurs in the simulation. However, in actual fire scenarios, passengers' choices of exits are greatly affected by the smoke movement. Though the parameters of the passengers are made in some special sets, it is still difficult to represent the evacuation process during a real fire scenario through a simple software simulation of an evacuation.

CHAPTER 8 CONCLUSIONS

Railway interchange stations are geometrically complex with crowds of passengers during the day-to-day operations of the railway. Fire safety in large interchange stations is particularly important in terms of the integration of a smoke management system, the design of evacuation routes, clear directional signage, the building materials used, and predicted evacuation times. The fire risk analysis and smoke simulation via CFD (Roh, et al., 2009) with the aid of predictive fire and evacuation models (IES, 2015) allow an understanding of the hazards associated with the design of railway stations.

Major findings of this thesis include a detailed review of the fire risk analysis of a particularly busy railway interchange station. The CFD technique is used to examine smoke spread and determine whether the smoke management system is adequate based on the configuration of the smoke control zone and the effects of the changes in fire load and occupant loading. The results are entirely different across the different fire sizes and occupant loadings.

The total fire safety concept (Chow, 2004b) consists of integrating all of the software and hardware related to fire safety provisions, including aspects such as the staff's ability to tackle fire incidents effectively and the operation of the smoke control and fire suppression systems. Since the occupant loading in most railway stations in Hong Kong is very high during rush hour, fire safety provisions must be carefully reviewed and planned well in advance of the construction of new railway stations. Fire hazards in the retail commercial shops (Chow, 2012a) should be reviewed regularly to limit the fire load inside the shops.

In terms of drafting a fire strategy for new railway stations, fire engineers should review all design provisions holistically based on the most accurate source of design data. The heat release rate, smoke management system, and emergency evacuation (Li and Chow, 2008) are the major issues to be considered in the design. Numerical methods (Li, 2003) should be applied to study the railway environment under different fire scenarios.

Evacuation from a large railway interchange station is an important aspect related to the fire safety of the station (Chien et al., 2004). The large circulation area, high ceiling headroom, long exit routes, and thus long travel distance will have a significant effect when a fire incident is initiated during rush hour. As observed from the predictive evacuation model, the jamming of evacuees at the exits is always the case during the evacuation in any scenarios.

The results of the predictive evacuation software model (IES, 2015) also show that evacuees choose the closest exit in the event of a fire evacuation. However, evidence has shown that evacuees will tend to leave the incident area via the exit with which they are most familiar, as they believe that it will lead them more safely outside of the building. This is due to the evacuees, especially those who frequently use the same railway station as their means of transportation, being familiar with the geography of the usual route and unfamiliar with the geography of the escape route to an unfamiliar emergency exit. This human behaviour (Pauls, 1995) suggests that purposely designed fire escape routes and emergency exits are likely to be avoided in the event of an emergency. Evacuees may consider the emergency exit routes that are not normally used to be locked or incapable of leading them to a safe place outside of the building. In consideration of these factors, the exit routes for use in an emergency would be more effective for evacuations if they are the same as the normal routes under normal operations of the railway station and have proper directional signage.

The analysis of evacuation times demonstrates that a proper arrangement of the exits can improve the efficiency of the evacuation flow. Based on the evacuation results from the SIMULEX software (IES, 2015), in terms of the early stages of a railway station design, exits can be relocated to streamline the flow of evacuees, thus reducing the evacuation time. By rearranging the locations of exits, as seen from the results of the SIMULEX predictive model, the overall evacuation time can be reduced by 10% from 300 s under scenario P1 of a full train load condition to 270 s under scenario P3, whereas the overall evacuation time can be reduced by 5% from 295 s under scenario P2 of an 80% full train load condition to 280 s under scenario P4.

Smoke is a hazard for evacuees as the smoke obscuration will have a negative effect on the evacuation, and the evacuation time will be prolonged. Since the smoke extraction system (NFPA 92, 2012) in railway stations provides a means of handling the spread of smoke, the capacity and reliability of the components of the smoke extraction system should be carefully checked by maintenance personnel to ensure the effective operation of the system in the event of an emergency. Other factors such as the availability of emergency lighting and the proper operation of the escalators will also help improve the evacuation by reducing the egress time.

Data obtained from the CFD model technique by using the FDS software are compared with the data obtained from the experiments conducted with the scale model of a tilted enclosed space. The CFD fire models developed in the study are validated with the experimental data to show good agreement between the two. Even though fire engineers actively use the CFD-FDS fire models (Chow, 2003a; Chow and Lo, 2008), the authorities still have some reservations about a complete reliance on the simulation results from fire modelling, due to the uncertainty about the accuracy of the input parameters (Chow, et al., 2008). There have not been many fire model verification and validation studies (Chow et al., 2009) based on the standard methodology (NUREG-1824, 2007a; 2007b; 2007c; 2007d; 2007e; 2007f; 2007g).

The analysis of the fire and smoke propagation in an enclosed space from the CFD-FDS simulation results, when compared with the experimental data obtained from the scale model, shows that the smoke temperature will decay near the ceiling in a symmetrical manner of distribution at the two ends of the fire source, with the neutral plane equal at the two ends of the enclosed space. In the tilted enclosed space with angles inclined 4^o and 6^o to the horizontal, the smoke temperature decay is different on two sides of the fire source. The driving forces for smoke movement in an enclosed space are the density difference, $\Delta\rho$, between the smoke and the air in the enclosed space, and between the air in the enclosed space and the outside air. Based on the ideal gas law, the density difference derives from the temperature difference, ΔT, and gas types. In tilted enclosed spaces, the stack effect will be present (Chow et al., 2016). There is a difference between the smoke movement in horizontal enclosed spaces and tilted enclosed spaces due to the additional driving force, $g(\rho - \rho_0)\sin\theta$, along the longitudinal direction. The accelerated smoke movement will have a greater momentum when moving upstream of the tilted enclosed space. An understanding of this phenomenon is important in the prediction of smoke movements through the building.

The fire dynamic principle, smoke control system, fire load, evacuation factors, evacuation time predictions, railway operation, and accidental factors due to the suspension of train operations leading to the congestion of passengers at exits are important points for consideration by fire engineers when designing a safe railway development as a complex transportation network.

With reference to the predicted ASET and RSET, the margins of safety used by fire engineers and the outcomes of the safety index vary across scenarios. In this study, four fire sizes of 2 MW, 2.5 MW, 5 MW, and 10 MW are chosen to represent different types of fire sources when determining the ASET. Under these four fire sizes, four different occupant loadings of 0.5 m^2/person, 1.0 m^2/person, 2.0 m^2/person, and 4.0 m^2/person are chosen to represent the different operation hours of the interchange railway station when determining the safety index based on the predicted ASET and RSET. The summary of the predictive results in Fig. 5.3 shows that the safety index in most of the fire scenarios with an occupant loading of 0.5 m^2/person is of a negative value, ranging from -0.4 to -0.04, which means that the occupants are unsafe in the event of a fire evacuation. In other words, a safe environment can hardly be achieved with the occupant loading of 0.5 m^2/person under most of the fire scenarios. It is observed that the occupant loading in particularly large railway interchange stations is approximately 0.5 m^2/person under crowded conditions in the event of train incidents or during festival days when people are using the railway as a major means of transport.

The analysis indicates that the RSET is longer than the ASET in most cases under crowded conditions. In cases where the RSET is closer to the ASET with a little margin of safety, fire safety management and procedures on handling fire incidents must be carefully worked out (Chow, 2001). The predictive results by the fire and evacuation modelling can be used as a reference in developing evacuation strategies for individual stations. Detailed analysis is also necessary to devise a comprehensive fire evacuation plan to ensure a safe evacuation or to minimise human injuries and deaths. As an interim solution, the railway operator should formulate a crowd-control management plan to reduce the passenger loading at the large railway interchange station, such as by shutting down some of the passenger entrance gates in the event of train incidents or during festival days, and by providing shuttle bus services to reduce the number of accumulated waiting passengers.

The use of timeline analysis in the performance-based fire engineering design should be reviewed by fire engineers with a solid background in fire dynamics. There are also challenges in the evaluation of the ASET/RSET concept (Babrauskas, Fleming, and Russell, 2010) of using timeline analysis in performance-based fire engineering since the ASET/RSET concept is highly simplistic and offers no incentive for improvements in fire safety by using a deterministic scheme improperly imposed upon a stochastic reality. Further systematic studies on human behaviour including a proper interpretation of the fire and evacuation predictive models with the RSET data supported by the field measurements of crowd movements are recommended. With the data obtained from the field measurements, the RSET data can be compared and validated with the data predicted by the evacuation software model. By doing so, the reliability of the RSET data can be improved with a validation test using the field measurements.

