THE HONG KONG POLYTECHNIC UNIVERSITY

DEPARTMENT OF BUILDING SERVICES ENGINEERING

Aspects on fire safety for the retail areas at the airport terminal in Hong Kong

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A thesis submitted in partial fulfillment of the requirements for the Degree of Doctor of Philosophy

November 2006

CERTIFICATE OF ORIGINALITY

I hereby declare that this thesis is my own work and that, to the best of my knowledge and belief, it reproduces no material previously published or written nor material which has been accepted for the award of any other degree or diploma, except where due acknowledgement has been made in the text.

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Abstract

The abstract for the thesis titled "Aspects on fire safety for the retail areas at the airport terminal in Hong Kong" submitted by NG MIN YEE CANDY in 2006 for the degree of Doctor of Philosophy at The Hong Kong Polytechnic University.

The Hong Kong airport terminal is a new architectural design with the utilization of the large halls with unobstructed spaces and high ceiling in the retail areas of the departure hall and arrival hall. Life safety and unobstructed operation of the airport terminal have to be ensured. The design target is not to have a fire. Even when a fire occurs, the fire risk should be low such that the occupants can be evacuated safely from the building. Therefore, detailed investigations on the fire risks in the retail and catering areas, evacuation of occupants, and heat release rate given by the combustibles inside the retail areas are carried out to develop the fire safety strategies for the airport terminal.

The thesis starts with a review on the fire safety provisions of the airport terminal. Engineering approach is used to carry out an intensive assessment on the safety of the airport terminal. Development of the fire safety strategies should be based on clearly defined goals and objectives. After defining the goals and objectives, the fire risks of the retail areas and Chinese restaurant are identified so as to determine the fire safety strategies for the airport terminal.

Models are applied for the fire risk analysis. Fire risks of the retail shops and Chinese restaurant inside the airport terminal are investigated. In order to get a

reference from other shopping malls and Chinese restaurants, some shops of a local shopping mall and a Chinese restaurant are selected for fire risk analysis using the software FRAME and simulation of the probable fire environments by the two-layer zone model FIREWIND. Fire safety management is then identified for the retail areas and Chinese restaurant of the airport terminal.

The fire risk analysis illustrated that life safety of the occupants is a matter of concern inside the airport terminal. Therefore, evacuation of occupants inside the halls and retail areas of the departure level and arrival level is investigated. As the occupant loading is important for the evacuation simulations, there are queries on using the data specified in the codes in designing the occupant loading of the airport terminal. A field survey on the transient occupant loading of the departure level and arrival level is carried out to justify the maximum allowed loadings specified in the design codes and standards.

After the verification of the occupant loading inside the airport terminal, different time components, such as evacuation time, Required Safe Egress Time (RSET) and Available Safe Egress Time (ASET), involved in the evacuation process are illustrated. Simulations under the normal and fire conditions are then carried out for the departure and arrival levels, using the computer software buildingEXODUS and SIMULEX. Total evacuation time (TET) of occupants in each scenario of the arrival level is simulated to identify the number of occupants who can escape within the targeted TET and hence illustrate the worst scenario for the occupants.

Simulation results of buildingEXODUS showed that the long TET of occupants is due to the waiting time incurred in the jamming condition. A Waiting Time Index (WTI) is derived to recognize the severity of congestion occurred in a building. Four scenarios of the retail areas and departure hall are taken as examples to illustrate the WTI and hence the jamming condition occurred around the staircases and exits of the departure level. Measures for reducing the waiting time of occupants are also identified.

Further, the heat release rate of combustibles inside the retail areas is determined to assess the fire environment of occupants. Full-scale burning tests are conducted for investigating the possible heat release rate of combustibles such as T-shirts and compact discs. The resultant heat release rates by burning those combustibles under pre-flashover and post-flashover conditions are studied. Reduction of the heat release rate of those combustibles by the sprinkler system and water mist fire suppression system are also determined.

According to the fire risk analysis, protections for property and business activities are adequate. However, the provision of life safety should be improved with respect to the results of the evacuation simulations. Workable fire safety strategies, i.e. passive building construction for fire safety, active fire services installation, fire safety management and control of risk factors, should be proposed to enhance the fire safety of the airport terminal to a higher standard. Utilization of modern fire services installation, i.e. deluge system, drencher system and WMFSS, is a good solution for improving the fire safety of the airport terminal.

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Chapter 1 : Introduction

The new airport in Hong Kong was opened on 6 July 1998 [Hong Kong Airport Internet Homepage 2006]. It is one of the biggest passenger terminals in the world, which has the gloss floor area of approximately 450000 m^2 and contains a wide variety of occupancies and functional areas [Lam 1995]. The airport needs to handle an annual capacity of 35 million passengers and 1.4 x 10^6 tons of air cargoes [Oakervee 1994]. Therefore, it is very important to ensure the life safety and operation.

An accidental fire happened before the airport was in use. That fire was upgraded to a ‘third-alarm fire’ quickly. The flame and smoke were also spread quickly throughout the building. Luckily, no one was injured [Hong Kong Standards 1998a; Sing Tao Daily 1998; South China Morning Post 1998]. It is very obvious that the target of the terminal building is not to have a fire, and even when a fire occurs, it has to be confined without spreading out to limit the number of occupants being affected and the losses incurred.

Airport handles many passengers and visitors. When there is a fire, it is characterized by a large number of people at risk. Frequent users, e.g. staff, are expected to recognize the nearest escape route easily and evacuate. However, the infrequent users, such as the passengers and visitors, might have difficulties in locating the escape routes as they are unfamiliar with the building [British Standards Institution 1997b].

Apart from property losses of the retail shops caused by heat, smoke and water from sprinklers, time loss in replacing the key fire-damaged objects would also be considered. Perturbation to the business of many retail shops inside the airport terminal will affect the public image and cause a huge amount of monetary losses [British Standards Institution 1999]. On the other hand, interruption to the airport services should be avoided. Even an accidental fire occurs inside the retail areas, the airport should be able to operate.

Since the airport is in a leading role among airports in the world, the fire safety is very important and should be further improved. As the airport terminal cannot be complied the local codes [Buildings Department Hong Kong 1995, 1996a, b; Fire Services Department Hong Kong Special Administrative Region 1998], it was designed in accordance with the performance based fire engineering approach and the construction cost of the passenger terminal building was very expensive and worth $ 10.1 billion [Hong Kong Standards 1998b].

As mentioned before, a ‘third-alarm fire’ happened prior to the airport was in use [Hong Kong Standards 1998a; Sing Tao Daily 1998; South China Morning Post 1998]. The fire fighters could not extinguish the fire in a short time such that the flame and smoke spread quickly throughout the building. The fire design of the building is not released to the public by the Airport Authority. The adequacy of the fire safety provision for the airport terminal is in doubt. Therefore, the fire safety of the airport terminal is studied in Chapters 2 to 11, so as to raise the public awareness and provide recommendations for the Airport Authority for carrying out the upgrading of the fire safety provision for the airport terminal.

Based on the research studies regarding the fire risk analysis and occurrence of flashover in Chapters 4 & 5, occupant loading in Chapter 6, evacuation time of occupants in Chapters 7 & 8, heat release rate of the combustibles in a retail shop in Chapter 9 and the utilization of modern systems in Chapter 11, the following is the designated guidance for the design of airport terminal for building designers to follow:

1. Prior to proceeding any design, the goals and objectives shall be clearly defined for developing several design options for the airport terminal.