FIGURES

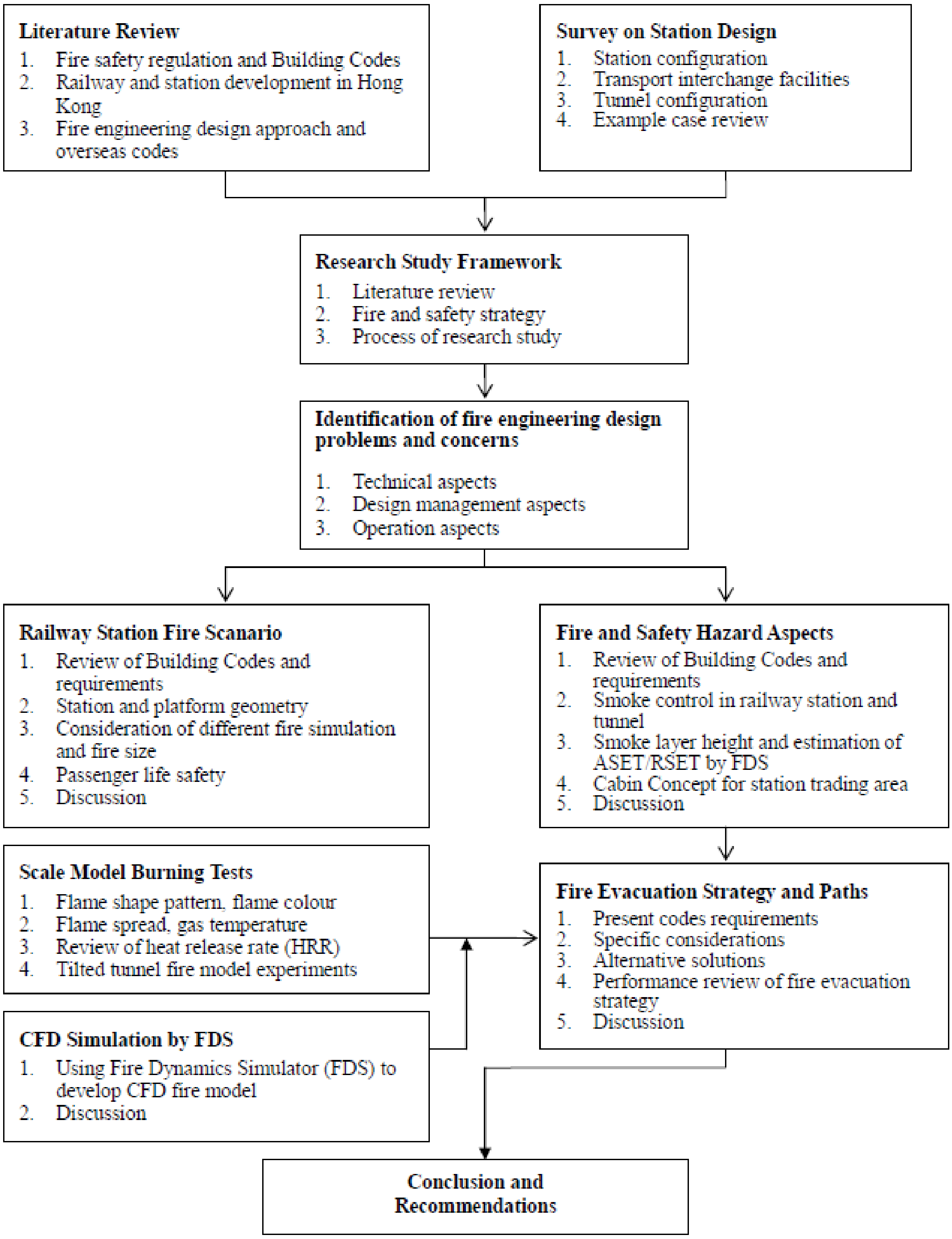


Figure 1.1 Flow Chart of the Study

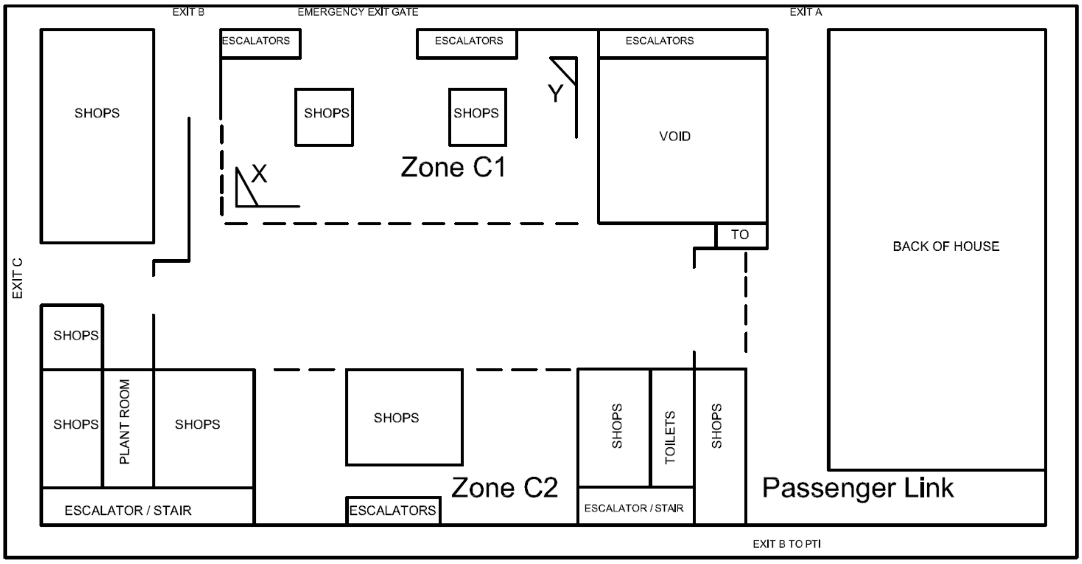


Figure 5.1 Concourse Layout of the Selected Railway Interchange Station

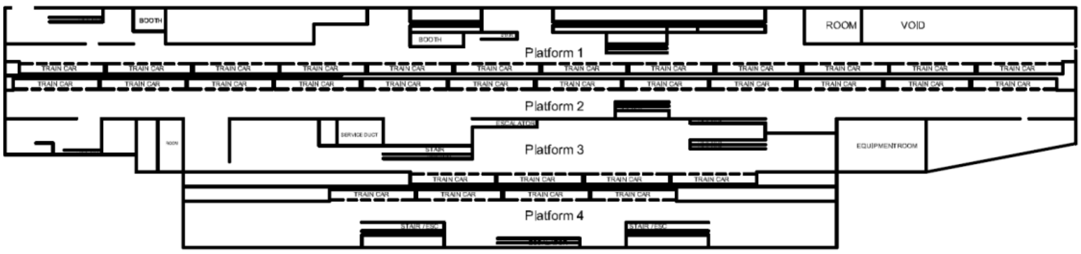


Figure 5.2 Platform Layout of Selected Railway Interchange Station

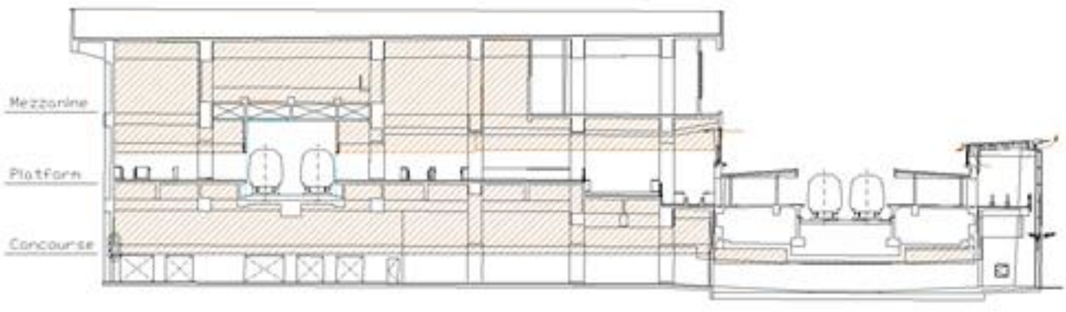


Figure 5.3 Sectional View of Selected Railway Interchange Station

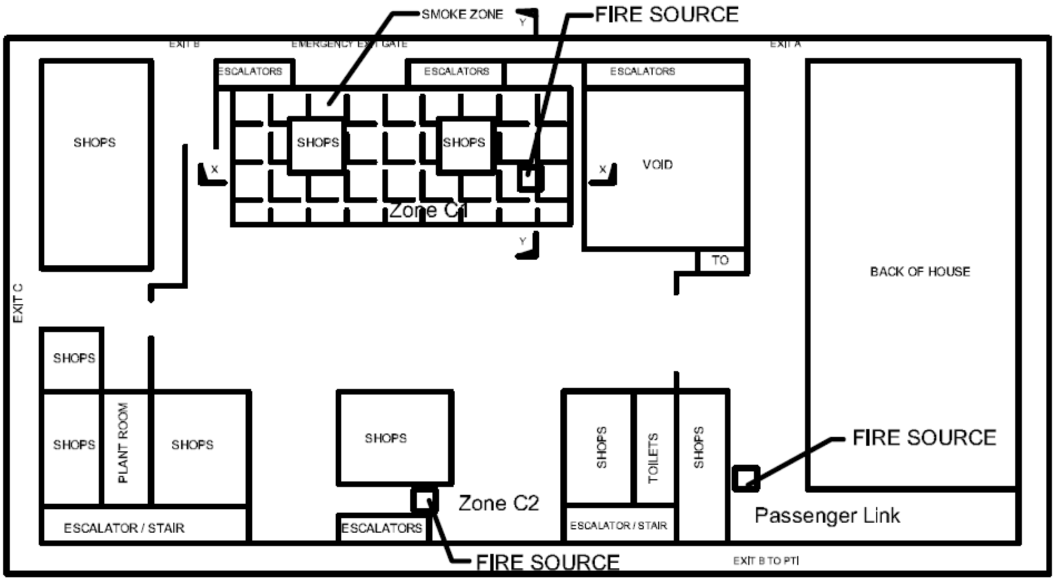


Figure 5.4 Location of the Fire Source at the Concourse Level

Figure 5.5 FDS Model for the Fire at the Concourse Level

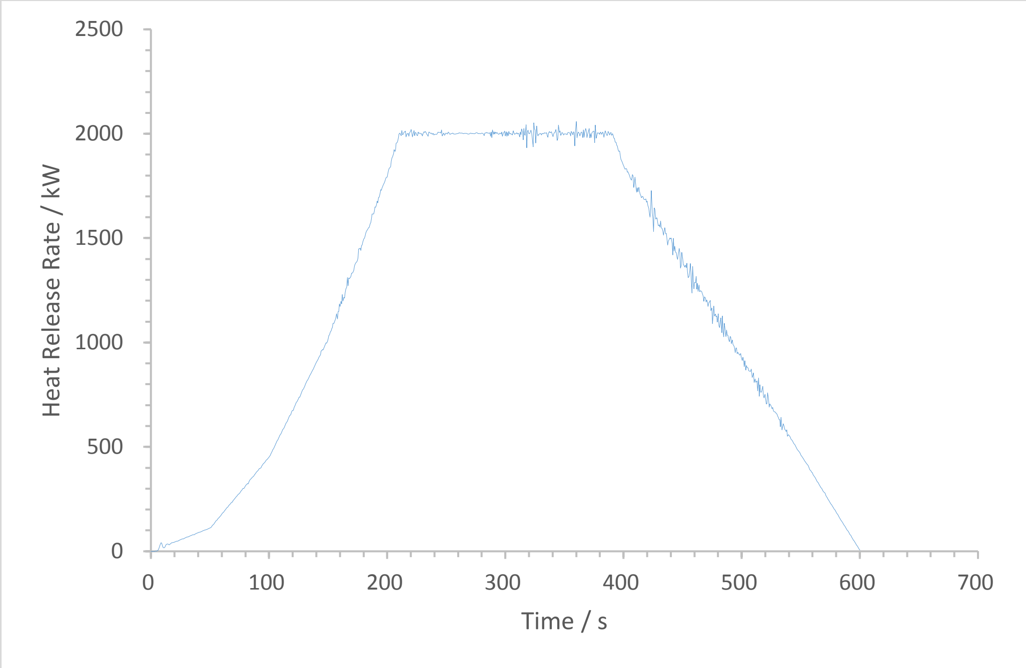


Figure 5.6 Fire Curve for the Baggage Fire of 2MW

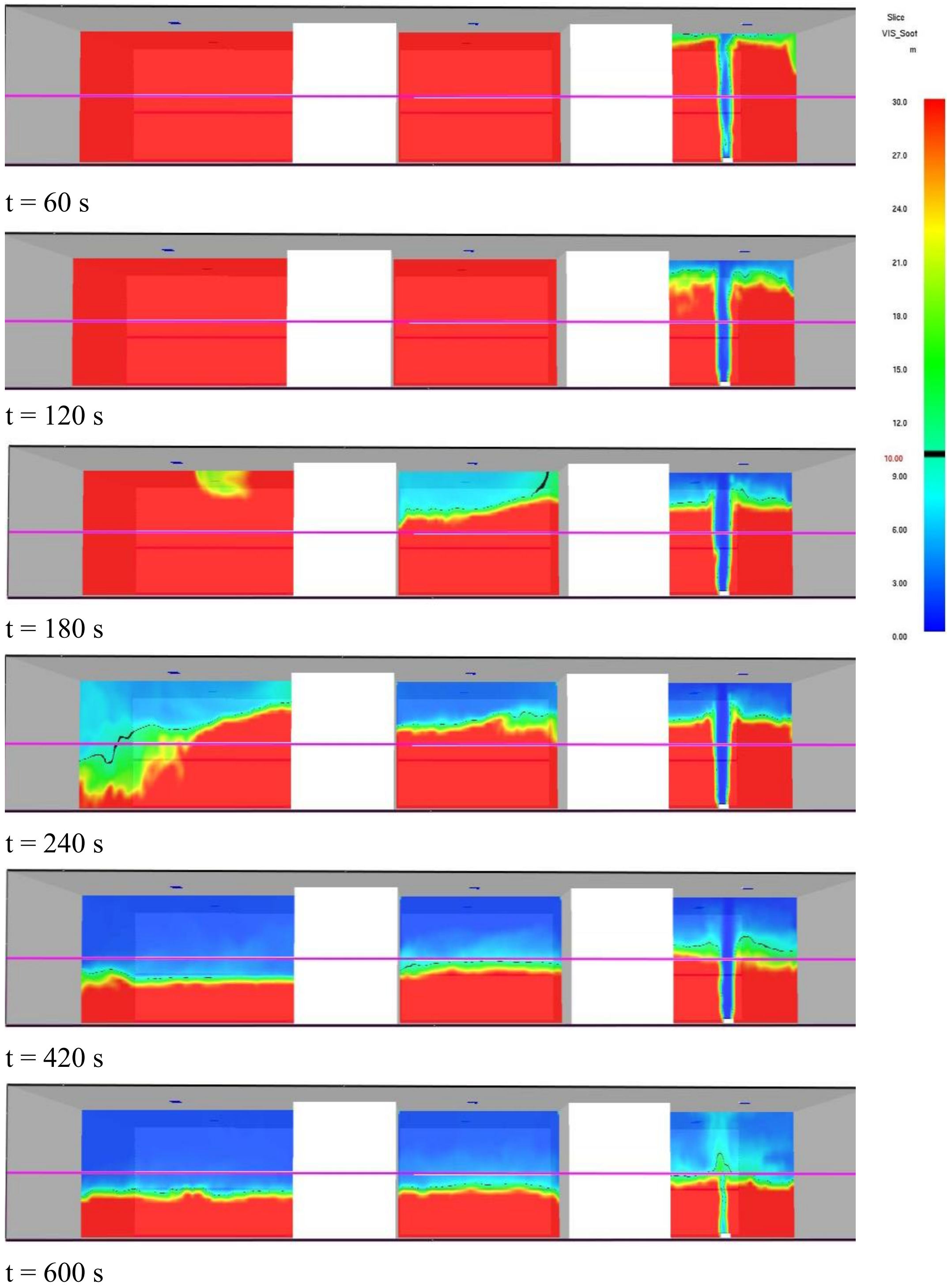


Figure 5.7 Zone C1 (F1=2MW), Visibility Contour in the X-direction

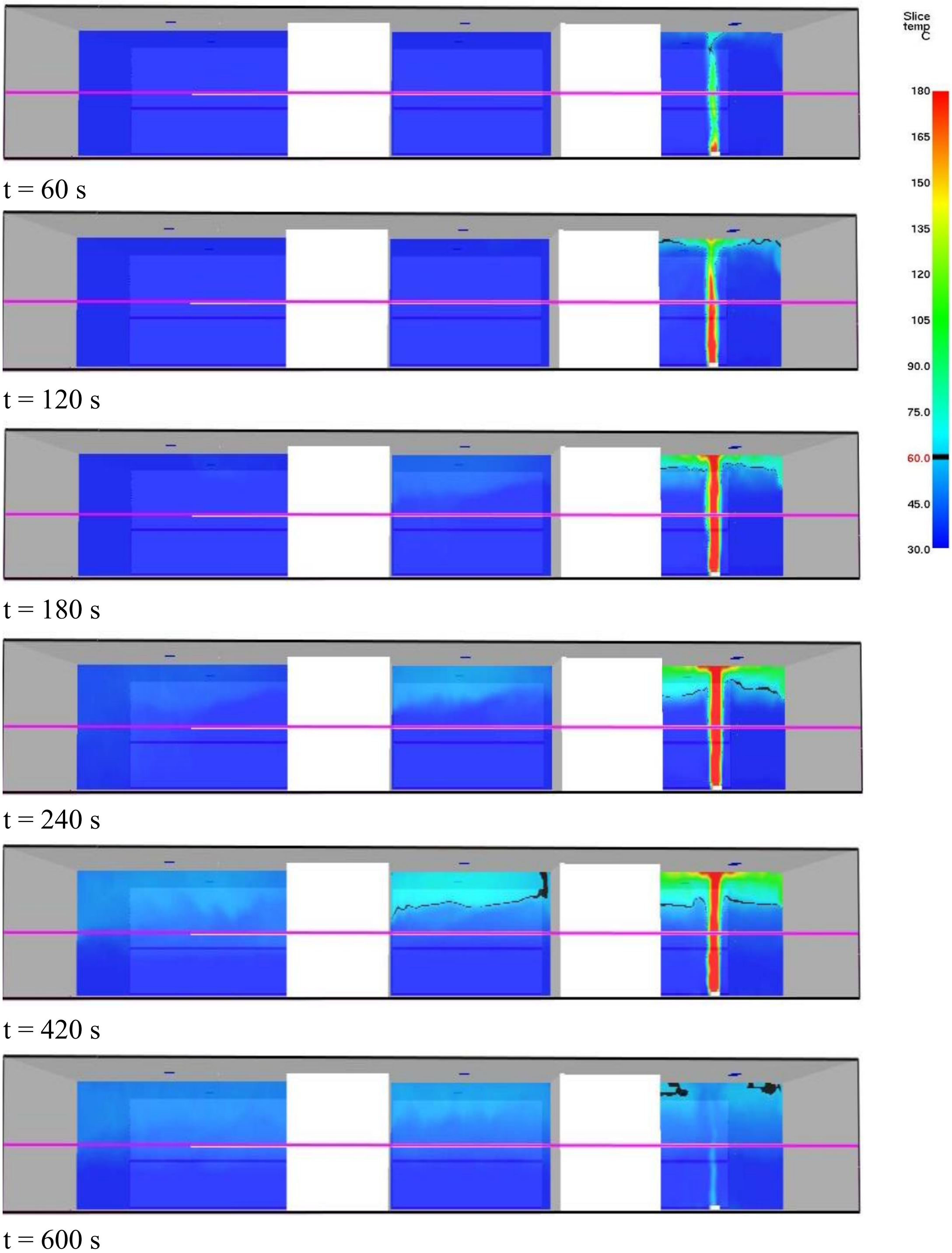


Figure 5.8 Zone C1 (F1=2MW), Temperature Contour in the X-direction

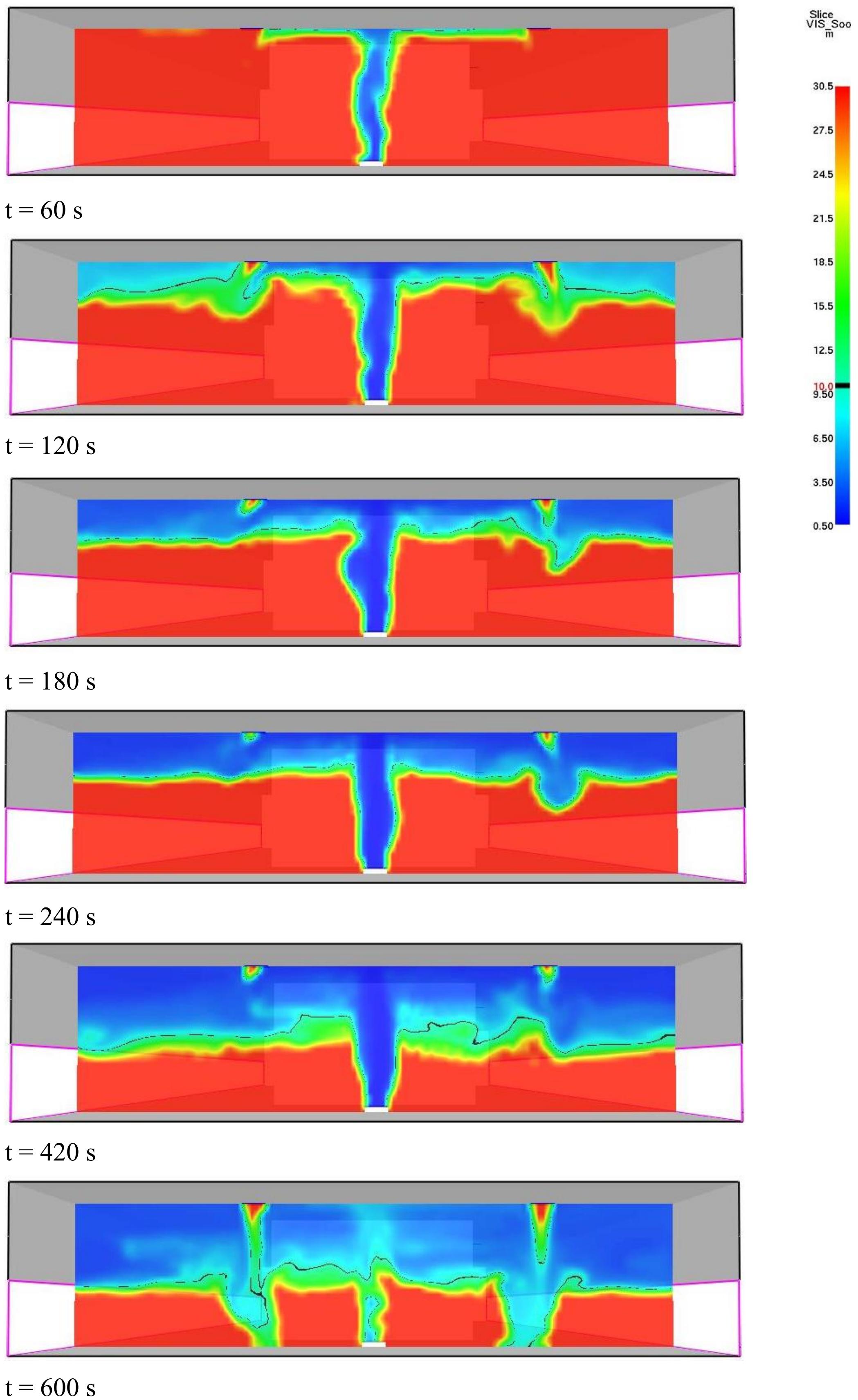
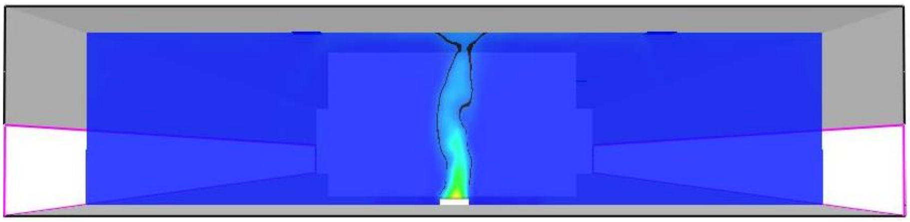
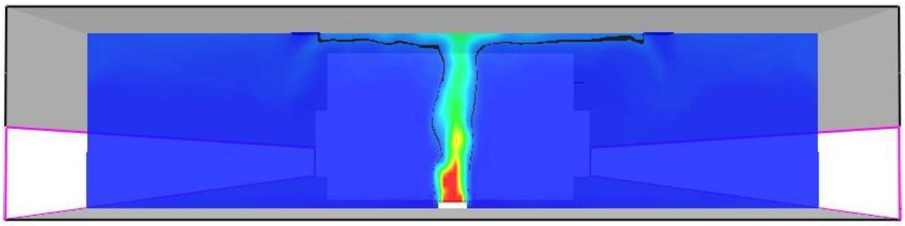


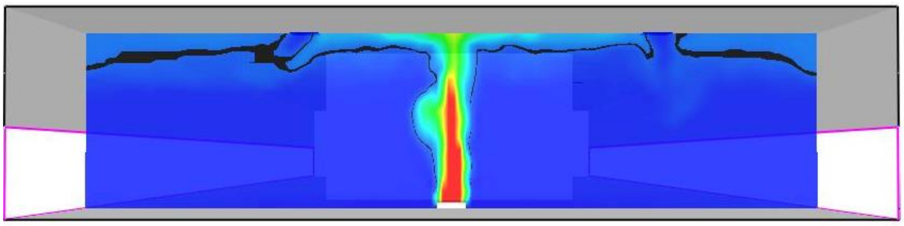
Figure 5.9 Zone C1 (F1=2MW), Visibility Contour in the Y-direction



t = 60 s



t = 120 s



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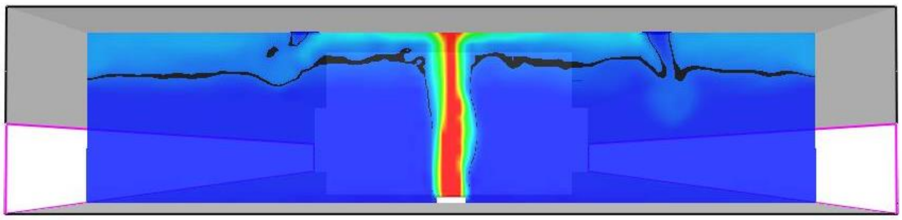
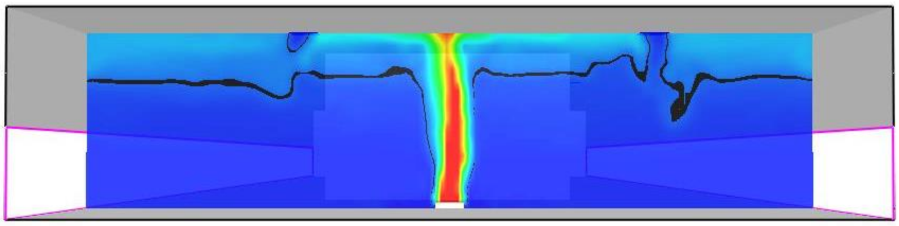
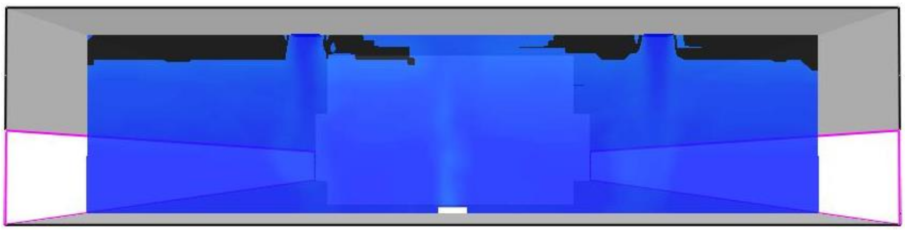


t = 240 s

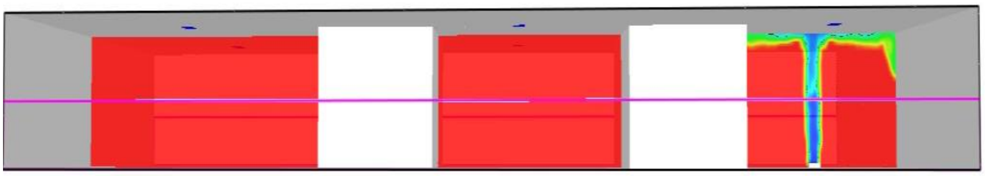


t = 420 s

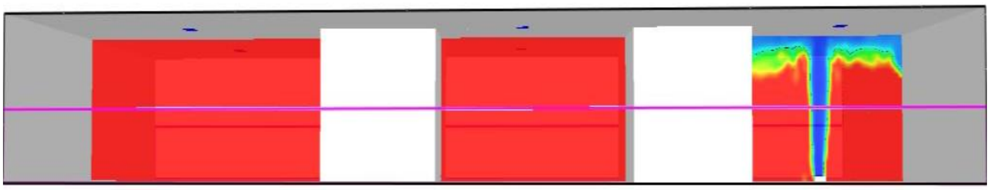


t = 600 s

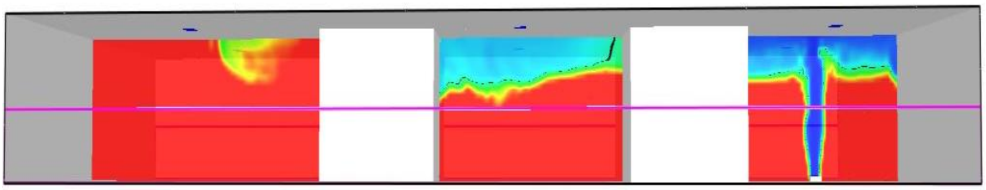
Figure 5.10 Zone C1 (F1=2MW), Temperature Contour in the Y-direction



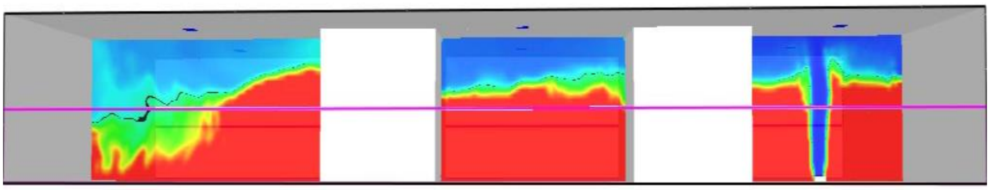
t = 60 s



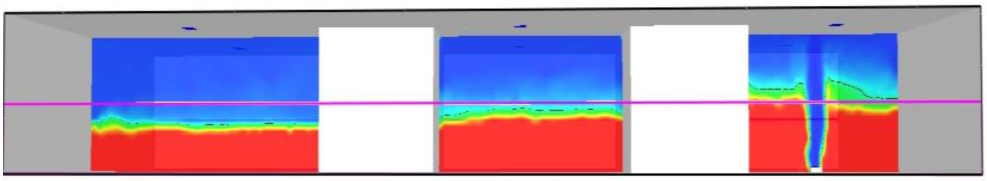
t = 120 s



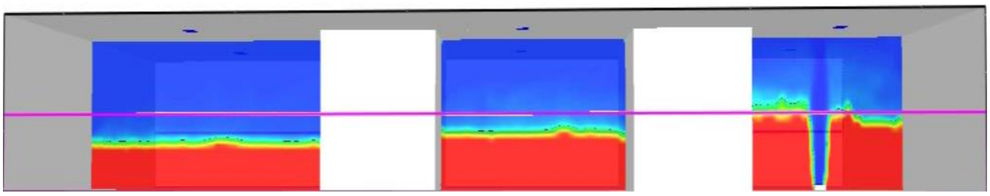
t = 180 s



t = 240 s



t = 420 s



t = 600 s

Figure 5.11 Zone C1 (F2=2.5MW), Visibility Contour in the X-direction

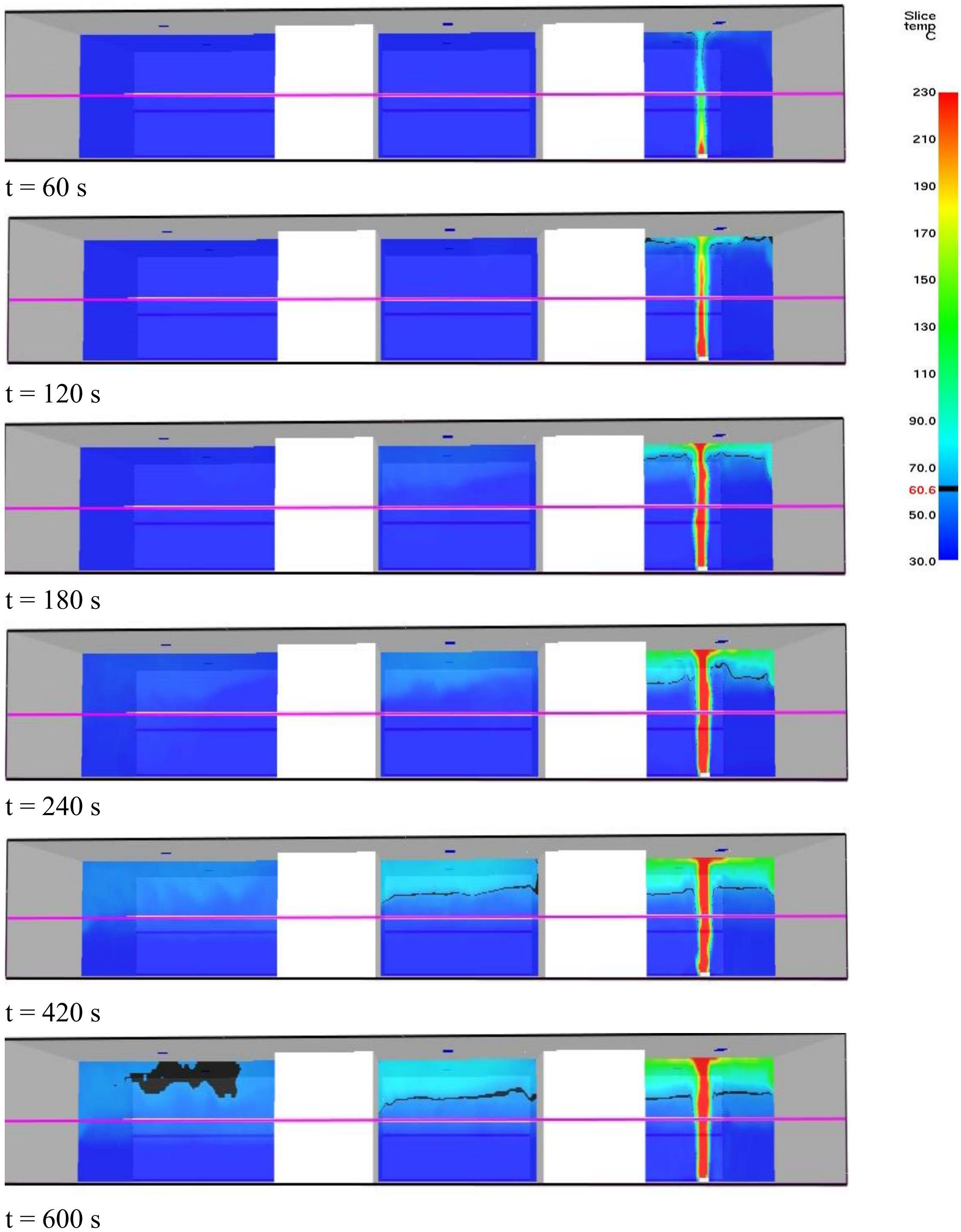
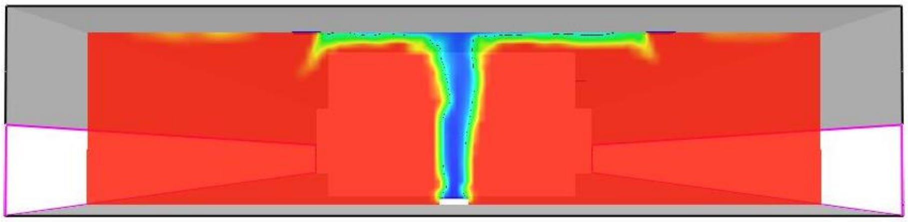
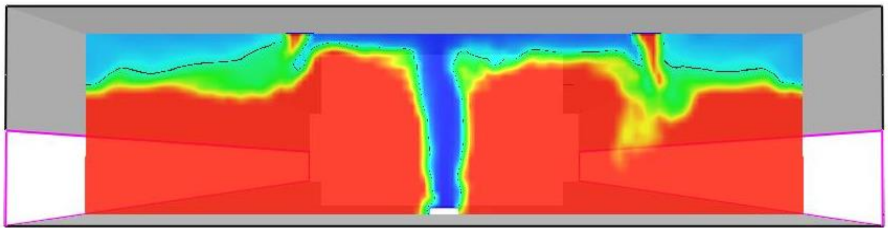


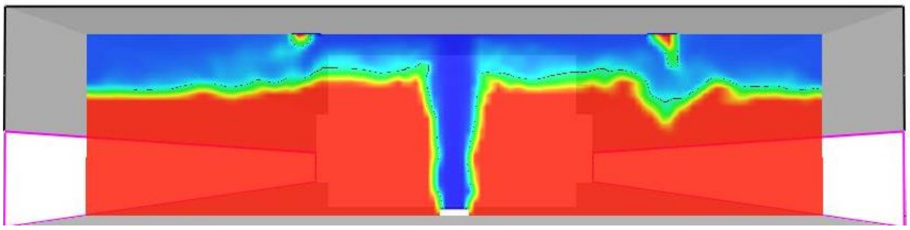
Figure 5.12 Zone C1 (F2=2.5MW), Temperature Contour in the X-direction