2. The design criteria for the departure level and arrival level of the airport terminal shall be developed.

    - Minimization of the fire risks for the occupants, property and business activities inside the halls and retail areas.
    - Prevention of the occurrence of flashover in the retail shops.
    - Restraint on the fire load for the retail areas and dining areas.
    - Limitation on the number of occupants exposed to fire.
    - Protection of the integrity of structure elements and fire spread from the fire zone to adjacent zones.
    - Shortening of the evacuation time of occupants in the halls and retail areas.
    - Effectiveness of the fire services installation to be utilized in the halls and retail areas.

3. Identification of the fire scenarios and assessment methods, such as the zone and field models, field surveys and full-scale burning tests, for the analysis of those design options.

4. Based on the results of the fire scenarios, the most appropriate design option for the airport terminal shall be selected.

5. The implementation of the fire safety strategies for the airport terminal, i.e. passive building construction, fire services installation, fire safety management and control of risk factors such as passenger loading and fire load density.

The fire protection 'cabin' concept [Law 1990] is applied in the retail areas. The areas are partitioned into many small shops. Each shop is covered by a ceiling to provide the sprinkler system and smoke reservoir. Dedicated smoke extraction facilities through "smoke vents" are installed in each shop to avoid smoke flowing to open areas [Beever 1991]. However, the considerations associated with the cabin, such as probability of getting flashover and its consequences [Chow 1997a, b; Chow and Kui 2000], possibility of the cabin to become big hot object [Chow 1997b] and effectiveness of the sprinkler system [Chow and Kui 2000] should be paid heed to. Any failure in the sprinkler system might lead a big burning object which entrains large amount of air to give a high quantity of smoke and endanger lives of occupants.

In order to identify the risks of occupants and monetary losses, a detailed investigation on the fire hazard and performance evaluation of different fire protection systems was carried out in Chapter 2 to understand the potential fire hazard. Fire safety goals and objectives based on the engineering approach were defined initially for the airport terminal in Chapter 3. The simulations of the probable fire environments and detailed fire risk analysis were also carried out for the retail areas and dining areas in Chapters 4 & 5 and Tables 4.1 to 4.4 & 5.1 to 5.2.

Field studies on airport terminal were carried out to illustrate the transient occupant loadings of the departure level and arrival level in Chapter 6. Different time concepts of occupants involved in evacuation were recognized in Appendix C. Evacuation simulations were performed in the departure and arrival levels to determine the Total Evacuation Time (TET) of occupants under the normal and fire conditions in Chapters 7 & 8. A Waiting Time Index (WTI) was also derived in Chapter 8 to reflect the severity of jamming occurred inside the departure level of the airport terminal.

Fire behaviour, particular the heat release rates of the combustibles in a shop were assessed in Chapter 9. Full-scale burning tests were conducted for identifying the possible heat release rate of combustibles, such as the T-shirts and CDs in the retail areas. Resultant heat release rate by burning those combustibles under the pre-flashover and post-flashover condition was studied.

Many useful data were measured from the zone models, evacuation models and full scale burning tests. The results were useful for Airport Authority to set up the relevant fire safety strategies of airport terminal as mentioned in Chapter 10. Last but not the least, feasibility of utilizing modern fire services installations such as the deluge system, drencher system and water mist fire suppression system was also analyzed in the departure hall, arrival hall and retail areas in Chapter 11, so as to recognize the suitability for utilizing those systems in the terminal building.

1.1 Proposed research work

The objectives of this research project are to study the fire safety aspects of airport terminal by means of zone models, full-scale burning tests and evacuation models. Its scope of works is limited to the Hong Kong Airport Terminal only. Owing to the security reasons, the restricted areas of the airport terminal are not available for carrying out the site survey and study. The study is confined to the retail areas of the non-restricted areas of airport terminal. It does not include any aircraft accidents or fire caused by aircraft crashing. The amount of combustibles, i.e. fire load, to be carried by passengers is not taken into account. On the other hand, arson fire, terrorist fire or fire caused by natural disaster, e.g. earthquake, will also not be considered.

As the architectural features of the Hong Kong Airport Terminal is similar to the airport terminals in other countries, e.g. Brussels Airport, the study can be extended to other airport terminals in other places of the world in future research. The research hypothesis and contributions in this study are illustrated as follows:

Research hypothesis

The departure hall and arrival hall of the airport terminal are constructed with large compartments. It is questionable of whether the fire will be confined without spreading out. As an accidental 'third-alarm fire' happened before the airport was in use had indicated that the flame and smoke would spread quickly throughout the building and endanger the occupants [Hong Kong Standards 1998a; Sing Tao Daily 1998; South China Morning Post 1998], the following research hypothesis has been made:

- The utilization of the cabin concept inside the airport terminal is not adequate for the protection of life, property and business continuation in case of a fire.

A series of research regarding the risk analysis, field surveys for the occupant loading, evacuation modelling and full scale burning tests will be carried out to verify the hypothesis.

Contributions

- Performance-based design procedures for Hong Kong in Chapter 3 are based on various standards to propose, such as British Standard, Australian

Code, NFPA (National Fire Protection Association) and SFPE (Society of Fire Protection Engineers) Handbooks, for implementing the Engineering Performance Based Fire Codes in Hong Kong.

- Fire environment encountered in the retail shops at the airport terminal is identified by the zone model FIREWIND version 3.5 in Chapter 4 to illustrate the minimum heat release rate for flashover under different ventilation conditions.
- Fire risks of wine shop, bookshop, department store and Chinese restaurant at the airport terminal are realized by FRAME 2.0 in Chapters 4 & 5 for investigating the risks of occupants, property losses and business interruption in the retail areas.
- Occupant loading of the airport terminal [Buildings Department Hong Kong 1996b] is verified by the field survey in Chapter 6 for justifying the maximum allowed loadings specified in the codes to be utilized for designing the occupant loading of the airport terminal.
- Total evacuation time (TET) of occupants in the departure level and arrival level is recognized by the evacuation models buildingEXODUS and SIMULEX in Chapters 7 & 8 for identifying the evacuation condition of occupants under the fire and normal conditions.
- The Waiting Time Index (WTI) of the airport terminal is developed with respect to the response time (RT), motion time (MT) and cumulative waiting time (CWT) in Chapter 8 for measuring the evacuation efficiency and hence assessing the evacuation design.

- Heat release rate of combustibles for retail shops, e.g. T-shirts and CDs, are determined by the full-scale burning tests in Chapter 9 for assessing the real fire environment of occupants inside the airport terminal.
- Fire safety strategies in Chapter 10 are based on the passive building construction, active fire services installation, fire safety management and control of risk factors to develop for improving the fire safety of the airport terminal.
- Feasibility of utilizing the modern systems, i.e. deluge system, drencher system and water mist fire suppression system (WMFSS), in the departure hall, arrival hall and retail areas of the airport terminal is determined by several case studies in Chapter 11 for recognizing the suitability of the utilization of those systems in the terminal building.

1.2 Outline of thesis

A flowchart showing the organization of this study was shown in Figure 1.1.

Geometry and fire safety provisions of airport terminal were reviewed and reported in Chapter 2. Several considerations of the airport terminal, such as architectural features, occupant loading, fire load density, life safety of the fire fighting personnel, property and disturbance of the normal operation, were illustrated in Chapter 2.3. Cabin concept utilized in the retail areas was also highlighted.

Goals and fire safety objectives were established in Chapter 3. The approaches on the fire safety objectives of different countries were studied in Chapter 3.3 and Table 3.1. The fire safety objectives regarding the prevention of the collapse of structure and fire spread to adjoining buildings, means of escape for occupants, life safety of the fire fighting personnel, protection of the building and other valuable contents, minimum perturbation on the airport operation and the environmental protection were also developed for the airport terminal in Chapter 3.5.