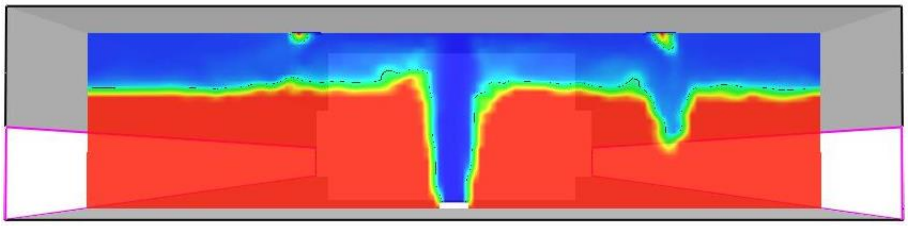
t = 60 s



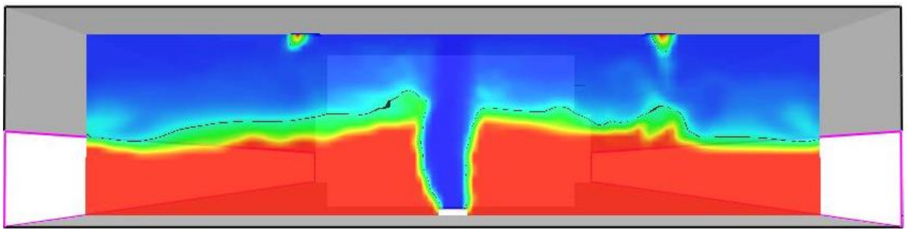
t = 120 s



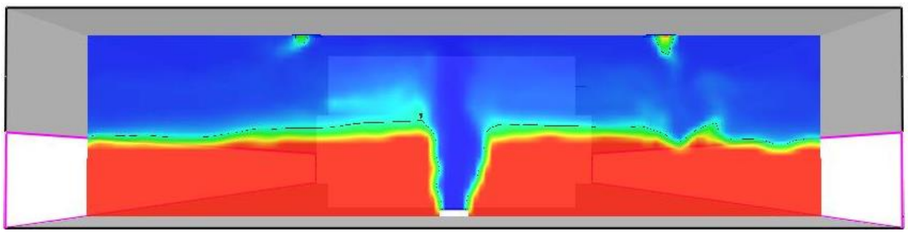
t = 180 s



t = 240 s



t = 420 s



t = 600 s

Figure 5.13 Zone C1 (F2=2.5MW), Visibility Contour in the Y-direction

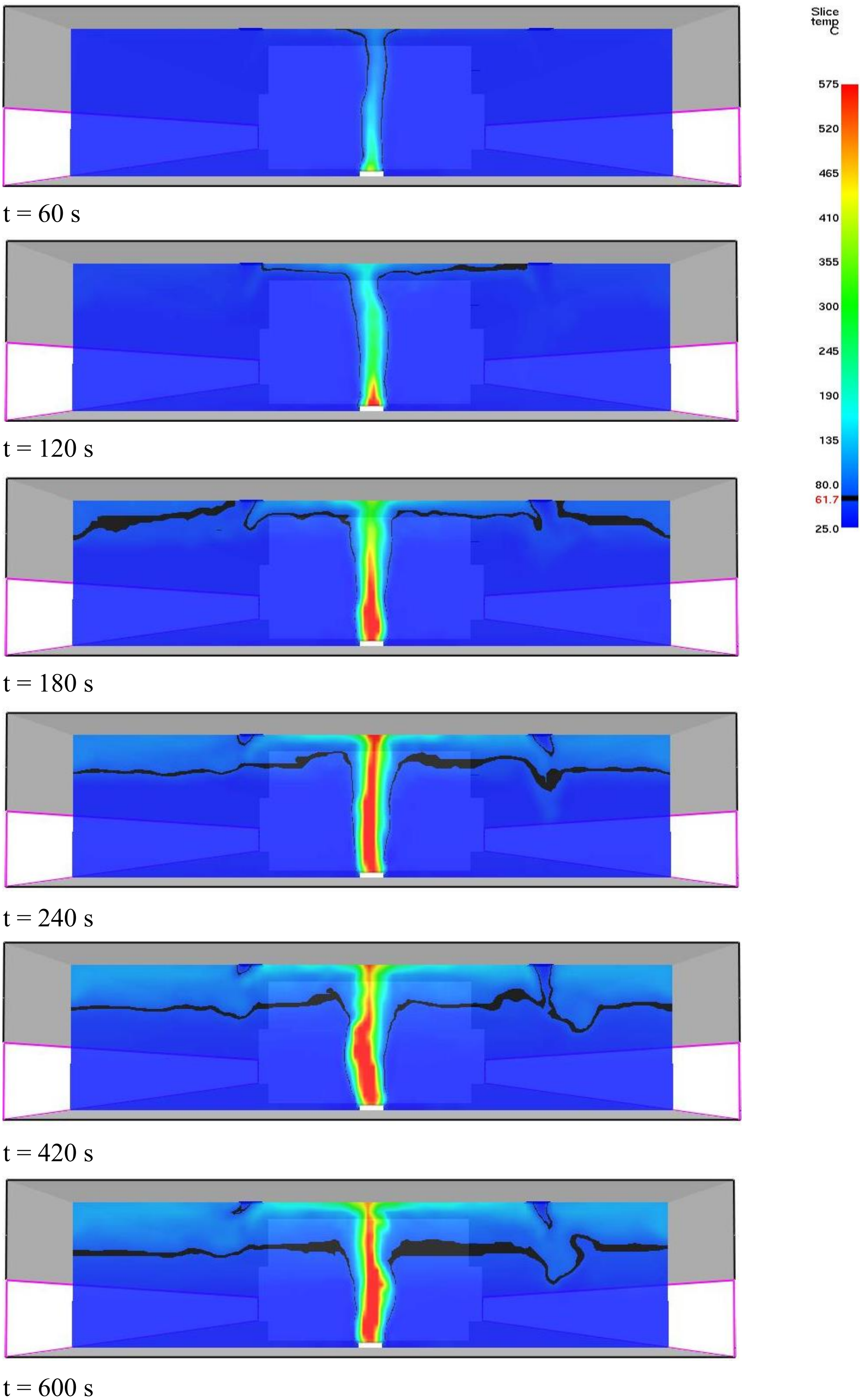


Figure 5.14 Zone C1 (F2=2.5MW), Temperature Contour in the Y-direction

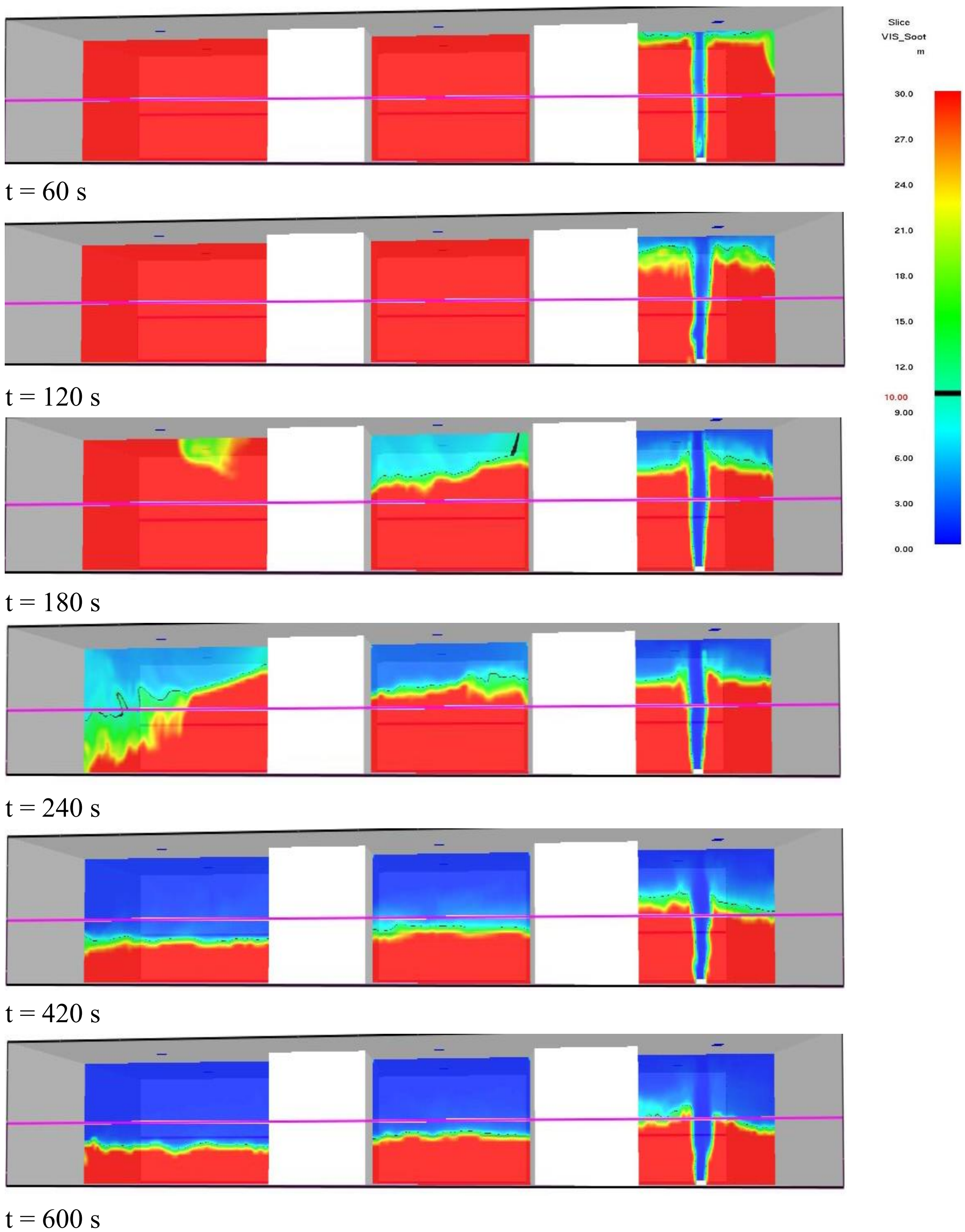


Figure 5.15 Zone C1 (F3=5MW), Visibility Contour in the X-direction

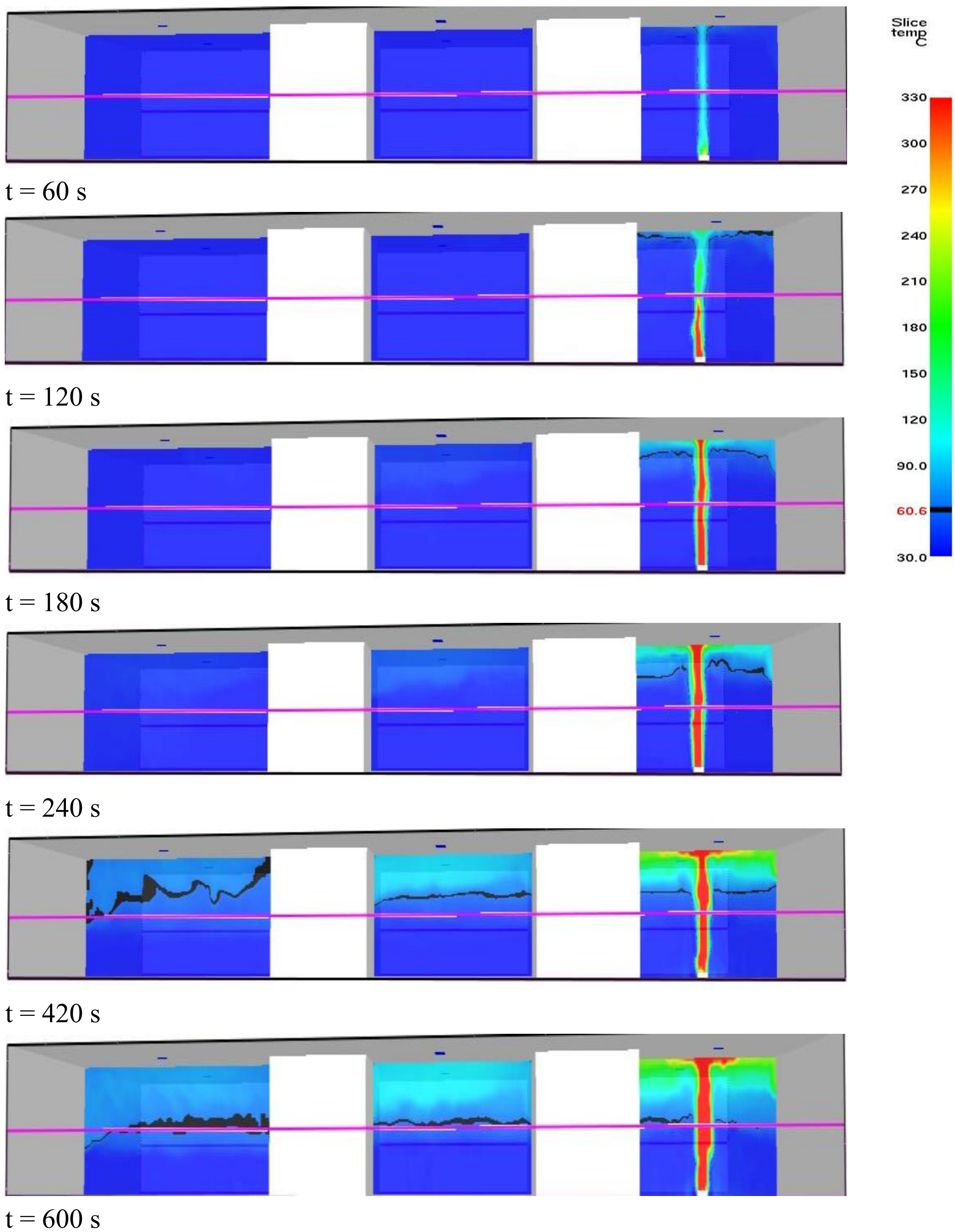
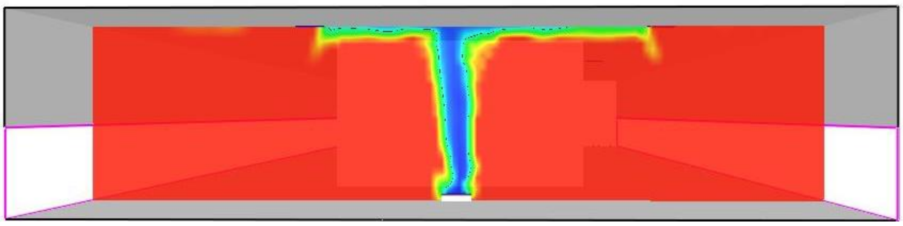
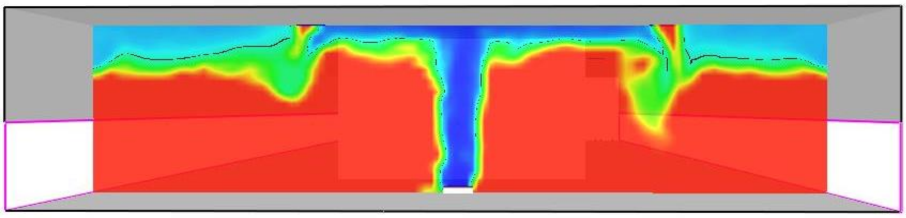


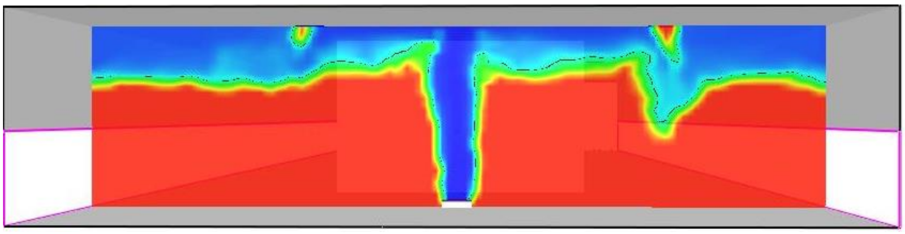
Figure 5.16 Zone C1 (F3=5MW), Temperature Contour in the X-direction



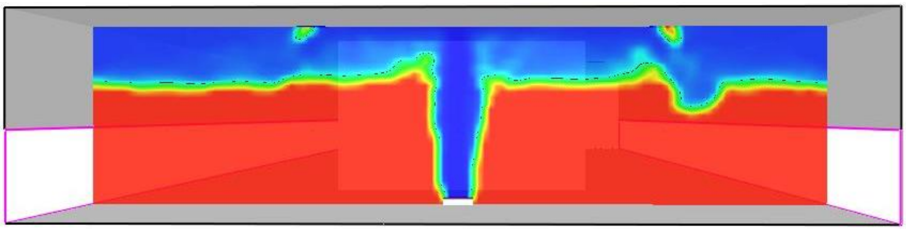
t = 60 s



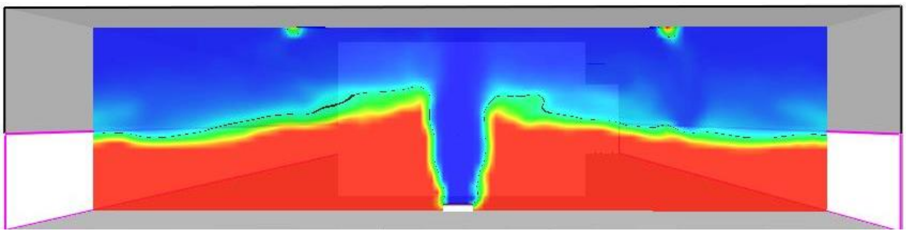
t = 120 s



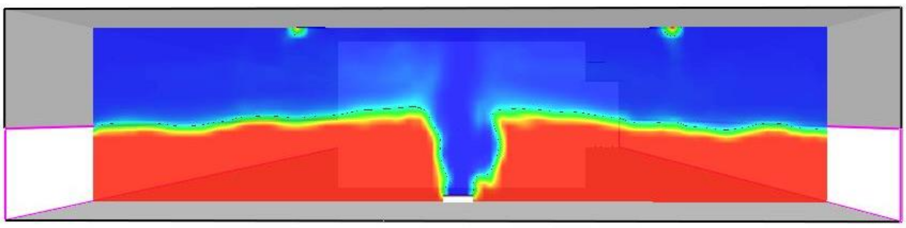
t = 180 s



t = 240 s



t = 420 s



t = 600 s

Figure 5.17 Zone C1 (F3=5MW), Visibility Contour in the Y-direction

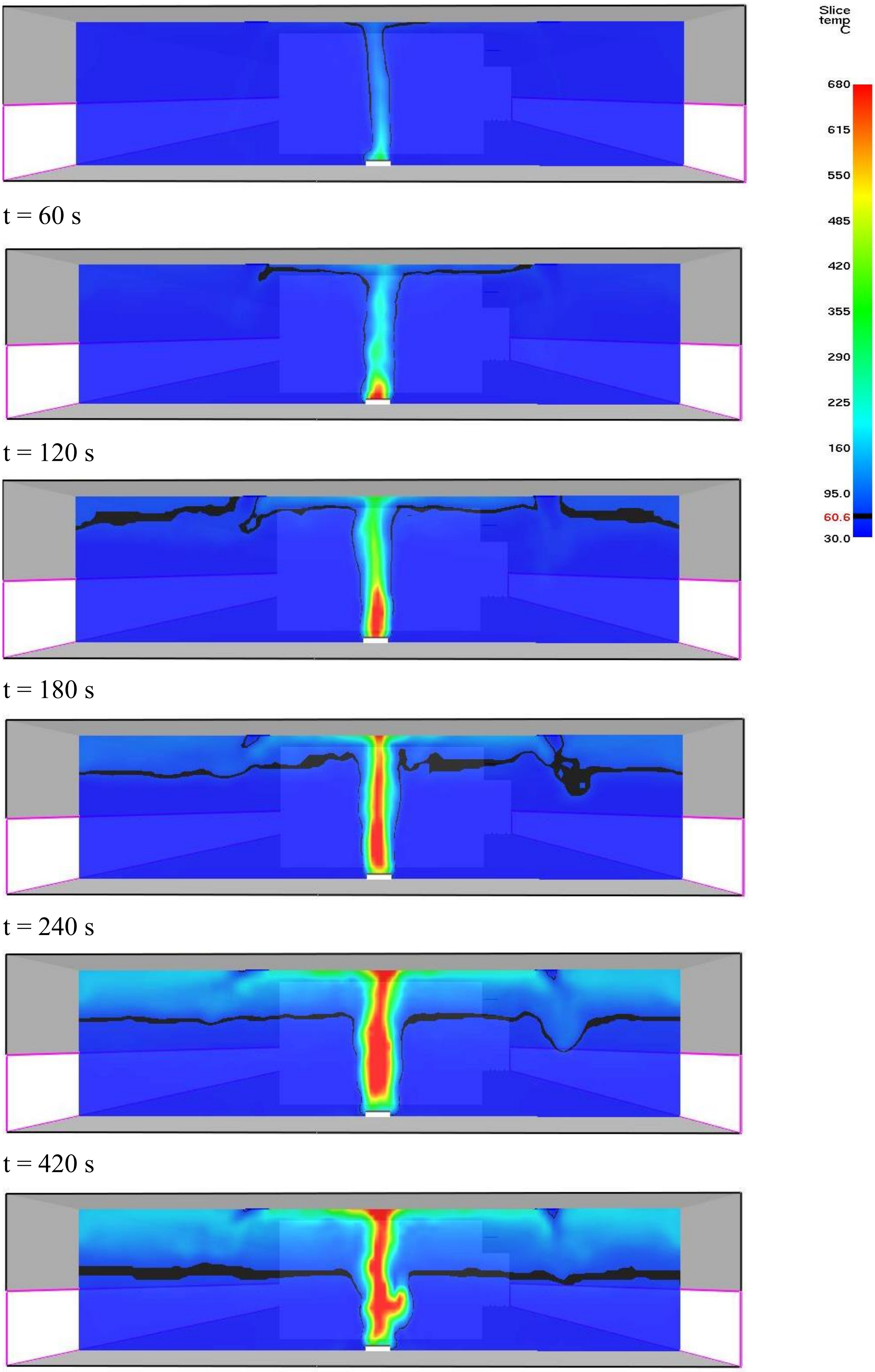


Figure 5.18 Zone C1 (F3=5MW), Temperature Contour in the Y-direction

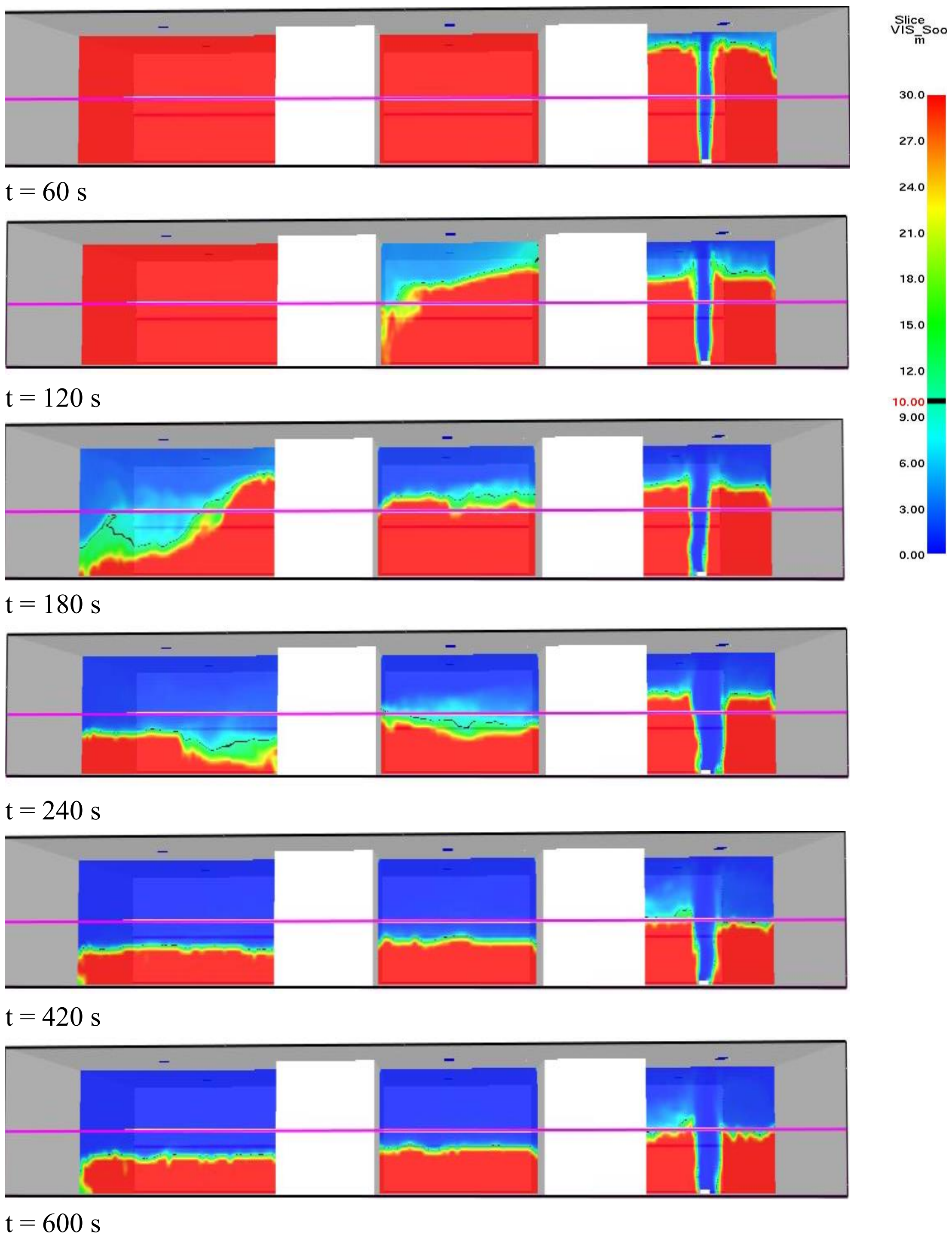


Figure 5.19 Zone C1 (F4=10MW), Visibility Contour in the X-direction

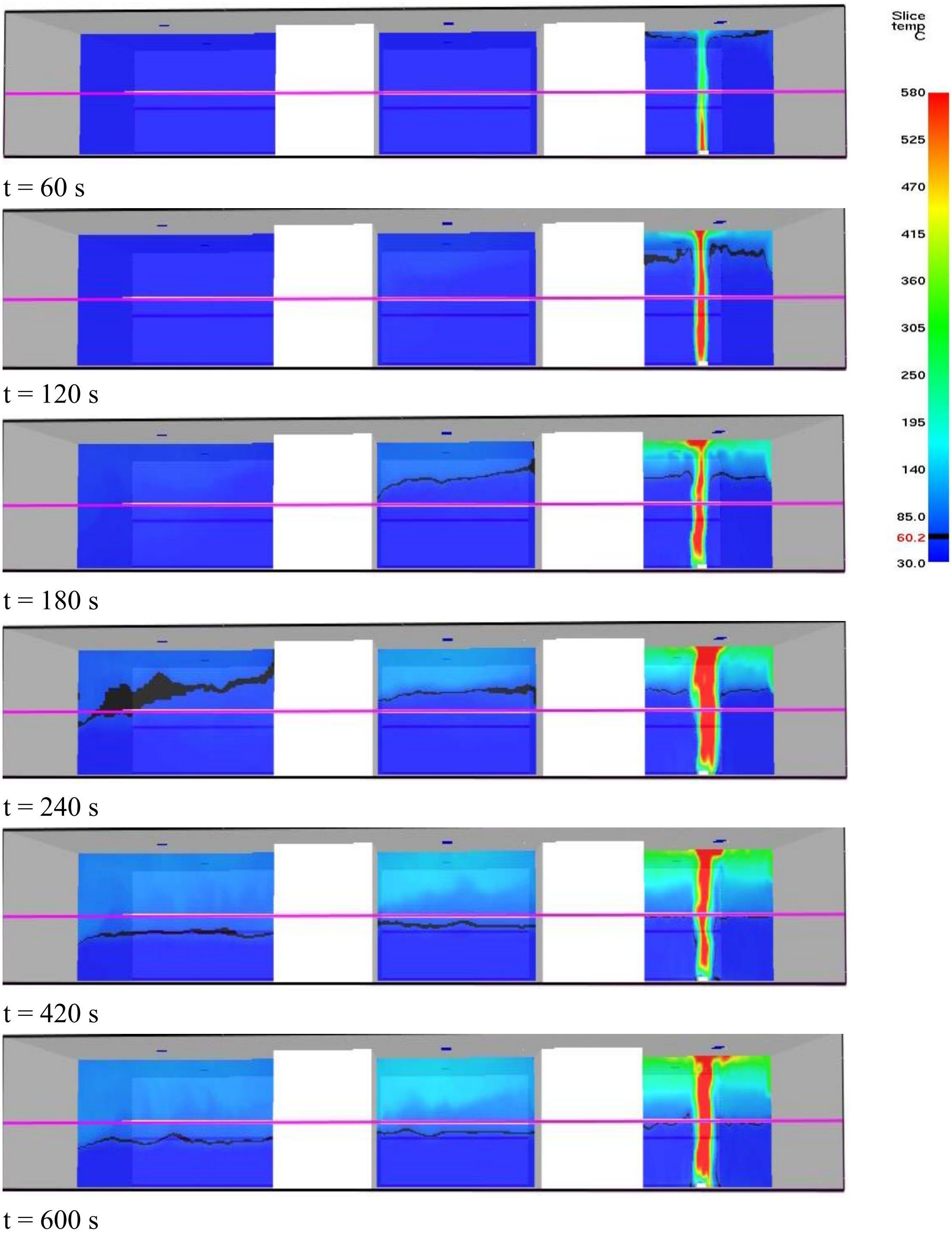


Figure 5.20 Zone C1 (F4=10MW), Temperature Contour in the X-direction

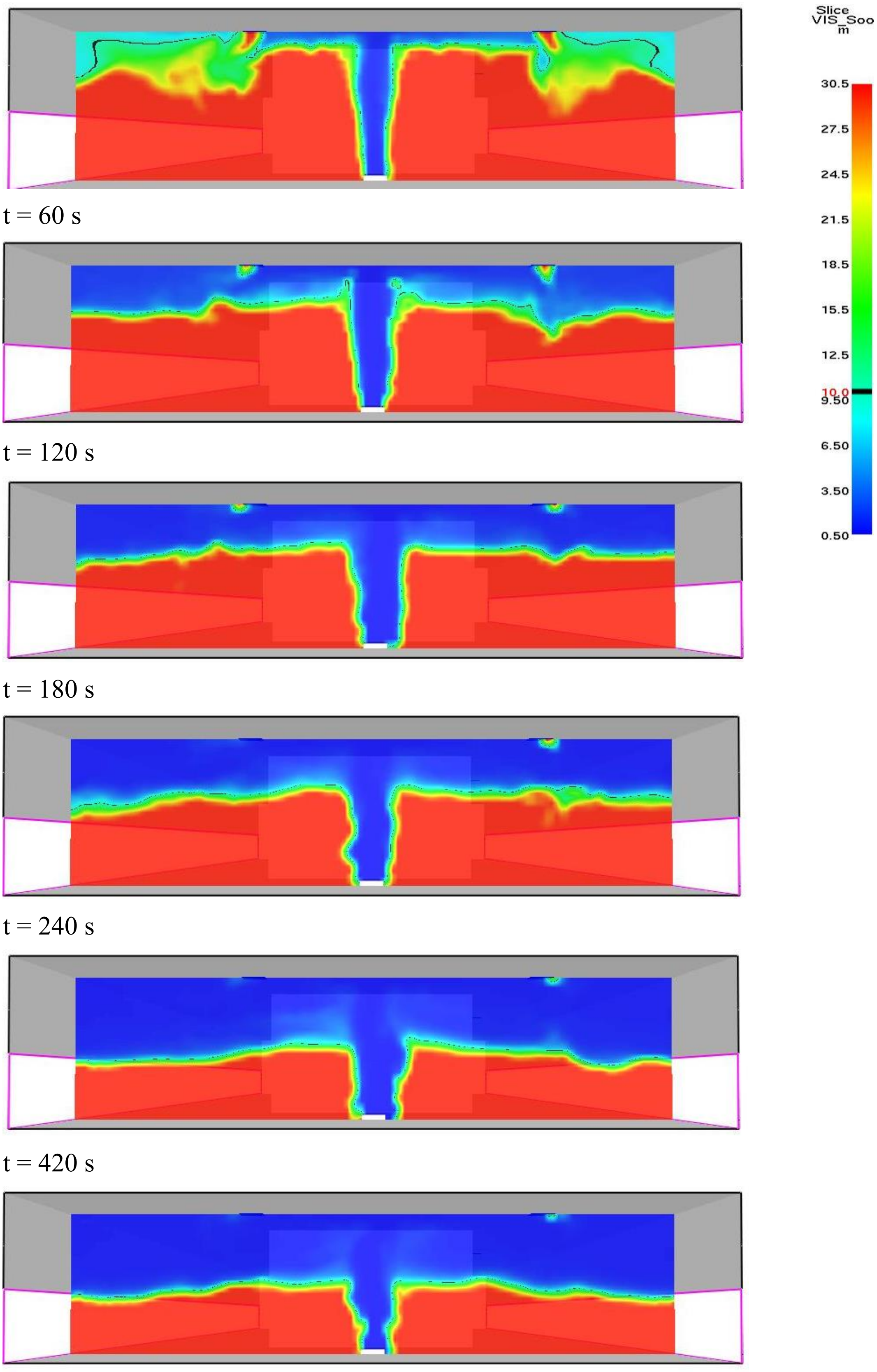
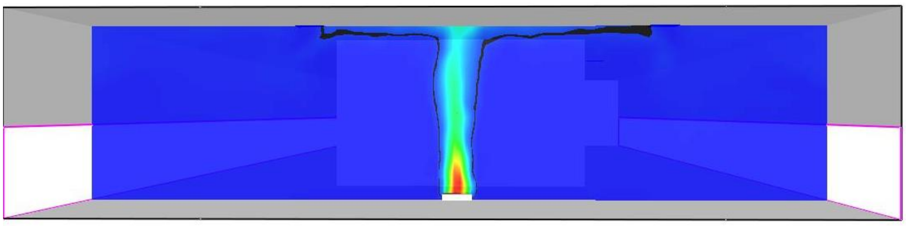
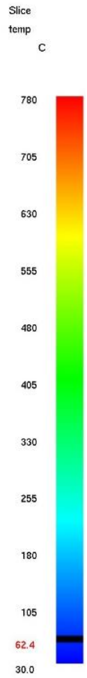
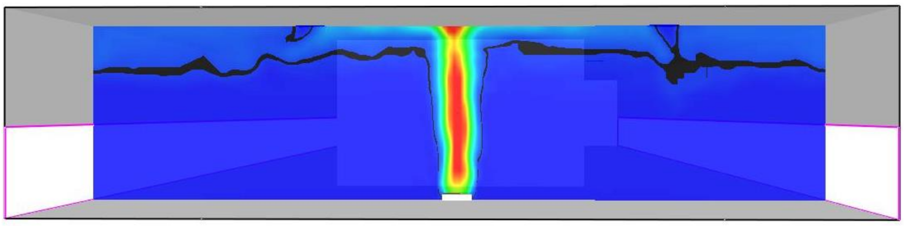


Figure 5.21 Zone C1 (F4=10MW), Visibility Contour in the Y-direction

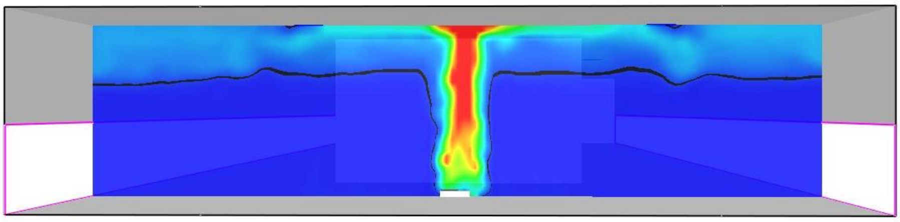




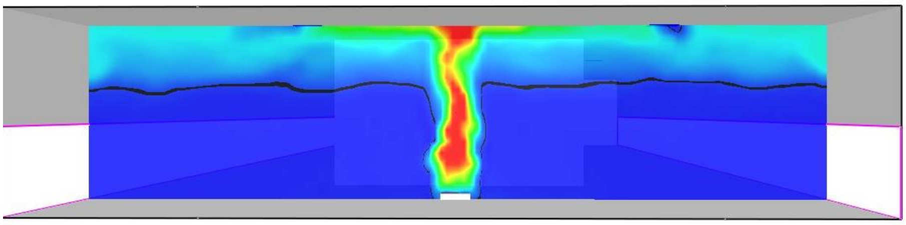
t = 60 s



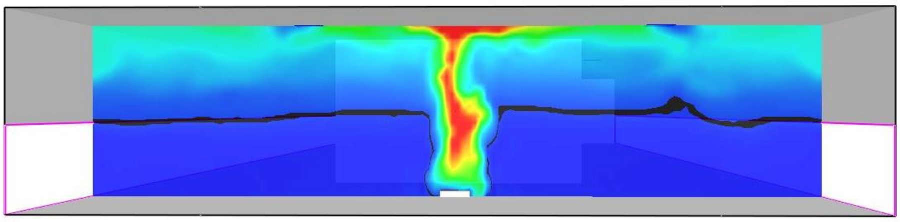
t = 120 s



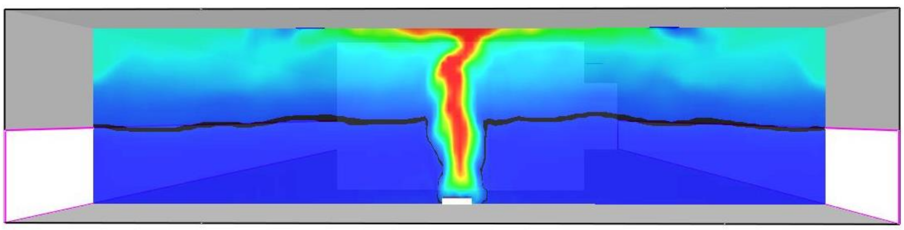
t = 180 s



t = 240 s



t = 420 s



t = 600 s

Figure 5.22 Zone C1 (F4=10MW), Temperature Contour in the Y-direction

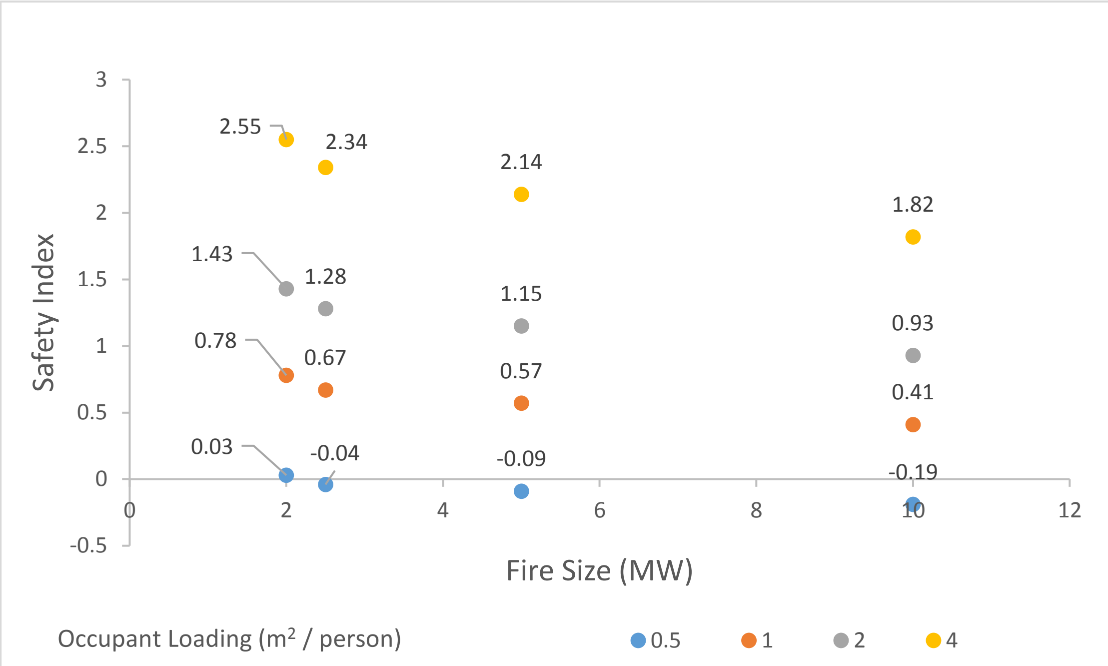


Figure 5.23 Variation of the Safety Index (Zone C1)

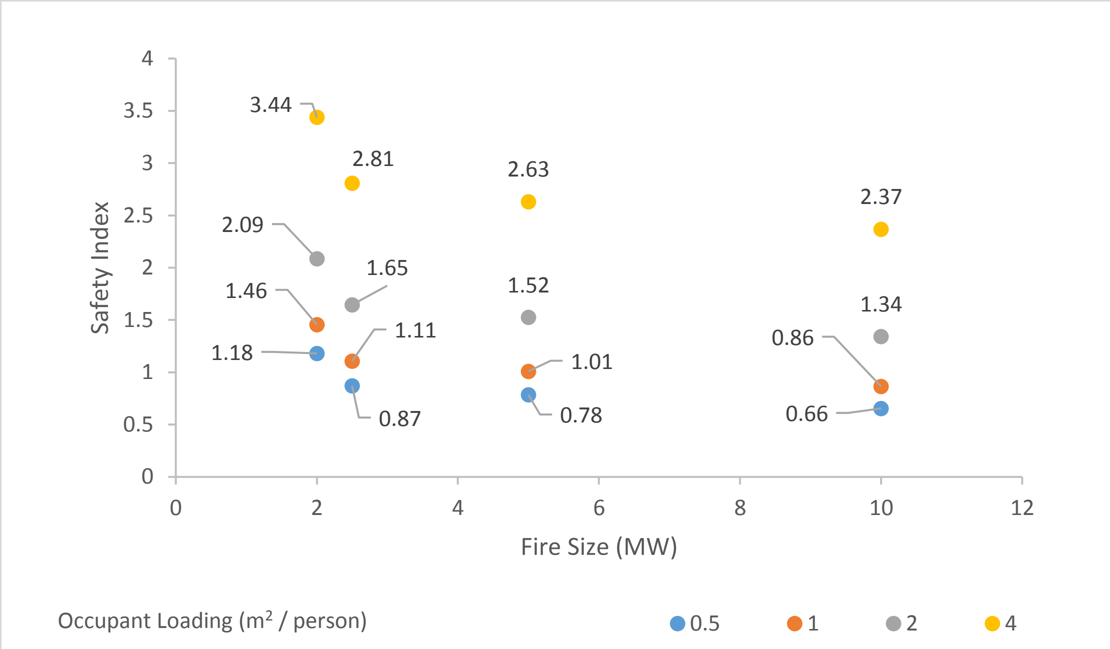


Figure 5.24 Variation of the Safety Index (Zone C2)

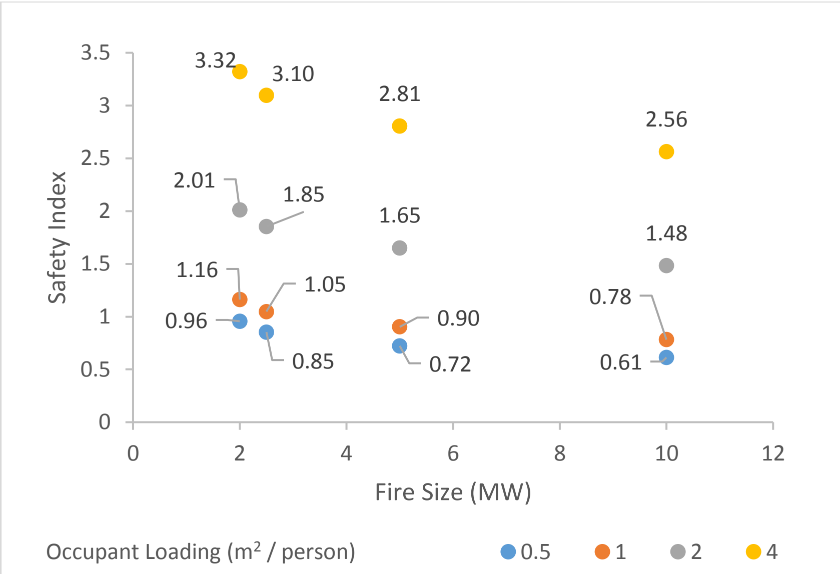


Figure 5.25 Variation of the Safety Index (Passenger Link Zone)

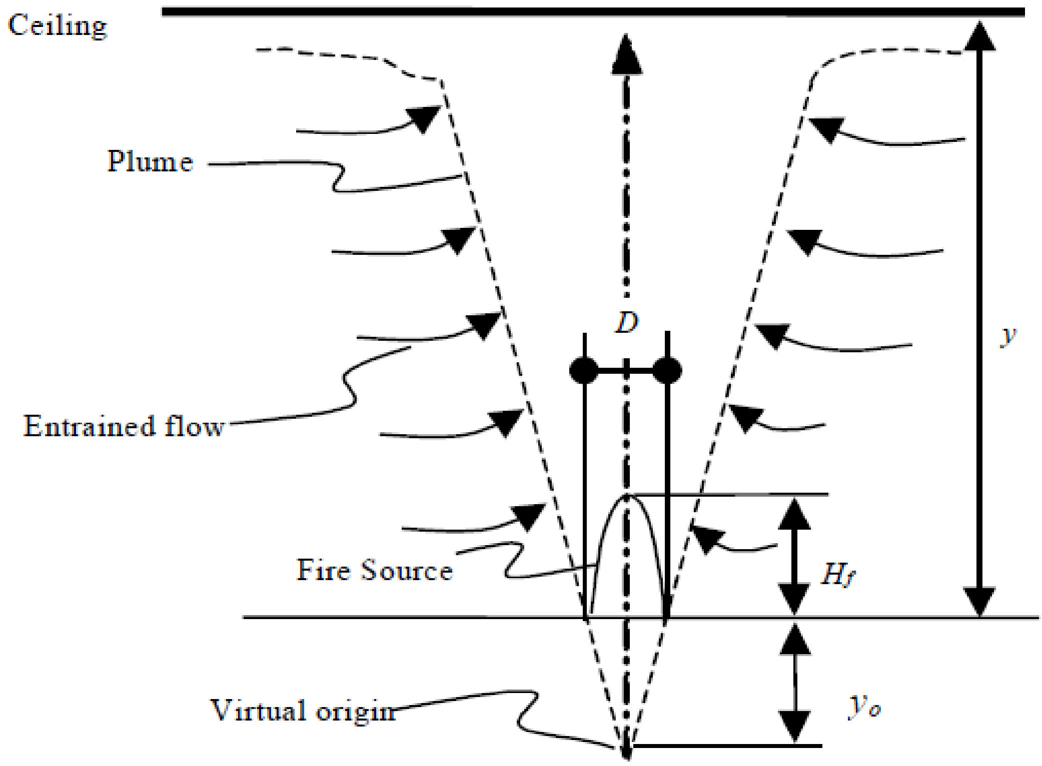


Figure 6.1 **Virtual Origin and Flame Height**

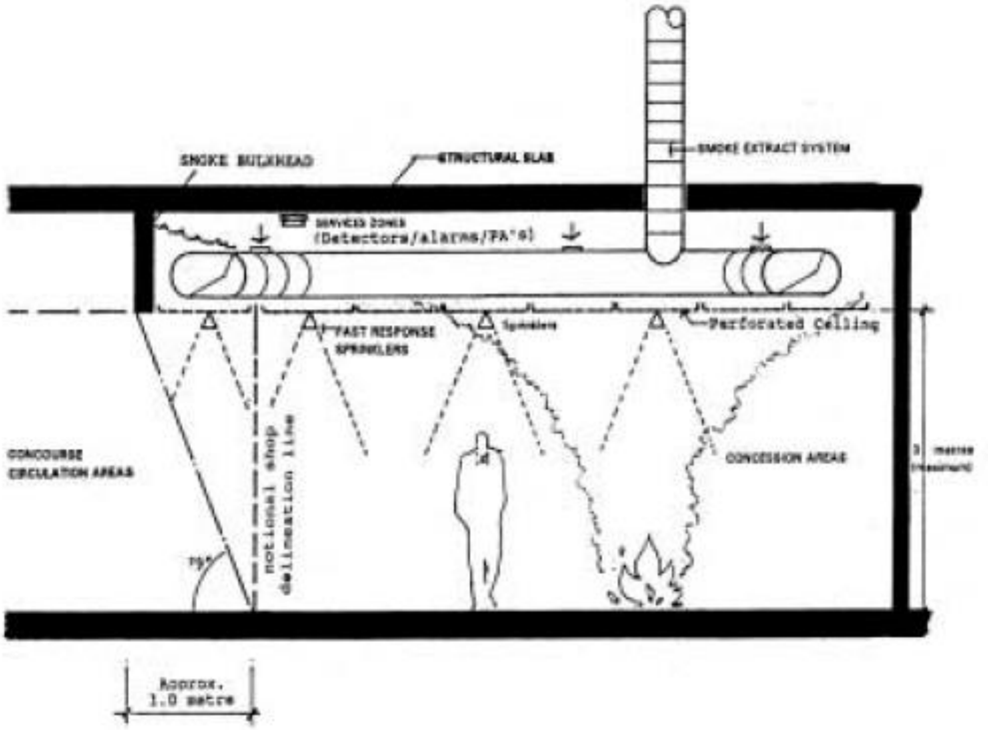


Figure 6.2 Schematic Diagram of the Cabin Concept Design (KCRC, 2007)