Fire safety aspects of the retail areas inside the non-restricted areas of the airport terminal were discussed in Chapter 4. Fire safety requirements for small shops in Hong Kong were reviewed in Chapter 4.1. The fire environment of the retail areas was studied in Chapter 4.2. Fire risk of the selected shops in the terminal building was recognized in Chapter 4.4. Apart from the analysis carried out in the airport terminal, fire safety aspects of the retail shops in a local shopping mall were also investigated in Chapter 4.5 for taking as a reference. The fire safety management was then developed for the retail areas of the airport terminal in Chapter 4.6.

General features and licensing requirements of the Chinese restaurants in Hong Kong were illustrated in Chapter 5. Points of concern for the Chinese restaurants were raised in Chapter 5.2. Fire risk of the Chinese restaurant in the airport terminal was analyzed by the software FRAME in Chapter 5.3 and Tables 5.1 to 5.2. Study on the fire environment of a local Chinese restaurant was reported in Chapter 5.4 for taking as a reference. The fire safety provisions and proper fire safety management were then proposed for the Chinese restaurant inside the airport terminal in Chapters 5.5 & 5.6.

The importance of the occupant loading in affecting the evacuation of occupants was recognized in Chapter 6. Field surveys on the occupant loading were conducted in the departure and arrival levels of the airport terminal during the normal operating days and peak seasons in Chapter 6.2. Methodology for conducting the surveys was pointed out in Chapter 6.3. The results were also reported in Chapter 6.4 to justify the accuracy of the design figures specified in the local codes and other overseas standards.

Evacuation models buildingEXODUS and SIMULEX were described in Chapter 7. Evacuation scenarios were designed for the arrival level of the airport terminal in Chapter 7.2. The design objectives and hazard parameters of the fire scenario were pointed out in Chapters 7.3 & 7.4. Results of those scenarios were illustrated in Chapter 7.5. Discussion of the results was highlighted in Chapter 7.6. Recommendations on the evacuation design were then provided for the airport terminal in Chapter 7.7.

The concept of waiting time was pointed out in Chapter 8. A Waiting Time Index (WTI) was developed in Chapter 8.2 to quantify the extent of congestion occurred in a building. Numerical simulations were carried out in the departure level of the airport terminal in Chapter 8.3. The WTI determined was used to reflect the severity of jamming occurred inside the departure level in Chapter 8.4. Measures on the reduction of waiting time were also illustrated in Chapter 8.5.

Full-scale burning tests carried out for the retail shops of the airport terminal were described in Chapter 9. Results of the tests for boutique and CD slips were reported and discussed in Chapters 9.2 & 9.3. Performance of the fire suppression systems such as sprinkler system and water mist fire suppression system on the combustibles was demonstrated. Consequences of the flashover fires for those tests were also studied in Chapter 9.4.

Fire safety strategies of the airport terminal were reported in Chapter 10. The possible fire risks and heat release rate for small retail shops were identified in Chapters 10.1 & 10.2. Four parts on the strategies, i.e. passive building construction, fire services installation, fire safety management and control of risk factors were then proposed for the airport terminal in Chapters 10.3 to 10.7.

Utilization of the modern systems, i.e. deluge system, drencher system and water mist fire suppression system (WMFSS) was studied in Chapter 11. Activation principle and extinguishing mechanisms of deluge system and drencher system were highlighted in Chapters 11.1 & 11.2. A comparison of the deluge system with the automatic sprinkler system was made in Chapter 11.3. Suppression mechanisms of the WMFSS were reported in Chapter 11.4. Case studies of those systems on the aircraft hanger and retail shops of the airport terminal were also illustrated in Chapters 11.7 & 11.8.

The thesis ended in Chapter 12 with a conclusion. Recommendations on the future research work in related areas were made in Chapter 12.7.

Chapter 2 : The airport terminal

General geometrical features, such as geometrical shapes, dimensions, facilities and services were surveyed in airport terminal. The airport is divided into restricted areas and non-restricted areas [Airport Authority Hong Kong 2001a, b]. Fire safety provisions were assessed in the non-restricted areas of the airport. Retail areas are identified as places with high fire risk. Due to functional and architectural reasons, there are some constraints on designing fire safety systems such as installation of conventional sprinkler system in those areas. Therefore, fire protection "cabin" concept was applied to the terminal building [Law 1990]. This is a good design for not providing long smoke extraction system and utilizing the space intelligently. However, several points should be considered in this design.

2.1 Geometry of the airport terminal

Dimensions of the airport terminal building are shown in Table 2.1 [Airport Authority Hong Kong 2001a, b]. The passenger terminal is of 1.2 km long and has a total area of 550,000 m^2. Non-restricted areas, such as arrival hall, departure hall and retail areas were investigated. Geometrical shapes of the arrival level (levels 5) and departure levels (level 6 and 7) are illustrated in Figures 2.1 to 2.3.

A spacious, bright, airy and comfortable environment is provided. Facilities and services provided are:

- 48 airbridge-served gates for wide-bodied aircraft and 27 remote stands.
- 2.5 km of moving walkways, a driverless train system operating along the 750 m long central concourse.
- A baggage handling system with 12 reclaim carousels to handle 19,200 pieces of luggage per hour.
- Ramps, travelators, lifts and escalators give horizontal transportation of passengers moving from one level to another.
- Simple and clear signposting throughout. Sensible provision has been made for the aged and those with disabilities.

There are eight levels in the terminal building with retail areas located in non-restricted areas (Landside) at level 5 and 7. The other retail zones are in the restricted areas (Airside) of level 7 and the whole level 6. Layout of the retail areas in non-restricted areas is shown in Figure 2.4. Level 8 is a non-restricted mezzanine floor where the whole zone is used for restaurants.

2.2 Fire safety provisions

Passive building design for fire safety is followed those required by the government Buildings Department (BD), i.e. the codes on Means of Access (MoA) [Buildings Department Hong Kong 1995], Means of Escape (MoE) [Buildings Department Hong Kong 1996a] and Fire Resisting Construction (FRC) [Buildings Department Hong Kong 1996b]. Active fire protection systems are provided according to the local codes on fire services installation (FSI) [Fire Services Department Hong Kong Special Administrative Region 1998] issued by the government Fire Services Department (FSD). The active and passive protection measures of terminal building were summarised in Table 2.2, following the argument by Malhotra [1987].

Concerning passive building design, emergency exits were observed in level 5 and 7 with provisions complied with the local MoE and MoA codes. The restaurant areas in level 8 and facade of the terminal building are constructed with curtain wall to give an aesthetic effect. Glass with special treatment is installed to avoid breaking into small pieces in case of fire. Though it cannot be judged whether the constructions are of adequate fire resistance period (FRP), it is believed that local FRC code was complied.

For the FSI of the airport terminal, the following was surveyed by the candidate during the field survey:

- Smoke detectors are not found in the departure hall and arrival hall but are discovered at the ceiling of the retail shops in level 7 and the main entrance of level 5. Fire detectors are located at the check-in counters.

- Sprinkler heads are found in the retail shops of level 5 and 7.

- Fire hydrants, hose reels, break-glass alarms are found near the access with 'EXIT' signs, and at the two ends of each group of check-in counters.

- Public announce systems are installed to assist the flow of people in case of an emergency.