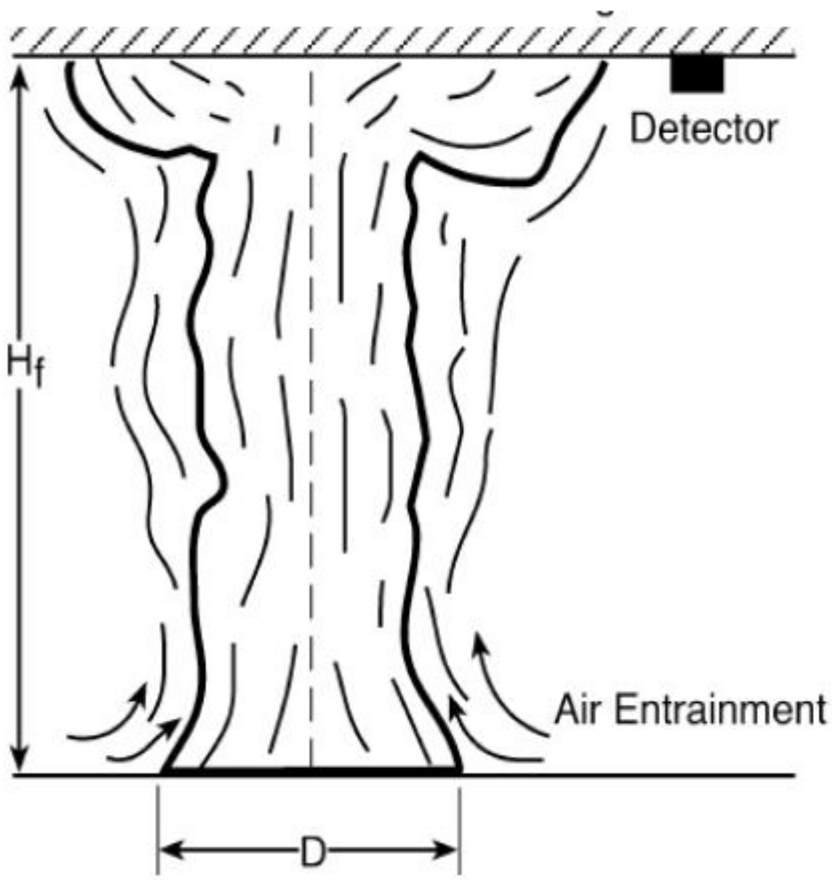


Figure 6.3 Flame Height of a Fire under Natural Ventilation

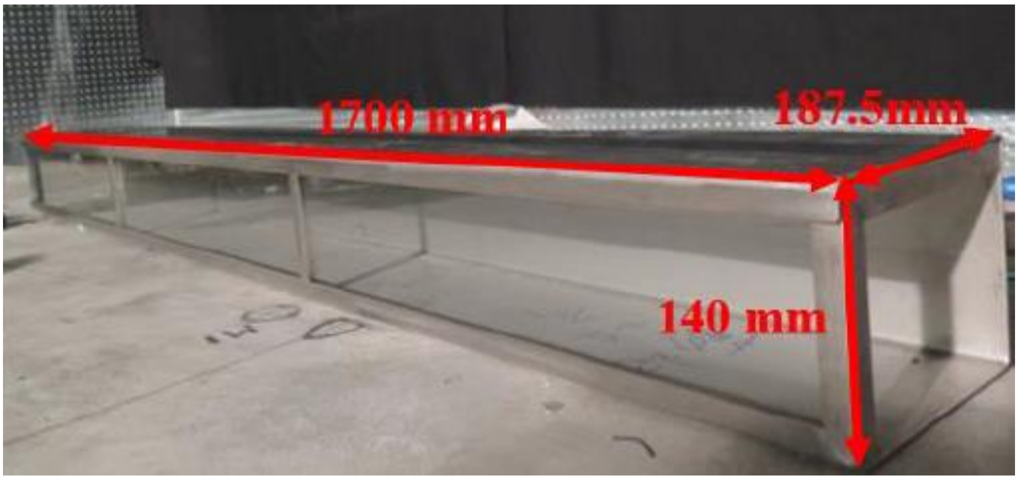


Figure 6.4 Scale Burning Test Model

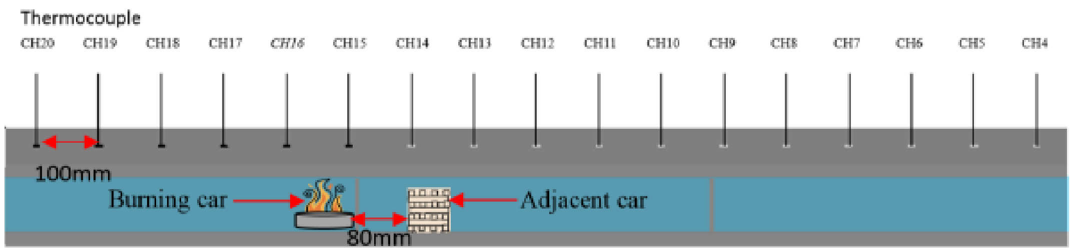


Figure 6.5 Experimental Setup

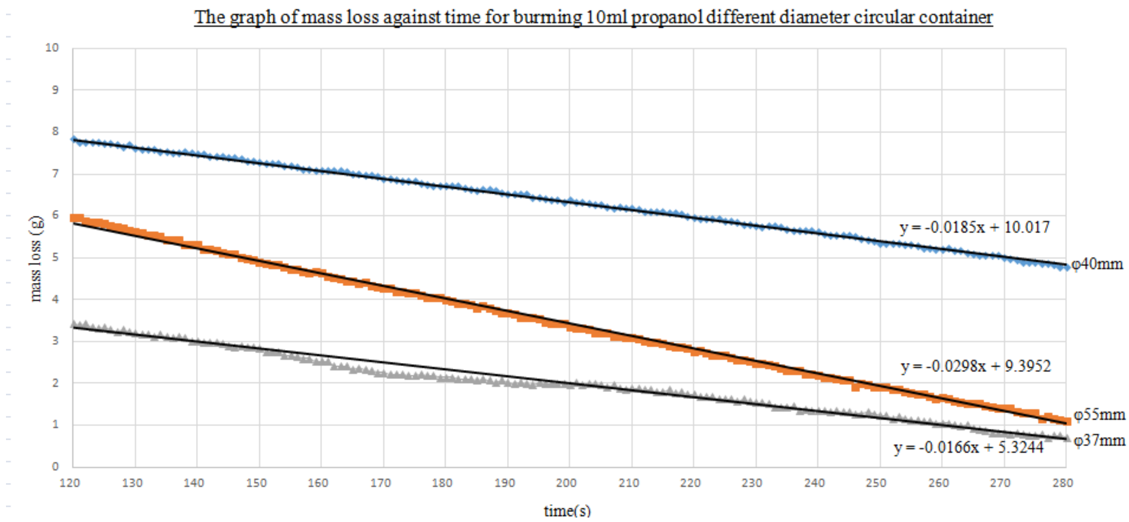


Figure 6.6 Graph of Mass Loss against Time for Burning 10 ml of Propanol

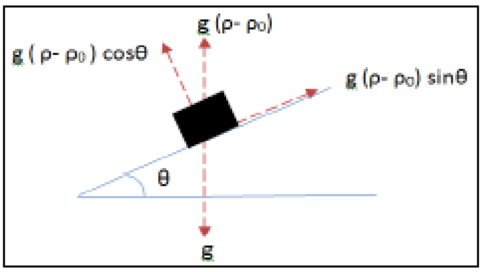


Figure 6.7 Force Acting on a Gas Control Volume of the Flame

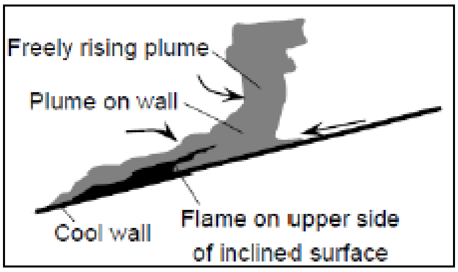


Figure 6.8 Flame on the Upper Side of an Inclined Surface

			
0^o	2^o	4^o	6^o

Figure 6.9 Flame Shape Pattern, Flame Colour and Flame Height

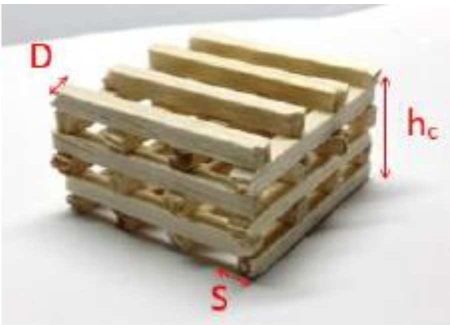


Figure 6.10 Wood Crib

30s	60s	300s	324s

Figure 6.11 **Flame Spread Rate Test at Tilted Angle of 0°**

30s	60s	300s	302s

Figure 6.12 **Flame Spread Rate Test at Tilted Angle of 2°**

50s	129s	132s	318s

Figure 6.13 **Flame Spread Rate Test at Tilted Angle of 4°**

50s	107s	110s	310s

Figure 6.14 **Flame Spread Rate Test at Tilted Angle of 6°**

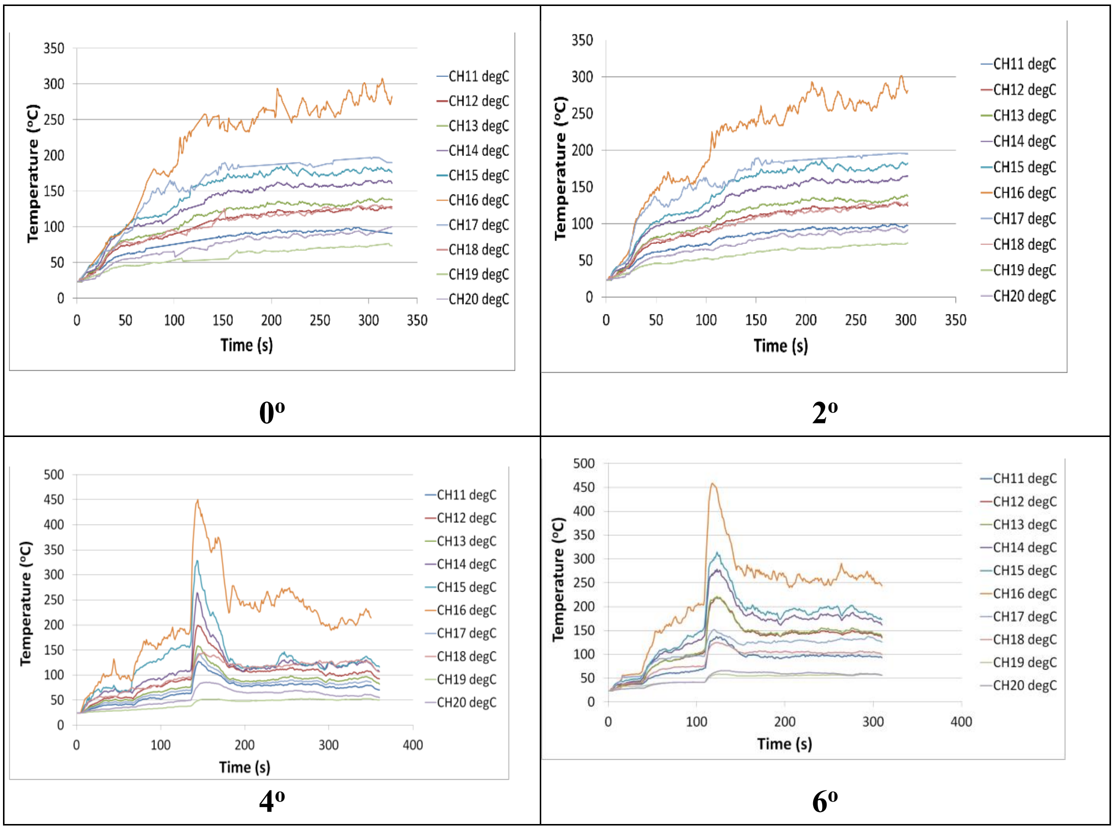


Figure 6.15 Graph of Hot Gas Temperature at Different Tilted Angles

Figure 6.16 CFD Simulation of the Tilted Enclosed Space Model

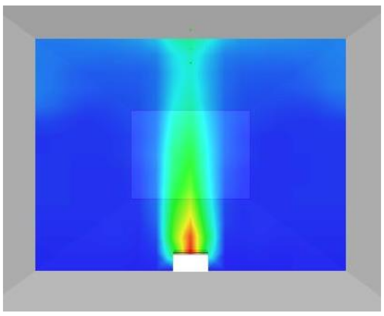


Figure 6.17 Sectional View of the Tilted Enclosed Space Model

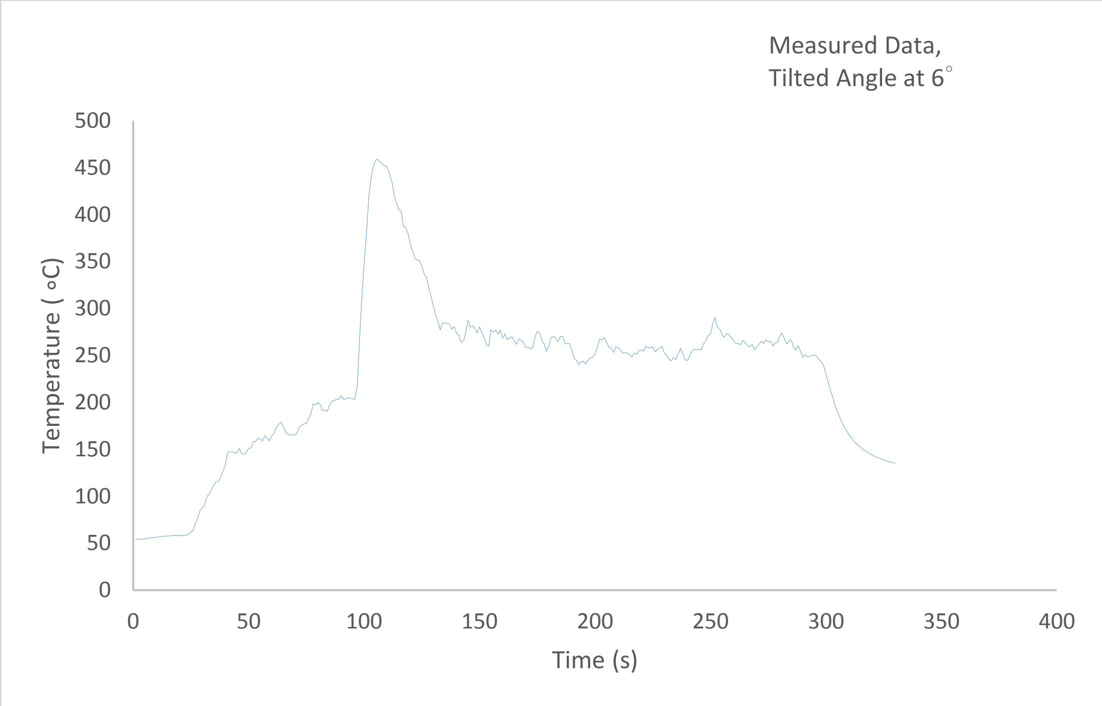


Figure 6.18 Measured Data (Tilted Angle of 6°)

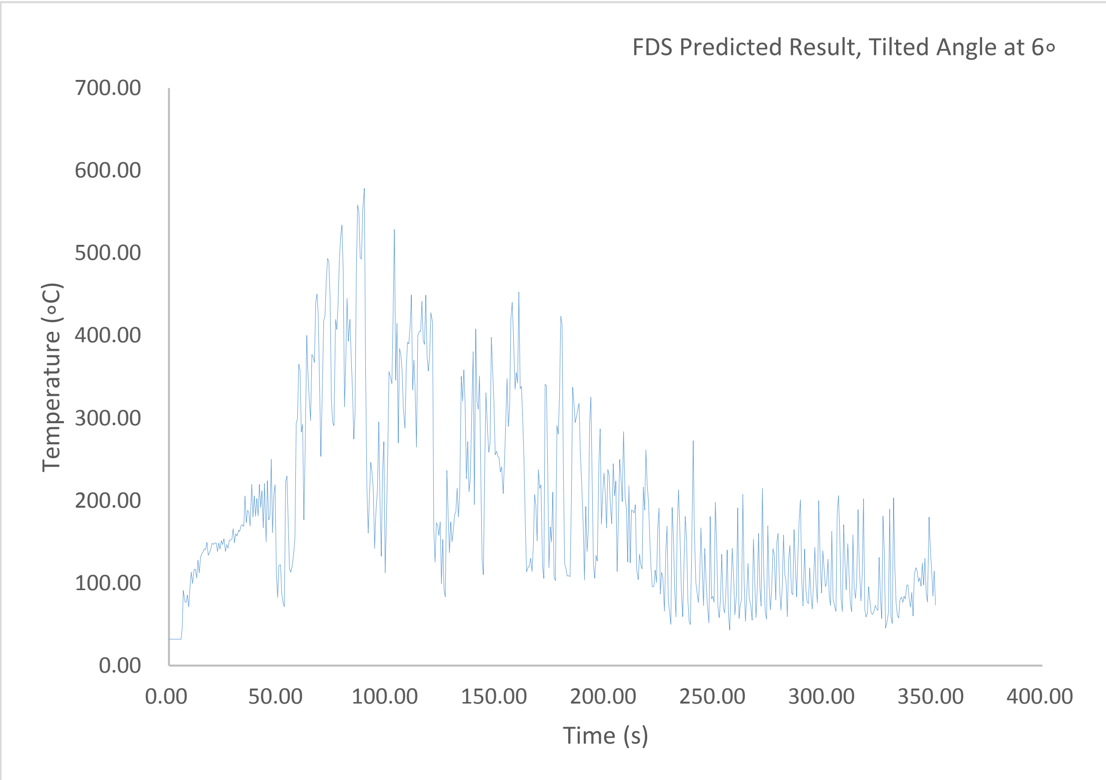


Figure 6.19 FDS Predicted Result (Tilted Angle of 6°)