2.3 Considerations of the airport terminal

In Hong Kong, buildings are divided into compartments by different elements of construction such as walls and floors to inhibit the spread of fire. The number of compartments subdivided in each storey of a building depends on the areas of the storey, amount of fuel and also the function of that particular floor. Prescriptive codes [Buildings Department Hong Kong 1996a] require that the space volume of a single compartment should not exceed the maximum allowed volume of 28000 m^3. In each compartment, the amount of fire load density is restricted to 1135 MJm^{-2} [Fire Services Department Hong Kong Special Administrative Region 1998] to prevent too many combustible materials stored in a place.

If the compartment volume and designed fire load exceed the specified requirements, static or dynamic smoke extraction system is required to be installed as indicated in FSI Code [Fire Services Department Hong Kong Special Administrative Region 1998]. There is no specific figure on designing the smoke extraction systems, but normally the extraction rates is about 6 to 10 air changes per hour of the space volume [Fire Services Department Hong Kong Special Administrative Region 1998]. It is not easy to provide such a large extraction flow rate for a big atrium, such as the departure hall and arrival hall of the airport terminal.

On the other hand, installation of the conventional sprinkler system on high ceiling is another concern [Chow 1996]. As a smoke plume rises above a fire, it entrains ambient air from the surroundings, cooling and diluting the combustion products [Fire Code Reform 1996]. For high ceiling, this effect is more serious, and the gases reaching ceiling level are significantly cooler than the smoke at lower ceiling heights. As a result, it takes longer for the sensitive element of a sprinkler to heat up to its operating temperature and the fire has to be larger to cause sprinkler operation. If the fire is larger and sprinklers activate, the spray is not effective in penetrating the fire plume and reaching the burning surface to bring about extinguishment or fire control. Therefore, the conventional wet pipe sprinkler system is ineffective against the fire growth and spread on high ceiling.

The temperature and velocity of the fire gases rising from a fire and spreading across a ceiling can be calculated by using a set of correlations developed by Alpert [1972] based on the theoretical analysis and comprehensive experiments carried out on the fires of steady heat release rate. The experiments were carried out under large unconfined ceilings with fire sizes ranged from 0.7 MW to 98 MW and ceiling heights varied from 4.6 to 15.5 m. It is concluded that sprinklers will not be effective at heights greater than 10 m above the floor level where combustibles are located, though it is increased to 15 m when fast response sprinklers are used.

As a result, considerations are given to the design, such as means of escape, sprinkler system and smoke extraction system. Attention should be paid on the followings things of the airport terminal:

- Architectural features

Large halls were utilized in level 5 and 7 due to the aesthetic and functional reasons, for examples, the desirable sense of space with large and unobstructed spaces, ease of access of occupants and clear instruction of escape routes leading to exits. Retail shops are provided inside those areas as illustrated in Figure 2.4. On the other hand, the building facade and restaurant areas in level 8 are constructed with curtain wall. Extensive use of glass is used to give an aesthetic effect.

As the ceiling height of those halls is very high and space volume is very large, putting conventional sprinkler heads at the roof and designing smoke extraction system for the entire space are not suitable as the spray from the sprinkler is unlikely to penetrate the fire plume and the smoke generated is difficult to reach the ceiling. The fire protection "cabin" concept [Beever 1991; Law 1990] was utilized in the retail areas of non-restricted regions inside the arrival hall and departure hall of the airport terminal.

Retail shops are considered as areas with high fire load and prevention of fire spread and smoke flow is very important. The cabin concept provides a high level of fire protection by means of smoke detection, sprinklers and smoke extraction system. Each shop is covered by a ceiling to provide sprinkler system and smoke reservoir. [Beever 1991]. When a fire occurs inside a cabin, it would be detected by smoke detectors. Smoke curtain at its boundaries is activated to create a smoke reservoir to prevent smoke flowing to outside. Smoke extraction system would be activated automatically to extract the smoke simultaneously [Lam 1995]. Sprinklers can also be actuated by the interaction between smoke and the glass bulb of sprinklers.

The concept is a good design for providing smoke extraction system and utilized the space intelligently. However, the following points should be considered [Chow 2002a]:

- Chance to have flashover and its consequences

  Fire load density inside the cabin would be high as it is used as a retail shop. The false ceiling would give strong downward radiative heat flux when it is heated up to high temperatures. As sufficient amount of fresh air can be obtained by the open cabin, a larger heat release rate is required for flashover to occur. The ventilation opening required to acquire the flashover under different height of opening will be studied in Chapter 4.2 and Table 4.1.

- Possibility for the cabin to become a big hot object

  When flashover occurs, the cabin can become a large heat source. A fire in the retail shop would become a big burning object with large air entrainment rate to give a very high smoke production rate. The smoke flowing out of the cabin would be entrained back to the thermal plume and more area is filled with smoke [Chow 1997b].

- Effectiveness of the sprinkler system

The effectiveness of the sprinkler system is a function of the system reliability and efficacy, which is the product of the two parameters [Fire Code Reform 1998]. The system reliability is represented by a number between 0 and 1, which gives the probability that the system will operate, while the system efficacy can be represented by a number between 0 and 1, which gives the level of performance of the system when compared with the level presumed by a standard or code.

The sprinklers can reduce the temperature inside the cabin, thus minimized the heat flux and chance for flashover to occur. Activation of the sprinkler system would extract heat in the burning cabin. However, any delay in activation will result in a higher heat release rate [Chow 1996]. If the sprinkler system fails to actuate, a big burning object entraining large amount of air and providing large quantity of smoke will be resulted. Huge amount of smoke will also flow out of the cabin when the smoke extraction system does not work properly [Klote and Milke 2002].

On the other hand, the amount of steam produced by the activation of the sprinklers should be paid heed to the evacuation of occupants [Chow 1996]. Dragging effect of water droplets would further pull the smoke layer down and affect the visibility of occupants. Therefore, the occupants/ users inside the cabin should be able to escape before the operation of the sprinkler system.

- Occupant loading

The occupancy of the airport terminal can be classified as the occupant loading which is similar to that of the assembly halls, auditoria and stadia without seating or with movable seating, i.e. 0.5 m^2/person, as illustrated in the local codes [Buildings Department Hong Kong 1996b]. The airport terminal is always crowded with occupants for departure or waiting for the arrival of passengers as illustrated in Figures 6.3 & 6.4. In case of fire, the escape route would be blocked due to the evacuation of the large number of occupants. On the other hand, the occupants would also be subject to uncertainty in locating the escape route, as they may not be familiar with the environment.

- Fire load density

Fire load density is the amount of combustibles stored in a given area, which is expressed as the heat potential per unit floor area (in kJm^{-2}) as illustrated in Equation (4.8) [British Standards Institution 1987]. Fire load can be classified into fixed and movable. The fixed fire load includes the structure such as wall, roof, floor and windows, while the movable fire load includes the goods and stocks inside a shop and the baggage carried by occupants. On the fixed fire load, it depends on the combustibles used in the building materials [Beever 1991]. Not much combustibles, such as the timber product, are utilized in the airport terminal.

As most of the occupants will keep the large or heavy luggage in the baggage storage area, the effect of luggage on the movement of people is not considered. Although the baggage would increase the fire load of airport terminal, fire load density inside the terminal building would not be largely increased as the hand baggage of passengers would only pose very low fire load density [Beever 1991]. The amount of luggage, which is expressed in equivalent heat H_{per} (in J), will be controlled by the management. It is unlikely to exceed the upper limit of fire load density as indicated in local fire codes [Fire Services Department Hong Kong Special Administrative Region 1998], i.e. 1135 MJm^{-2}. Fire load density is related to H_{per} and the maximum number of passengers N_{max} allowed to stay inside the airport terminal [Fire Services Department Hong Kong Special Administrative Region 1998], i.e.

$$\text{FLD} = \frac{N_{max} \cdot H_{per}}{\text{Floor area}} << 1135\,\text{MJm}^{-2} \qquad \dots (2.1)$$

However, the fire load density in the retail areas would be high. Therefore, they are grouped together and protected separately from the other parts of building. A detailed investigation illustrated in Table 4.2 on the amount of combustibles present in the shops is necessary to recognize the fire risk of occupants, property and business interruption in the retail areas of the airport terminal.

- Life safety of the fire fighting personnel

  Apart from users, life safety of fire fighting personnel is also important. In case of fire, the fire fighting personnel will access the airport terminal to extinguish the fire when the occupants are escaped from the building simultaneously. Owing to the architectural features such as large halls with cabin design, flame and smoke would spread easily if the cabin is not ‘enclosed’. Life safety of fire fighting personnel is a matter of great concern when fire occurs inside the airport terminal.

- Property

  According to the local codes [Buildings Department Hong Kong 1996a], the element of construction within each compartment and every compartment wall or floor shall have a specific FRP. In case of a fire, the retail shop may become a large heat source for the airport terminal when flashover occurs. Once the FRP of the structure of terminal building is exceeded, the building may be entirely burnt down and collapsed. A great economic loss will be incurred.

- Disturbance to normal operation

  Unlike a normal business, the operation of the airport terminal cannot be easily stopped as many flights will be departed and arrived within a short time period. Immediate interruption of the airport services would be dangerous. Therefore, fire safety measures for continuing the operation during the outbreak of fire should be considered for the airport terminal.

For the fire safety design of the airport terminal in other places of the world, a number of airport terminals, e.g. Brussels Airport, have been reviewed. Cabin design is also utilized in the Brussels Airport [Goetynck 1996], with the compartments divided into three types:

- Principal fire compartment

  The stairways and the staircases forming the vertical escape route are the principal compartments. When a fire occurs, the staircases will be automatically pressurized to prevent the spread of fire.

- Fire compartment

  The area of the fire compartments is limited to 2500 m^2 and each compartment is constructed with an FRP of 2 hours. Communication between compartments is realized by lobbies with an FRP of 1 hour. For large public areas, the fire compartments are installed with natural and/or smoke extraction systems.

- Smoke compartment

  In the event of fire, smoke screens will be automatically descended, forming the smoke compartments. The area of each compartment is also restricted to 2500 m^2. To avoid the risk of smoke logging and reduction in visibility of the fire services at low level, the length of the compartments is limited to 80 m.

The studies relating to mass transit terminals have been reviewed [Chow 2002d]. Fire safety strategy of the mass transit terminals is taken as a reference for the implementation of the fire safety strategy for the HK airport terminal. On the other hand, there are studies on the general performance of airport terminals [e.g. Lam 1995], e.g. baggage handling, automated people mover and destination cooled vehicles, which may include fire safety aspect. The fire load of the baggage handling for sorting of incoming and outgoing baggage is regarded as moveable fire loads [Beever 1995]. Therefore, the combustibles comprised in the baggage handling shall be paid attention to. On the other hand, the automated people mover and destination cooled vehicles shall be prohibited to be utilized for evacuation in case of a fire.

2.4 Conclusion

General features of the terminal building in the airport were reported in Chapter 2.1. Fire safety provisions, both passive building design and active fire protection system, indicated that sufficient fire safety is provided inside the airport terminal.

Care should be taken for not keeping excessive amount of combustibles inside the retail areas. On the other hand, several things of the airport terminal should be considered carefully. For example, the retail areas are protected by 'cabin concept' [Law 1990; Beever 1991]. This is a good design in utilizing more hall space without installing an excessively large smoke extraction system. However, the following things should be concerned:

- Likelihood of flashover in the cabin and its consequences of occurrence [Chow 1997b].
- The 'cabin' becomes a big heat source to give large production rate of smoke [Chow 1997b].
- Effectiveness of the sprinkler system [Chow 1996].

Chapter 3 : Review on fire safety requirement in airport terminal

Development of the fire safety strategies should be based on clearly defined goals. They should be stated clearly in order to provide a safe, cost-effective and sustainable building. The main fire safety objectives and methods applied to achieve these in different countries, such as USA, UK, New Zealand, Japan and Hong Kong, were surveyed in Chapter 3.3 and Table 3.1. After identifying the fire safety goals and objectives, it is necessary to identify fire scenarios for further analysis in Chapters 4 & 5 and thus develop the fire safety strategies for the building in Chapter 10.

The research works of Chow [1997a, b] and Lam [1995] relating to the fire protection design in airport terminal buildings have been reviewed in Chapter 2.3. Fire safety design of buildings in Hong Kong follows prescriptive codes and standards. Passive building construction (PBC) is considered by Buildings Department (BD) [e.g. Buildings Department 1996a, 1996b]. Active fire protection system known as Fire Services Installation (FSI) is taken care by Fire Services Department (FSD) [Fire Services Department Hong Kong Special Administrative Region 1998]. A pictorial view on the application procedures to these two departments is reviewed by Chow [2002b] as in Figure 3.1.

Buildings with new architectural features would have difficulties to comply those codes. As there are no engineering performance-based fire codes (EPBFC) at the moment, ‘Fire engineering approach’ (FEA) is accepted on PBC in this transition period [Buildings Department Hong Kong Special Administrative Region 1998].

This approach is similar to performance-based design (PBD) on applying fire safety engineering to a building when the design cannot comply the prescriptive codes. In PBD, the level of fire safety performance should be met by building materials, assemblies, systems, components and construction methods so as to co-ordinate with the goals and objectives. According to PNAP 204 [Buildings Department Hong Kong Special Administrative Region 1998], various standards are available describing FEA to design such as British Standard, Australian Code, NFPA (National Fire Protection Association) and SFPE (Society of Fire Protection Engineer) Handbooks. Therefore, the PBD procedures are proposed to follow SFPE [Society of Fire Protection Engineers 2000], but further modified to suit the local requirements [e.g. Chow 2002b]. The proposed performance-based design procedures for fire safety in Hong Kong would be shown in Figure 3.2.

3.1 Establishment of goals

Prior to proceeding any design, goals must be clearly defined so as to develop a complete fire safety objective. The establishment of goals is appropriate to the particular design aspect [British Standards Institution 1999]. In general, the definition is interpreted slightly different in different standards. Goals are desired fire safety outcome expressed in qualitative terms [e.g. Society of Fire Protection Engineers 2000]. It is a non-specific outcome to be achieved and measured on a qualitative basis [Coté 2000]. They are non-controversial statements that reflect a common aim [Meacham 1998]. As stated in other literature [British Standards Institution 1999], goals are fundamental elements that can enable the full development of methodology with appropriate calculation methods and data, and apply in a cost-effective way to the design and management of buildings.

To develop a fire protection system, a certain level of fire safety performance should be fulfilled. Defining the goals is the first step in evaluating the design based on the performance-based fire safety design method. Four basic fire safety goals should be clearly defined for developing the fire safety objectives [e.g. Meacham 1998; Society of Fire Protection Engineers 2000]:

- Goals on protection of life

  Detailed items for ensuring the safety of occupants, firefighters and others that entered the building are:

  - The occupants are able to remain in place, evacuate to other parts of building (e.g. refuge areas) or totally evacuate from the building without being subject to hazardous (e.g. injury or incapacitating) or untenable conditions due to the loss of visibility, exposure to toxic and irritant products, or exposure to heat.

  - For people with disabilities, special arrangements should be made to assist the wheelchair bound persons or others with mobility problems without relying on the assistance from fire brigade.