Figure 7.1 Typical Tilted Passenger Corridor

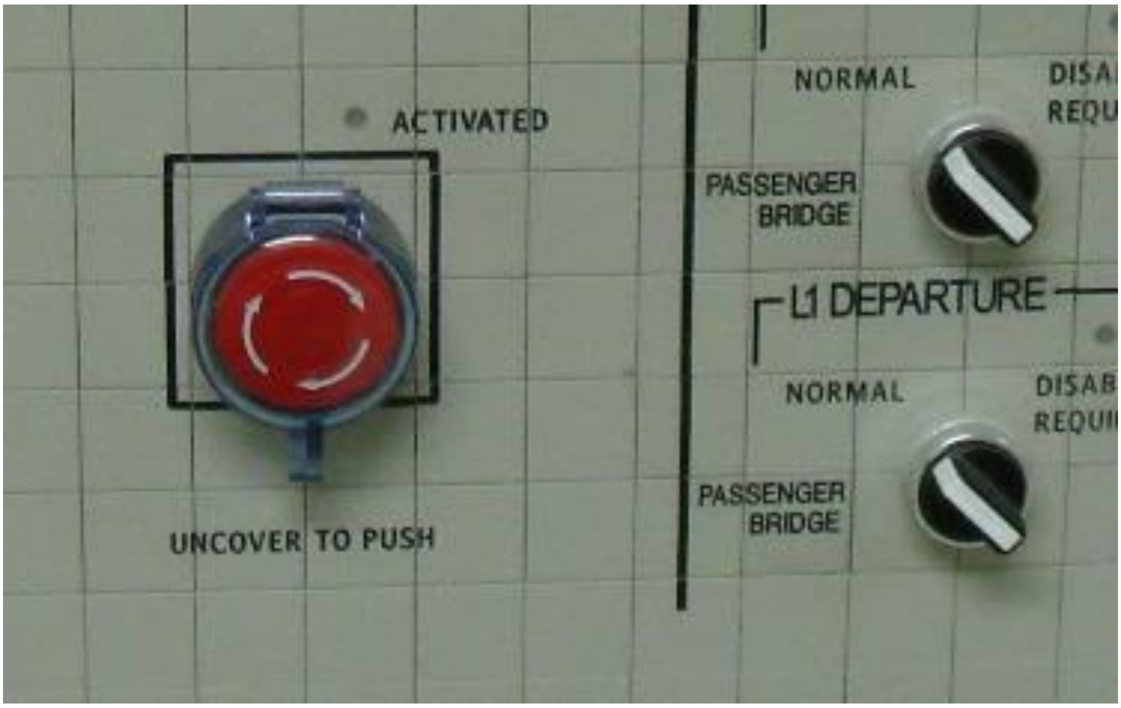


Figure 7.2 Typical Local Control Button for the Initiation of Evacuation

Figure 7.3 **Typical Evacuation Exit Door**

Figure 7.4 **Typical Perforated Ceiling for the Smoke Extraction System**

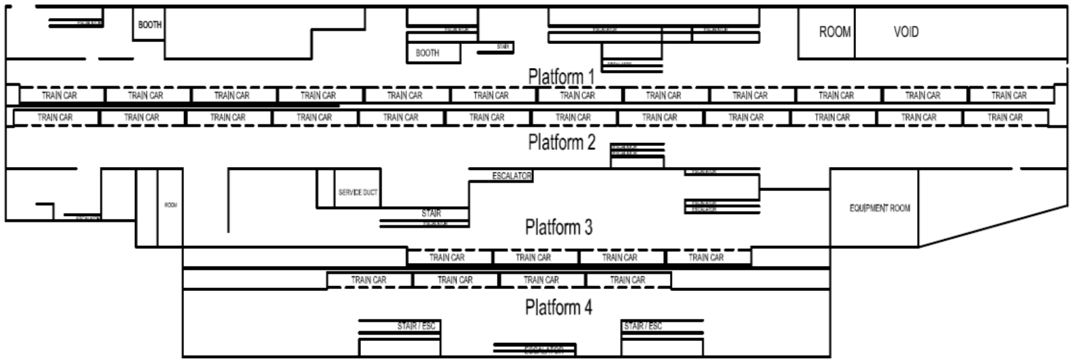


Figure 7.5 Platform Layout of the Evacuation Simulation

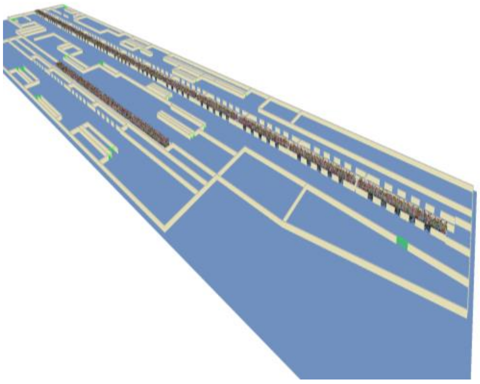
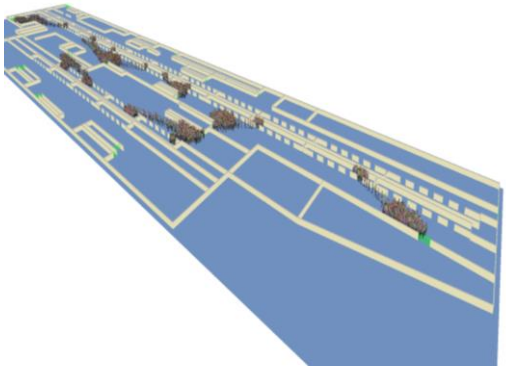
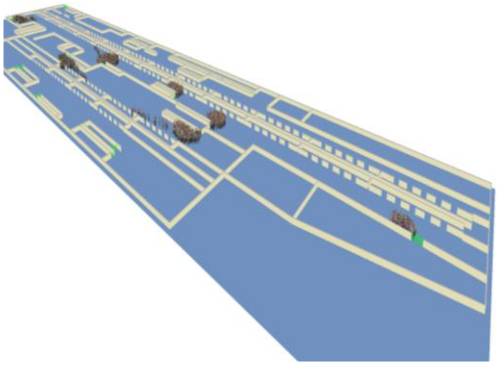
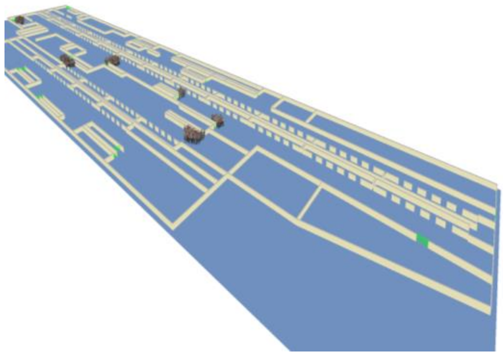
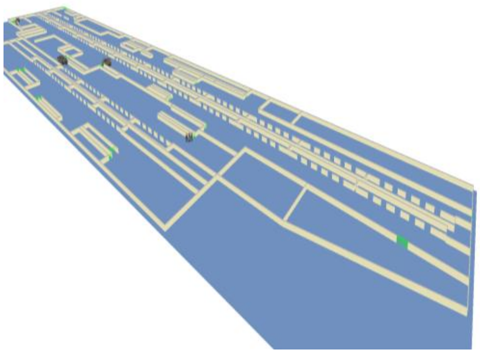
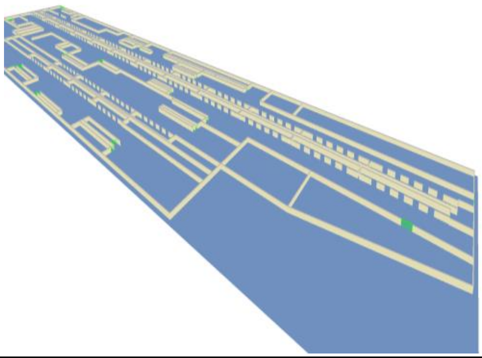
	
t = 0 s	**t = 60 s**
	
t = 120 s	**t = 180 s**
	
t = 240 s	**t = 300 s**

Figure 7.6 Evacuation Simulation by SIMULEX - Scenario P1

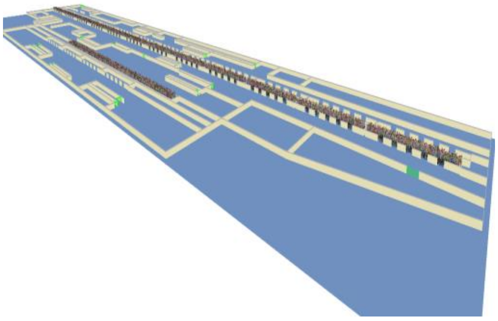
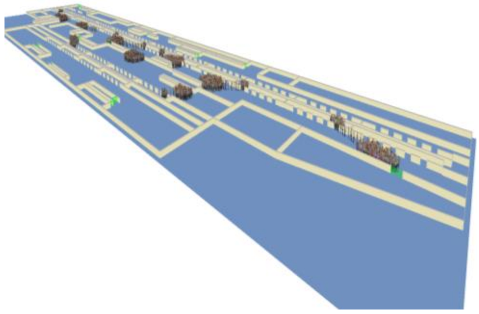
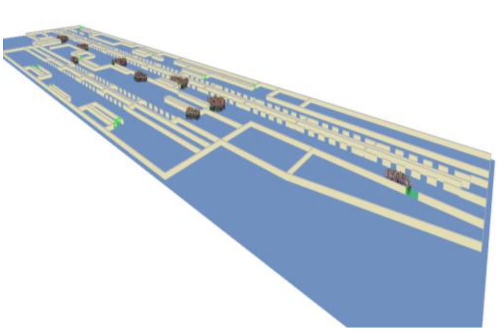
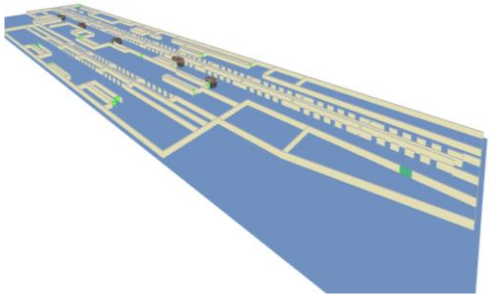
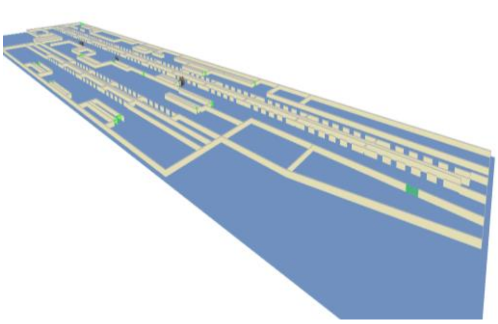
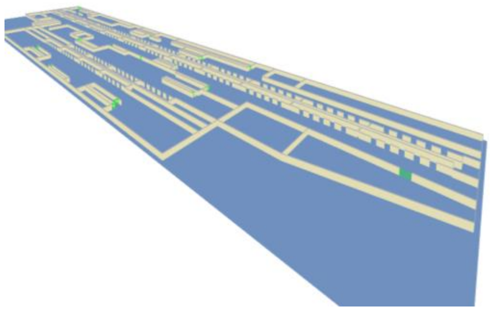
	
t = 0 s	**t = 60 s**
	
t = 120 s	**t = 180 s**
	
t = 240 s	**t = 295 s**

Figure 7.7 Evacuation Simulation by SIMULEX - Scenario P2

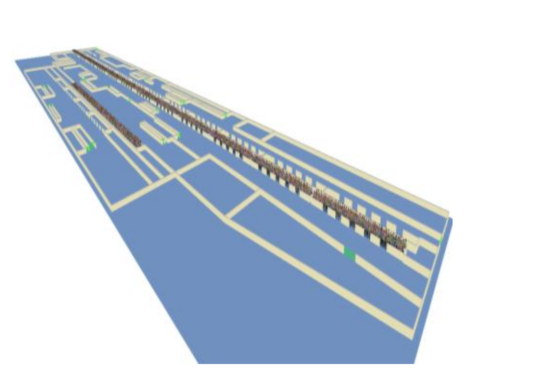
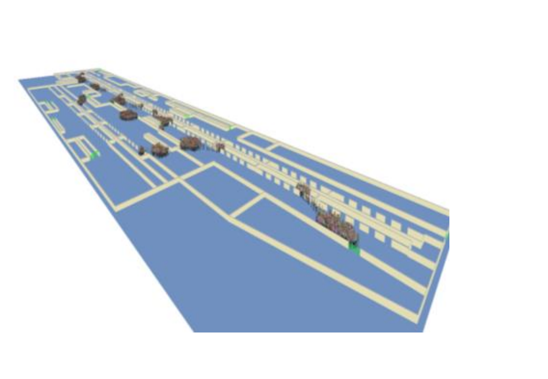
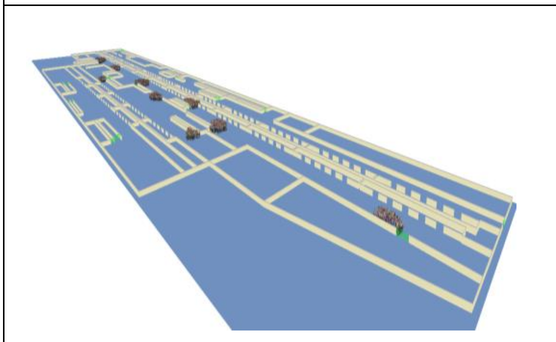
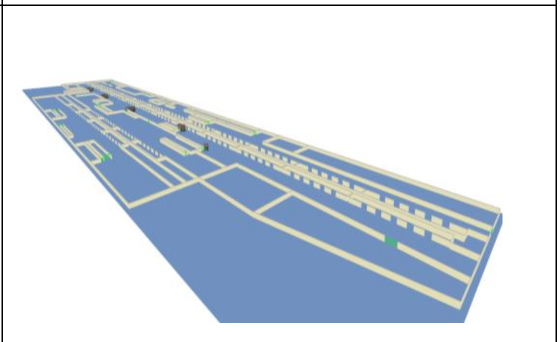
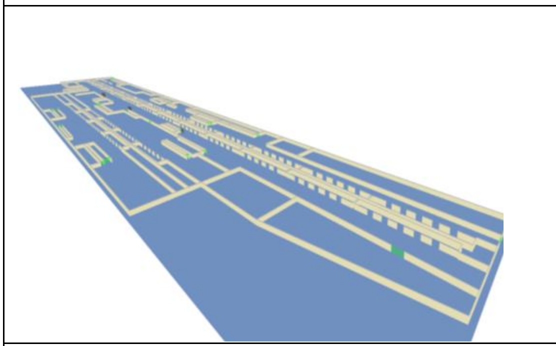
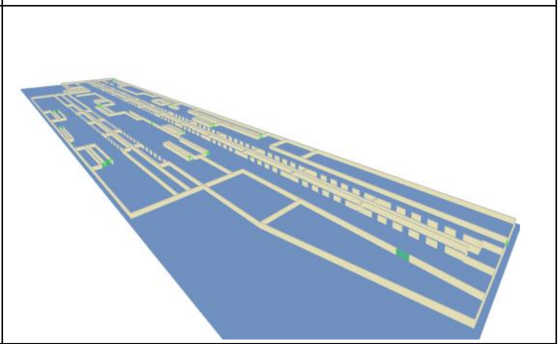
	
t = 0 s	**t = 60 s**
	
t = 120 s	**t = 180 s**
	
t = 240 s	**t = 270 s**

Figure 7.8 Evacuation Simulation by SIMULEX - Scenario P3

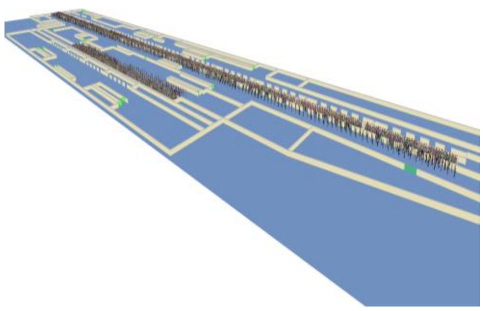
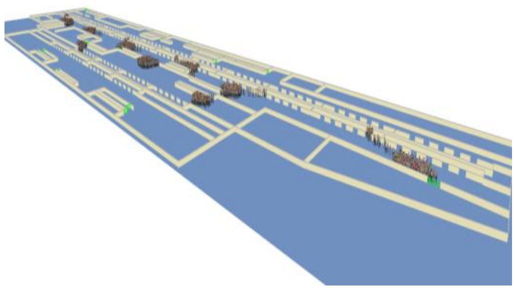
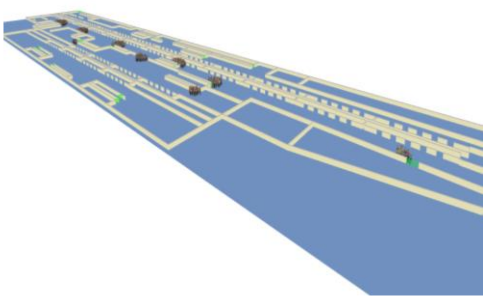
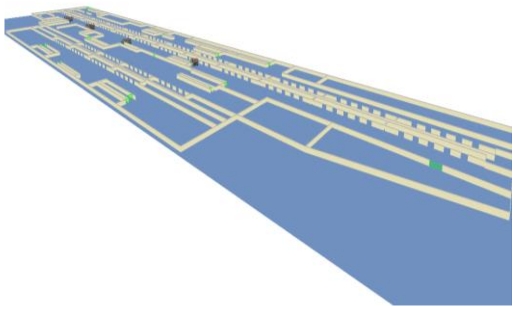
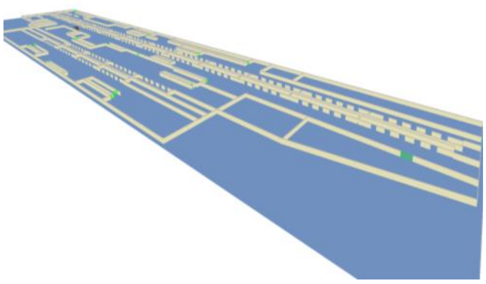
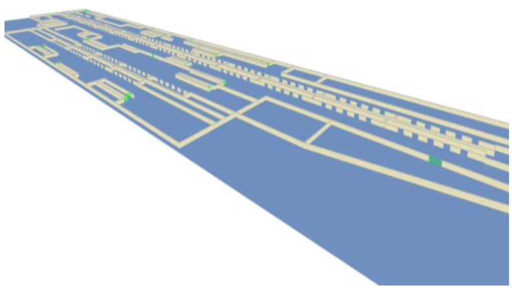
	
t = 0 s	**t = 60 s**
	
t = 120 s	**t = 180 s**
	
t = 240 s	**t = 280 s**

Figure 7.9 Evacuation Simulation by SIMULEX - Scenario P4

TABLES

Table 3.1 PTIs Adjacent to the Railway Station

	PTI location
1.	**Choi Ming Shopping Centre**
2.	Disneyland Resort
3.	**East Tsim Sha Tsui Station (Mody Road)**
4.	Hang Hau Station
5.	Hong Kong Station
6.	**Kam Sheung Road Station**
7.	Kowloon Station
8.	LOHAS Park Station
9.	Lok Ma Chau Station
10.	Long Ping Station (North)
11.	Long Ping Station (South)
12.	Nam Cheong Station
13.	Olympic Station adjoining Cherry Street
14.	Olympic Station adjoining Hoi Wang Road
15.	**Olympic Station adjoining Lin Cheung Road**
16.	Siu Hong Station (North)
17.	Siu Hong Station (South)
18.	Sunny Bay Station
19.	Tai Wai Station
20.	Tin Shui Wai Station
21.	Tiu Keng Leng Station
22.	Tseung Kwan O Station
23.	Tsing Yi Station
24.	Tsuen Wan West Station
25.	Tuen Mun Station
26.	Wu Kai Sha Station
27.	Yuen Long Station (North)
28.	Yuen Long Station (South)