- Firefighters are able to operate safely to assist evacuation, effect rescue and prevent extensive spread of fire.

- Collapse of structure should not endanger people (including firefighters). As the failure of structural elements can threaten the life of individuals inside the building when the evacuation is not completed, adequate FRP should be provided.

• Goals on protection of property

Property protection objectives can be stated in terms of monetary losses or spatial extent of damage from fire and its effects. The damage can also be caused by water for firefighting from the fire suppression system such as sprinklers or the activities of occupants and firefighters.

• Goals on protection of mission (continuity of operations)

The effects of fire on the continuation of a business can be substantial. Consideration should be given to the limitation of damage to the structure and fabric of building; building's contents; ongoing viability of the business and public image of the business.

- Goals on protection of environment from the unwanted effects of fire and fire control

  There are increasing concerns on protecting the environment. The use of chlorofluorocarbons has the contribution to fire resistance [Carlos 1990]. However, the release of hazardous materials from chlorofluorocarbons would have an environmental impact when the fire is conflagrated to other buildings.

  Consideration should, therefore, be given to the limitation of:

  - The effects of fire on adjacent buildings or facilities.
  - The release of hazardous materials to the environment, such as smoke, toxic gases and corrosive gas evolution.

3.2 Fire safety objectives

After established the goals, the objectives should be ascertained so as to provide a detailed aspect to achieve the goals. As defined in NFPA 101 [Coté 2000], objective is a requirement that needs to be met to achieve a goal. It can be decided quantitatively and achieved through the attainment of a skill or knowledge [National Fire Protection Association 2002a]. Objective is the criteria that subdivided from each goal to develop a complete fire safety strategy [e.g. Bukowski and Babrauskas 1994]. Establishment of objectives should be based on the following criteria:

- Stakeholder objective or client loss objective

  Those are specified by the clients on how much they can tolerate the loss, and afford to pay on fire safety, such as the investment on initial installation and the consequent operation, and maintenance costs.

- Functional objective

  The functional objective describes how a building or its systems can meet the fire safety goals. For example, the structure integrity, compartmentation and active/passive fire protection system.

- Design objective or performance requirement

  To integrate with the functional objective or stakeholder objective in the system design, the design objective should be specified such that the building and its system can maintain the life safety of staff and occupants

Examples on fire safety objectives [British Standards Institution 1999], such as the life safety of staff, occupants and fire fighting personnel, property protection, minimum disturbance to normal operation and environmental concern, would be illustrated in Appendix A.

3.3 Approaches on fire safety objectives of different countries

Fire safety objectives are slightly different in different standards or codes of practice. Approaches in different countries, i.e. USA, UK, New Zealand, Japan and Hong Kong, are summarized in Table 3.1.

- Approach in USA

  Performance-based fire safety design methods were established in order to develop a suitable design for the building to meet the fire safety goals and performance criteria. It is an engineering approach based on the fulfillment of fire safety goals, objectives and design objectives; evaluation of fire initiation, growth and development by deterministic and probability procedures; the physical and chemical properties of fire and fire effluents; and quantitative assessment of the design method against goals and objectives [e.g., Meacham 1998; National Fire Protection Association 1995b; Society of Fire Protection Engineers 2000; Tubbs 1999].

  In the PBD, goals and objectives are the foundations for designing fire protection systems [National Fire Protection Association 1995b; Society of Fire Protection Engineers 2000]. In order to allow flexibility and further innovation, alternative approaches can be applied in order to meet the intent of the performance-based requirements.

- Approach in UK

The prescriptive codes of fire safety in UK have been evolved to performance-based approach in 1985. The Approved Document B is to make the fire safety engineers aware of the relevant issues and the needs to examine the fire safety systems. It provides a framework for developing a rational methodology for achieving the fire safety of buildings. The fire engineering approach was introduced by the guidance document, which is developed by a multi-disciplined expert group [e.g. British Standards Institution 1997b]. It is a guideline for designers and others involved in devising and approving the fire safety systems for buildings.

The fire engineering approach of UK [e.g., British Standards Institution 1999, 2004; Chartered Institution of Building Services Engineers 1997; Lillicrap 2000] is similar to that in USA. Although USA and UK utilize the PBD method, the standards of UK provide more suggestions for the considerations needed in the objectives. As a result, the guidelines of UK standards are much detailed and systematic for engineers to follow when the PBD method is utilized.

- Approach in New Zealand

Performance-type building code is mandated in 1991 [e.g., Buchanan 1998, 1999]. It is concerned with legal aspects of implementation. However, the code contains no provisions for property protection whereas it is a matter between building owner and insurance company. Therefore, the insurance companies will impose additional requirements to the building owners for protecting their property.

- Approach in Japan

The evolution of the performance-based fire code of Japan is quite early [Bukowski and Tanaka 1991; Koya *et al.* 1998; Tanaka 1989, 1991, 1994a, b, 1995, 1998, 1999, 2000; Tanaka *et al.* 1996]. A performance-based method which can be applied to establish equivalency to the Building Standard Law of Japan was published in 1988. The goals are established, and availability of the proposed design should be evaluated to determine whether it meets the established goals or not. Other than limiting the damage to the third parties, such as occupants in the adjacent buildings, the protection of property is not concerned.

The nature of the Article 38 of the Building Standard Law is to provide a guideline for the engineers to develop an innovative ‘Design System for Building Fire Safety’, while the 1998 amendments are the supplements for the Building Standard and Law of Japan for developing the systems for enhancing the building safety in case of a fire.

- Approach in Hong Kong,

  The local fire codes [Buildings Department Hong Kong 1995, 1996a, b] are the guidelines for the design of buildings in Hong Kong. However, parts of the codes were outdated and referred to old buildings with several storeys only [e.g., Chow 1999, 2002b, 2004; Chow *et al.* 2006; Wong and Chow 1997]. Therefore, equivalent approach and various standard documents such as British Standards [e.g. British Standards Institution 2004], NFPA Fire Protection and SFPE Handbook [National Fire Protection Association 1992; Society of Fire Protection Engineers and National Fire Protection Association 1995] shall be considered for designing the systems for different types of building. This alternative approach is always accepted by the Building Authority with reasonable justification of the protection of people and property from fire.

3.4 Fire safety strategies

'Fire safety', as explained in NFPA 550 [National Fire Protection Association 1995a], means the measures taken to protect the exposed so as to satisfy a specified objective. 'Strategy' can be understood by following definitions:

- As defined in NFPA 1051 [National Fire Protection Association 2002b], 'strategy' is the general plan or direction selected to accomplish incident objectives.

- It is defined in NFPA 1035 [National Fire Protection Association 2000d] as a comprehensive organization plan that is designed to eliminate or mitigate risks that endanger lives, health, property, or the environment through public fire and life safety education programs.
- It is a goal or a set of goals in NFPA 1561 [National Fire Protection Association 2002c] to manage incident scene operations from which an incident action plan is developed.

Combining the definitions of the two terms 'fire safety' and 'strategy', 'fire safety strategy' can be given. There are some definitions of 'fire safety strategy' in the literatures [CIB Report 2001; Capital Management Guideline 2001]:

- Following CIB W014 [CIB Report 2001], fire safety strategy is a coherent and purposeful arrangement of fire protection and developed fire prevention measures which attain specified fire safety objectives.
- Fire safety strategy [Capital Management Guideline 2001] is regarded as a combination of physical and human measures/factors including maintenance and management systems which have been specified to achieve nominated fire risk management objectives.