Table 5.1 Details of the Fire Simulations and ASET Results

Fire scenario		F1 (2 MW)	F2 (2.5 MW)	F3 (5 MW)	F4 (10 MW)
Available Safe Egress Time	Passenger Link Zone	268	254	236	221
	Concourse (Zone C2)	253	217	207	192
	Concourse (Zone C1)	231	217	204	183

Table 5.2 Summary of the Evacuation Scenarios and RSET Results

Evacuation scenario			Required Safe Egress Time (RSET) (s)
Occupant Loading (m^2 / person)	Concourse (Zone C1)	0.5	225
		1	130
		2	95
		4	65
	Concourse (Zone C2)	0.5	116
		1	103
		2	82
		4	57
	Passenger Link Zone	0.5	137
		1	124
		2	89
		4	62

Table 5.3 Calculation of the Safety Index (SI) under Different Fire Scenarios

Scenarios			F1	F2	F3	F4
Passenger Loading (m^2 / person)	Passenger Link Zone	0.5	0.96	0.85	0.72	0.61
		1	1.16	1.05	0.9	0.78
		2	2.01	1.85	1.65	1.48
		4	3.32	3.1	2.81	2.56
	Concourse (Zone C2)	0.5	1.18	0.87	0.78	0.66
		1	1.46	1.11	1.01	0.86
		2	2.09	1.65	1.52	1.34
		4	3.44	2.81	2.63	2.37
	Concourse (Zone C1)	0.5	0.03	-0.04	-0.09	-0.19
		1	0.78	0.67	0.57	0.41
		2	1.43	1.28	1.15	0.93
		4	2.55	2.34	2.14	1.82

Table 6.1 HRR of a Burning Luggage with Different Sizes of Containers

Container size in diameter (mm)	Mass loss rate (g/s)	HRR_M (kW)	HRR_F (MW)
55	0.0298	0. 897	8.684
40	0.0185	0.557	5.881
37	0.0166	0.500	5.058

Table 6.2 Flame Height at Different Tilted Angles

<table>
<tr><th>Titled angle (˚)</th><th>0</th><th>2</th><th>4</th><th>6</th></tr>
<tr><td>Flame height (mm)</td><td colspan="2">140</td><td>105</td><td>96</td></tr>
</table>

Table 6.3 Flame Spread Time at Different Tilted Angles

<table>
<tr><th>Titled angle (˚)</th><th>0</th><th>2</th><th>4</th><th>6</th></tr>
<tr><td>Flame spread time (s)</td><td colspan="2">No fire spread</td><td>129</td><td>106</td></tr>
</table>

Table 7.1 Summary of Evacuation Times (Scenario P1)

Platform 2					
Exit Number	Effective Exit Width (m)	Number of People Past	Distance to Exit (m)	TET (By Hydraulic Calculation) (s)	Evacuation Time (by Simulex) (s)
18	3	355	58	133	260
8	1	258	50	237	250
10	2	800	58	301	300
11	1	41	33	59	200
20	1	307	33	260	205
12	1	440	29	358	215
26	3	441	46	162	155
Platform 3					
9	2	243	62	129	300
19	1	197	62	201	300
16	1	302	46	267	250
24	1	138	46	143	250

Table 7.2 Summary of Evacuation Times (Scenario P2)

Platform 2					
Exit Number	Effective Exit Width (m)	Number of People Past	Distance to Exit (m)	TET (By Hydraulic Calculation) (s)	Evacuation Time (by Simulex) (s)
18	3	352	58	132	255
8	1	252	50	233	245
10	2	773	58	293	295
11	1	40	33	58	185
20	1	304	33	258	200
12	1	411	29	336	205
26	3	425	46	158	140
Platform 3					
9	2	223	62	122	270
19	1	183	62	191	270
16	1	289	46	258	235
24	1	138	46	143	230

Table 7.3 Summary of Evacuation Times (Scenario P3)

Platform 2					
Exit Number	Effective Exit Width (m)	Number of People Past	Distance to Exit (m)	TET (By Hydraulic Calculation) (s)	Evacuation Time (by Simulex) (s)
18	3	573	37	167	235
8	1	368	21	296	270
10	2	506	29	184	250
11	1	303	13	240	245
20	1	93	12	81	75
12	1	391	29	321	190
26	3	441	46	162	155
Platform 3					
9	2	128	42	76	165
19	1	95	42	107	165
16	1	440	33	361	165
24	1	220	25	188	170

Table 7.4 Summary of Evacuation Times (Scenario P4)

Platform 2					
Exit Number	Effective Exit Width (m)	Number of People Past	Distance to Exit (m)	TET (By Hydraulic Calculation) (s)	Evacuation Time (by Simulex) (s)
18	3	581	37	169	240
8	1	358	21	289	280
10	2	470	29	173	230
11	1	266	13	212	220
20	1	90	12	78	70
12	1	356	29	294	175
26	3	394	46	149	135
Platform 3					
9	2	107	42	69	145
19	1	93	42	106	140
16	1	441	33	362	160
24	1	206	25	177	160

APPENDIX A – COMMON TERMINOLOGY AND EQUATIONS USED IN FIRE STRATEGY REPORT

The following terms and terminology are commonly used in most of the Fire Safety Strategy report (KCRC, 2007) developed by the railway operators:

Retail Shop Areas

Designated areas for retail trades and services located within the railway stations where the fire load of the goods in stock may be greater than 2 MW.

Escape Route

The path or paths used by passengers and other station occupants to reach a Safe Discharge Point

Fire Fighting Access Point

The entrances to a non-public area of the railway stations for the purposes of fire-fighting from a protected lobby served by a Fireman's Stair, a Supplementary Fireman's Stair or other equivalent access that are considered suitable

Integrated Entrance

The entrance to the Station leads directly from the adjacent property development. Such entrance is under the direct control of the railway operator's management. There is a certain period of fire-rated protection in a form of fire shutter. The entrance is not to be used for evacuation in the event of a fire in the railway station.

Non-public Areas

Those areas of railway stations which are not accessible to the general public or passengers and which are used for daily railway operations including offices and staff areas, or installations associated with the railway or for building services relating to the station.

Place of Safe Passage

An area under railway operator's control through which passengers and other station occupants will pass in the event of a fire or an emergency and in which safe conditions are to be maintained primarily for fire evacuation by smoke control measures for a minimum period of 30 minutes. This is very often the next level above, below or an area adjacent to that in which fire has occurred.

Place of Ultimate Safety

A safe location in the open air at grade or street level which offers adequate provision for the safe dispersal of passengers and occupants.

Point of Safety

This is the entrance to a Place of Safe Passage or a Protected Route leading to a Place of Ultimate Safety.

Protected Route

A route leading from a Point of Safety to a Safe Discharge Point to provide physical fire-rated protection and separation.

Safe Discharge Point

The entrance leading to a Place of Ultimate Safety from a Place of Safe Passage or Protected Route.

Station Areas

Station areas are the areas used for railway activities and services including platforms, concourses, paid areas, un-paid areas, shops and commercial facilities in the circulation areas including the staff accommodation and equipment plant rooms.

Station Related Areas

Areas under the direct control of the railway operator staff that are supplementary or essential to the operation of the Station, including the vehicle drop-off, picking up points, queuing areas and access roads.

Fire Growth

Real fires do not instantaneously grow from the initial fire to their peak heat release rate. Rather, fire sources experience a function of growth period. This growth period has been shown as a function of time. This is often referred to as the t-squared fire and represented as:

$$Q \propto t^2$$

Where

Q = heat release rate (kW)

T = time (s)

That is

$$Q = at^2$$

The t-squared fire formula, which expresses the heat release rate of a fire as a function of the square of time, has been widely used and accepted worldwide to define the fire scenarios of fire growth in different conditions. There are four accepted design fires in t-squared formula, namely, ultra-fast, fast, medium and slow growth fires.

Fire type	a (constant)
Ultra-fast	0.1778
Fast	0.04444
Medium	0.01111
Slow	0.002778

The ultra-fast growth fire is typically produced by thin plywood, fast burning upholstered furniture and pool fires such as petrol and other flammable liquid fires. The fast growth fire is applicable to shop and restaurant fires, and the medium growth fire is applicable to office fires (NFPA 92B).

The t-squared fire formula more closely represents a real fire than the steady state fire. It is more realistic to analyse the tenability conditions and to assess the fire evacuation procedure using the results of the t-squared fire simulation model. The t-squared fire is often used to estimate the fire size at the first sprinkler activation in the design of cabins.

Fire Source

The plume models are on the assumption of using a point fire source. In reality, a fire source occupies a finite area. The virtual origin is introduced to correct this deviation. Virtual origin is the elevation of an imaginary position of the point fire source apart from the fuel surface. The position is determined by extrapolating the boundaries of the plume to a crossing point as shown in Fig. 6.1.

The virtual origin is expressed as y_0. If y_0 is negative, the virtual origin lies below the top of the fire source. It is suggested that the virtual origin be expressed as follows:

$$y_0 = 0.083xQ^{2/5} - 1.02D \qquad \text{(A.1)}$$

where

Q = total heat output of a fire (kW)

D = the diameter of the fire source (m) or the effective diameter such that

$$\mathrm{D} = \sqrt{\frac{4A_{eq}}{\pi}} \qquad \text{(A.2)}$$

A positive value of y_0 means that the virtual origin is above the fuel surface and a negative value denotes that the virtual origin is under the fuel surface.

The expression provided for calculating the location of the virtual origin, Equation A.1, is limited to fire sources, which do not have substantial deep-seated combustion. In many cases, especially involving high storage, it will be difficult to determine whether the deep-seated combustion is substantial, ie. Whether

Equation A.1 is applicable. In such cases, the virtual origin be chosen coincident with the top of the combustible.

ie. $y_0 = 0$

Definition of Flame Height

The visible flames above a fire source trace out the space where combustion reactions are occurring. Typically, the lower part of the flaming region appears fairly steady in luminosity, while the upper part appears to be intermittent. The flame height is generally defined as the height at which the flame is observed at or above that height 50% of the time. The plume relationships depend on the flame height. The models of the flame height are part of the plume models.

$$H_f = 0.230Q^{\frac{2}{5}} - 1.02 \ \mathrm{D} \qquad \text{(A.3)}$$

where

H_f = the mean flame height (m)

Q = the total heat output of a fire (kW)

D = the diameter of the fire source (m), or the effective diameter such that

$$D = \sqrt{\frac{4A_{eq}}{\pi}}$$

Limitation of Equation 5.3

Equation A.3 is a purely empirical correlation from a wide range of experiments. The relationship is valid when $Q^{2/5}$ / D has a value between 7 and 700. The flame height relations have not been tested outside these ranges.

Equivalent Area of Fire

$$A_{eq} = \frac{Q}{q} \tag{A.4}$$

where

Aeq = the equivalent area of the fire (m^2)

Q = the total heat output of a fire (kW)

q = the rate of heat release per unit area (kW/m^2)

For fuel controlled fires, the value of q is taken as 500 kW/m^2

Total Heat Release Rate

The total heat release rate Q, is the total heat output from a fire and is the product from the heat of combustion and mass release rate of combustibles.

Convective Heat Release Rate

The proportion of the total heat release rate that is in the smoke plume varies with the type of combustible material. Based on CIBSE TM19, it is estimated that one third of the total heat output is emitted from flame. Hence, the fire plume carries two thirds of the total heat output to the smoke layer and is referred to as the convective heat release rate, Q_c.

$$Q_c = \frac{Q}{1.5} \tag{A.5}$$

Smoke Extraction Rate

After ignition, the fire plume carries fire products diluted in entrained air to the ceiling. A layer of diluted fire products, or smoke, forms under the ceiling, which thickens and generally becomes hotter with time. The fire environment is intimately tired to the behaviour of this layer, which in turn, depends to a major extent on the mass flow rate of the plume into the layer.

The mass flow rate of smoke at a particular elevation in a fire plume is nearly completely attributable to air entrained by the plume at lower elevations. The mass flow contributed by the fire source itself is insignificant in comparison.

Extensive measurements of mass flow rates in plumes have been found to fit theoretical predictions based on the plume relation. Two prediction relationships are used, one pertaining to the essentially non-reacting plume extending above a limiting elevation, and one pertaining to the reacting, flaming region at an elevation lower than a limiting elevation. The limiting elevation is an elevation in the plume, which corresponds closely to the mean flame height; specifically it is defined as the elevation in the plume where the temperature difference between the centre-line of the plume and the ambient is equal to 500K.

The mean flame height replaces the limiting elevation defined above.

(a) The non-reacting plume case is applicable when the flame height H_f, is less than the smoke clear height y (ie. $H_f \leq y$)

(b) The reacting plume would then be applicable when the flame height H_f, is greater than the smoke clear height y (ie. $H_f > y$)

Flame Height Lower Than Smoke Clear Height

For $H_f \leq y$ and normal atmospheric conditions, the predictions for mass flow rate in the plume, M_1, is :

$$M_1 = 0.071 Q_c^{\frac{1}{3}} \; (y - y_0)^{\frac{5}{3}} \qquad (H_f \leq y) \qquad \text{(A.6)}$$

Flame Height Greater Than Smoke Clear Height

For $H_f > y$ and normal atmospheric conditions, the predictions for mass flow rate in the plume, M_2, is :

$$M_2 = \frac{0.0054 \; Q_c \; y}{0.166 \; Q_c \; \frac{2}{5} + y_0} \qquad (H_f > y) \qquad \text{(A.7)}$$

Equation A.6 and A.7, Q_c is the convective part of the total heat release rate of a fire.

Limitation of Equation A.6 and A.7

The following limitations apply to Equation A.6 and A.7:

Equation A.6 and A.7 are limited to fire sources, which do not have substantial deep-seated combustion. In addition, Equation A.7 is limited to pool fires or horizontal-surface fires. Equation A.7 particularly becomes inaccurate for the fire sources with substantial deep-seated combustion. If there is deep-seated combustion, then the virtual origin y_0 in Equation A.7 is set to zero, and:

$$M_2 = 0.033 y Q_c^{\frac{3}{5}} \qquad (H_f > y) \qquad (A.8)$$

Limitations to the flame height are also applicable to Equations A.6 and Equation A.7. That is, the above relationships are only valid when $Q^{2/5}$ / D has a value between 7 and 700.

Temperature Rise in Plume

The convective heat carried by the smoke plume will heat up the air entrained into the plume. From energy conservation, it will become:

$$Q_c = M C_p \Delta T \qquad (A.9)$$

where

M = the smoke production rate or entrained air flow rate (kg/s),

which is equal to M_1 or M_2 whichever is applicable

Cp = the specific heat capacity of air or smoke

(Cp = 1.02 kJ/kg.K at 1 atmosphere, temperature between 0^0C and 300^0C)

ΔT is the rise of the plume temperature over the ambient temperature (K)

Thus,

$$\Delta T = \frac{Q_c}{MC_p} = \frac{Q}{1.5MC_p} \qquad \text{(A.10)}$$

Limitation of Equation A.10

Equation A.10 calculates the plume temperature at the ceiling directly over the fire source and is used in the method to calculate the temperature of the entire smoke layer. Equation A.10 is conservative for the work contained as it will over-estimate the average temperature of the smoke layer by ignoring the heat losses when smoke spreads across the ceiling.

Smoke Production Rates and their Relationship

The volume of smoke depends on the mass of smoke production and the temperature of the smoke. From the universal gas law:

$$\frac{P_v}{T} = \frac{P_0 v_0}{T_0} \qquad \text{(A.11)}$$

where

P = Pressure

T = Temperature and

v = Specific volume of air or smoke

The subscription $_0$ denotes the value at the standard or ambient conditions

$P = P_0$

$v = 1/\rho$

$v_0 = 1/\rho_0$

Therefore,

$$\frac{v}{T} = \frac{v_0}{T_0} \qquad \text{(A.12)}$$

and

$$\frac{1}{\rho} = \frac{T}{T_0}\frac{1}{\rho_0} = \frac{T_0 + \Delta T}{T_0}\frac{1}{\rho} = \left(1 + \frac{\Delta T}{T_0} \right)\frac{1}{\rho_0}$$

It therefore follows that the volume of smoke can be expressed as:

$$V = \frac{M}{\rho} = M\left(1 + \frac{\Delta T}{T_0}\right)\frac{1}{\rho_0} = \frac{M}{\rho_0} + \frac{M\Delta T}{T_0\rho_0} = \frac{M}{\rho_0} + \frac{Q}{1.5\rho_0 T_0 C_p}$$

$$V = \frac{M}{\rho_0} + \frac{Q}{1.5\rho_0\ T_0 C_p} \tag{A.13}$$

Limitation of Equation A.12

The limitation of Equation A.10 is also applicable to Equation A.12. Since Equation A.10 over-estimates the average temperature of the smoke layer, Equation A.12 over-estimates the volume of smoke produced, and thus will lead to a conservative calculation of the smoke extract rate.

Critical Mass Extraction Rates

The extraction rate of smoke from a given extract point can affect the efficiency of the system. The maximum extraction rate before non smoke-laden air is drawn up through the smoke layer (ie. The plug hole effect) depends on the smoke layer depth with respect to the extract point and temperature. An empirical correction has been developed by the Fire Research Station and has been incorporated into CIBSE TM19. Equation A.13, derived from these sources, predicts the critical mass extraction rate at one extraction point in order to avoid plug holing.

$$M_{crit} = \beta \left(\frac{g d^5 T_0 \Delta T}{(\Delta T + T_0)^2} \right)^{0.5} \qquad \text{(A.14)}$$

where

β = a constant

d = smoke depth (m) in the reservoir, which is defined as a distance from the centerline of the smoke extraction inlet to the bottom of the smoke layer.

β=2.0 where an extraction point is near a wall

β=2.8 where the extraction point is distant from a wall

To be conservative, the value of β is sometimes taken as 2.0 in the calculation

Number of Extraction Points

The minimum number of the extraction points can therefore be calculated from Equation A.14 as below:

$$N = \frac{M}{M_{crit}} \qquad \text{(A.15)}$$

where

N = the number of extract points

M = the Smoke Mass Production / Extraction Rate

The Summary of Smoke Control Equations is shown below:

Symbol	Description	Equation
y_0	Virtual origin	$y_0 = 0.083xQ^{\frac{2}{5}} - 1.02D$
D	Diameter of fire source	$\mathrm{D} = \sqrt{\frac{4A_{eq}}{\pi}}$
H_f	Mean flame height	$H_f = 0.230Q^{\frac{2}{5}} - 1.02\ \mathrm{D}$
A_{eq}	Equivalent area of the fire	$A_{eq} = \frac{Q}{q}$
Q_c	Convective heat release rate	$Q_c = \frac{Q}{1.5}$
M_1	Mass flow rate in the plume	$M_1 = 0.071Q_c^{\frac{1}{3}}\ (y - y_0)^{\frac{5}{3}}$ ($H_f \leq y$)
M_2	Mass flow rate in the plume	$M_2 = \frac{0.0054\ Q_c\ y}{0.166\ Q_c\ \frac{2}{5} + y_0}$ ($H_f > y$)
ΔT	Rise of the plume temperature	$\Delta T = \frac{Q_c}{MC_p} = \frac{Q}{1.5MC_p}$
V	Smoke production rate	$\mathrm{V} = \frac{M}{\rho_0} + \frac{Q}{1.5\rho_0\ T_0C_p}$
M_{crit}	Critical mass extraction rate	$M_{crit} = \beta\ \left(\frac{gd^5T_0\Delta T}{(\Delta T + T_0)^2} \right)^{0.5}$

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