Therefore, fire safety strategy can be understood [e.g. Barker 2000] as the basic documentation of the planned approach to achieve the prescribed fire safety objectives. It should be clearly identified for a particular building or organizations so as to achieve a good fire safety standard. More quantified approaches [Law 1994] are necessary for buildings with special architectural features, e.g. airport terminal.

3.5 Fire safety objectives of the airport terminal

- Prevention of the collapse of structure

  To avoid imposing any hazards on the occupants or fire fighting personnel, glass with special treatment should be installed inside the airport terminal to avoid breaking into small pieces in case of fire. Other structural elements should be constructed with a FRP such that escape and extinguishment can be carried out safely. The use of fire retardants on the construction and finishing materials is also an essential element in strengthening the fire resistance of the structure, so as to withstand high temperatures when a fire occurs.

- Prevention of fire spread to adjoining buildings

  Although most buildings are far away from the airport terminal, there is a hotel and car park at about 100 m away from the left of the terminal building. To prevent the conflagration of fire and smoke spread to adjoining buildings, the following safety measures should be taken:

  - Smoke extraction system should be activated efficiently for the clearance of smoke from covered area.

- The access should not be obstructed such that the firefighters can reach the fire area quickly and extinguish the fire before conflagration.
- A fire requires fuel, oxygen and heat to sustain. Removal any one of them would extinguish the fire. Therefore, the system for firefighting is very important in retarding the fire growth and spread.

- Means of escape for the occupants

Various types of occupants are stayed inside the airport terminal. Frequent users, e.g. staff, are expected to have a good knowledge of the nearest and alternative escape routes in case of fire. They should evacuate efficiently, particularly if subjected to emergency training and evacuation drills. For occupants who are infrequent users, such as passengers and visitors, it is most likely that they will leave by the route they entered the building and rely on the signs. As the effectiveness of public announcement system may affect people's reaction, efficient public announce systems should be installed such that emergency announcements can be made to control the flow of people when there is a fire [Ng and Chow 2001a; Beard and Weinspach 1996].

Points to note are:

- Sea rescue:

  As the airport terminal was reclaimed from sea, the terminal buildings are close to the sea. In the event of an aircraft crashing into the sea or terminal buildings, the sea rescue unit will assist the occupants to escape by providing a vessel equivalent to a 250-300 passenger capacity jet catamaran with inflatable rafts, which can accommodate 250 to 300 passengers.

- Travel distance:

  Dimensions of the public access areas are huge. The departure hall and entrance hall are 31350 m^2 and 13200 m^2 respectively as shown in Figures 2.1 & 2.3. Evacuation pattern has to be considered carefully. In order to minimize the travel distance of the occupants, the staircases and direct exits should be distributed uniformly throughout the area. Apart from evenly distributing the exits, providing clear exit signs, more direct exits and staircases of adequate width are the other means to minimize the travel distance.

- Smoke filling process:

  It would take a long time to fill up the huge space with smoke and also difficult to have flashover in the hall unless there is an enormous fire. However, psychological effects, such as the ‘negative’ panic behaviour, i.e. behavioral inaction, and responsiveness of occupants have to be considered under crowded conditions. Another Lan Kwai Fong tragedy [South China Morning Post 1993] may happen if there is no control on the number of occupants.

There are some occupants who are physically disabled. Therefore, the escape routes should be wide enough to avoid jamming of wheelchairs. The movement of disabled occupants would be significantly influenced by their disability and the building elements such as doors, ramps and the stairs. Some of them are immobile and have to rely entirely on the actions of others to effect their evacuation.

- Life safety of the fire fighting personnel

When people escape from the airport terminal, fire fighters will enter the building simultaneously to extinguish the fire. The width of escape routes is important as jamming would be occurred between the occupants and fire fighters if the routes are too narrow. The narrowed escape routes will affect the evacuation of occupants and also the rescue procedures of the fire fighting personnel. Separate means of access should be provided for the fire fighters to enter the airport terminal.

- Protection of the building and other valuable contents

The cost of the whole airport is $ 155 billion, while the cost for the 1.3 km long passenger terminal building of areas 515000 m^2 is $ 10.1 billion [Hong Kong Standards 1998b]. In case of fire, it would not only damage the structure of the terminals, but also incur great economic losses in Hong Kong. The interruption of the airport transport services, business of the retail shops, refurbishment cost and replacement cost would also pose enormous losses.

Therefore, property protection is very important in limiting the huge amount of monetary losses.

Excessive water damage is also an important point to consider. The water discharged by fire suppression system (e.g. sprinklers) or actions of occupants and fire fighters will cause serious damages on retail shops. Fire suppression system should be selected carefully to minimize the loss due to the water damage and provide a better fire safety inside the retail shops.

- Minimum perturbation on the airport operation

As the airport needs 24 hours to operate daily for different flights to land, immediate interruption of the airport service is dangerous. For example, the passengers of the flight would be in jeopardy if the plane does not have enough fuel to go to other countries. Therefore, it is important to limit the fire area by controlling the contents and separating the flammable materials inside the terminal building.

- Environmental protection

Smoke released from fires contains gases, liquids and small particulate matters. It will be dispersed from fire by convective flow and contaminate the building contents and environment. Therefore, the fire should be extinguished as soon as possible to prevent the generation of huge amount of smoke. Some fire-extinguishing agents, such as halon, will deplete the ozone layer and allow harmful ultraviolet radiation to reach the Earth's surface. It is better to use other ingredients such as carbon dioxide to act as the fire suppressing agent, which has no or lower ozone depletion potential.

3.6 Conclusion

Fire safety goals and objectives were discussed in Chapters 3.1 & 3.2. There are four basic fire safety goals for developing the fire safety objectives, i.e. protection of life, protection of property, protection of mission and protection of environment from unwanted effects of fire and fire control. The approaches on fire safety objectives used in different countries, i.e. USA, New Zealand, Japan and Hong Kong, were reviewed in Chapter 3.3. There is no EPBFC in Hong Kong at this moment. An engineering approach [Buildings Department 1998] for designing the suitable fire safety system in different types of buildings is allowed if those buildings fail to comply the prescriptive codes.

Clarifying the fire safety objectives is very important for implementing the EPBFC in Hong Kong. An example is taken on recognizing the fire safety objectives of the airport terminal in Chapter 3.5. The fire safety objectives are preventing the collapse of structure, preventing the fire spread to adjoining buildings, providing the means of escape for the occupants, ensuring the life safety of fire fighting personnel, protecting the building and other valuable contents, minimize the perturbation on the airport operation and protecting the environment.

Chapter 4 : Retail areas of the airport terminal

Fire safety aspects of the retail areas in airport terminal were discussed. Fire safety requirements for small shops [British Standards Institution 1985] were reviewed in Chapter 4.1. Retail shops were inspected with their minimum heat release rate for flashover in Chapter 4.2. A design fire was suggested for studying the probable fire environment in 41 retail shops, with the two-layer zone model HotLayer of FIREWIND version 3.5 [FIREWIND version 3.5 2000] as the simulating tool. Four retail shops were selected for further fire risk analysis with the software FRAME version 2.0 [Smet 1998] in Chapter 4.4. Key parameters such as the fire load density of each shop were estimated in Table 4.2.

In order to get a reference from other retail shops, fire safety aspects of a local shopping mall were investigated in Chapter 4.5. The mall is always crowded with people, especially teenagers. Access in the corridors is very difficult. If a fire occurs, the lives of people will be put in jeopardy. A study on such a shopping mall was carried out to identify the potential fire hazard in Table 4.4. The hazards of building and its contents, life safety and the activities being carried out would be studied. Fire safety management would then be developed for the retail areas of the airport terminal in Chapter 4.6.

4.1 Fire safety requirements for small shops

In case of fire, the primary escaping stage is to locate the escape route from the shop to shop exit [British Standards Institution 1991; Home Office and Scottish

Home and Health Department 1971]. For small shops of floor area less than 280 m^2, escape in one direction is accepted [British Standards Institution 1991]. However, consideration on reducing the number of exits, certain restrictions and management arrangements should be implemented to the shops [Hume 1997]:

- Capacity of the shop should be controlled by the shops' management to restrict the number of people entering the shop simultaneously. The shop should be in a single occupancy.

- The shop should be uncompartmented to maintain a clear vision, such that the exit can be clearly seen, and emergency exit can be easily accessible to occupants. In order to distinguish the exit signs at a very long distance, the signs shall be installed above doorways or suspended along escape routes and illuminated green "exit" sign in English and Chinese displayed on a white background. The luminaries can be single or double faces, box type or plate type as required.

- The shop should not be used for sale or storage of flammable liquids or materials.

- The shop cannot be served by a single staircase.

In fact, small shops in Hong Kong are quite different from those in foreign countries. Occupancy of small shops inside a mall is not mentioned. The usable floor area per person for shopping areas in basement, G/F, 1/F and 2/F is 3 m^2

per person, while it is 4.5 m^2 per person for upper floors [Buildings Department Hong Kong 1996b]. However, small shops in the densely populated districts such as Mong Kok may not satisfy this requirement, especially during weekends and public holidays.

Statistical data show that the fire risk for occupants in shopping malls is not significant [Fire Code Reform Research Program 1998]. Majority of these fires are small fires, which can be extinguished before spreading to other areas. There are no sleeping risks as in a hotel and low rate of deadness is expected [British Standards Institution 1999]. However, the increase in fire load will result in a higher fire hazard. As rental price of the retail shops in Hong Kong is expensive, goods are always stocked up and stored inside the false ceiling. This would lead to a high fire load density in the shops and constitute a rapid fire growth rate.

4.2 Minimum heat release rate of retail areas

Dimensions of the retail shops with opening areas are listed in Table 4.1. The two-layer zone model HotLayer in the fire engineering calculator FIREWIND version 3.5 [FIREWIND version 3.5 2000] was used to simulate the fire environment. The FIREWIND version 3.5 is an user-friendly computer software package with various programs for different aspects of fire technology and fire protection science. It is a zone model in which multiple design fires and entry files can be saved. As the values of the heat release rate for two compartments can be generated simultaneously and summarized in a neat table by the model, it is similar to CFAST and taken as an example to simulate the fire environment.

On the other hand, the first version of FDS was officially released in 2000, in which most of the validation work has not been carried out to evaluate the model's ability until the Version 4 of FDS released in 2004 [McGrattan 2004]. During this study period, FDS is not properly developed and has not undergone a comprehensive validation for the prediction of the transport of heat and exhaust products from a fire through an enclosure. Therefore, FDS is also not utilized to determine the fire situation in this study.

A 1.3 MW design fire, which is similar to burning a soft toy mountain [Garrad and Smith 1999] or a computer workstation [National Fire Protection Association 2000b], was taken in the case. The heat release rate Q_c (in kW) at time t (in s) is given by:

$$Q_c = \begin{cases} 1000\left(\dfrac{t}{300}\right)^2 & t \le 342\text{s} \\ 1300 & t > 342\text{s} \end{cases} \qquad \ldots (4.1)$$

Heat release rate curve was measured experimentally in a sprinkler calorimeter. Results for the cases with and without the application of sprinklers are shown in Figure 4.1. The fire will be decayed at 1520 s if there is no sprinkler system. Its heat release rate will be around 1.3 MW at 342 s. With the activation of the sprinklers, the heat release rate given by the fire can be decreased tremendously within a short time period. At 342 s, the heat release rate becomes very small, i.e. 0.02 MW. The design fire gives a good description on the probable fire size in a small retail shop before flashover, with the heat release rate of 1.3 MW as the cut-off value at 342 s.

When the door gap is small, a fire will become ventilation controlled. Heat release rate under this regime is controlled by the rate of air inflow. According to the method of Thomas [Society of Fire Protection Engineers and National Fire Protection Association 2002], the mass flow rate of air inflow m_a' [Society of Fire Protection Engineers and National Fire Protection Association 2002] can be approximated by the area of opening A_v (in m^2), height of the opening H_v (in m) and width W_v (in m) as:

$$m_a' \approx 0.5 A_v \sqrt{H_v} \qquad \ldots (4.2)$$

where

$$A_v = W_v \times H_v \qquad \ldots (4.3)$$

The term $A_v \sqrt{H_v}$ is known as the ventilation factor. An expression for the net radiative and convective heat transfer from the upper gas layer q_{loss} (in kW) can be expressed by the total area of the compartment-enclosing surfaces A_t (in m^2), convective heat transfer coefficient h_e (in $kWm^{-2}K^{-1}$), temperature of the upper gas layer T_g (in K), temperature of the upper walls T_w (in K), temperature of the floor T_{flr} (in K), emissivity of the hot gas ε, and Stefan-Boltzmann constant σ (5.67×10^{-11} $kWm^{-2}K^{-4}$) as:

$$q_{loss} \approx h_e\left(T_g - T_w\right)\frac{A_t}{2} + \varepsilon\sigma\left(2T_g{}^4 - T_w{}^4 - T_{flr}{}^4\right)\frac{A_t}{6} \qquad \ldots (4.4)$$

From the experimental data developed by Thomas [Society of Fire Protection Engineers and National Fire Protection Association 2002], an average for q_{loss} of $7.8A_t$ is determined. Using an upper layer temperature of 577 ^oC for flashover criterion and specific heat of gas of 1.26 $kJkg^{-1}K^{-1}$, the minimum heat release rate for flashover Q_{fm} (in kW) in a shop of length L (in m), width W (in m), height H (in m), A_t (in m^2) and ventilation factor of $A_v\sqrt{H_v}$ under a ventilation controlled fire can be calculated by using the equation proposed by Thomas [1981]:

$$\begin{aligned} Q_{fm} &= 7.8A_t + 378A_v\sqrt{H_v} \\ &= 7.8A_t + 756m_a' \qquad \ldots (4.5) \end{aligned}$$

where

$$A_t = 2\left[LW + (L+W)H\right] - A_v \qquad \ldots (4.6)$$

The applicability of those equations is based on the assumption that oxygen will not be completely consumed inside the retail shop. Q_{fm} can be understood as the minimum heat release rate for flashover to be occurred in a shop. Two ventilation conditions on opening the door with H_v 2.3 m and closing the door with a gap of H_v 0.01 m are considered in calculating Q_{fm}. Flashover will occur in a retail shop if the heat release rate is higher than Q_{fm}. Bigger shops, such as Shop 19, require a 14.4 MW fire for flashover when all the doors are opened. If the door is closed with a gap of only 0.01 m high, Q_{fm} is reduced to 1.4 MW.

Q_{fm} of 41 retail shops at levels 5 and 7 of the airport terminal are shown in Figure 4.2. The ventilation condition V2 of H_v 0.01 m has been utilized for identifying the maximum smoke layer temperature T_s and minimum smoke layer interface height y_s during the steady burning period 342 to 1200 s as illustrated in Figure 4.1. The results of T_s and y_s are shown in Table 4.1. Note that the smoke would fill up most of the shop but the smoke layer temperature is not too high. Simulated values of the maximum smoke layer temperature vary from 179 to 462°C. All are lower than the flashover temperature of 500 to 600°C.

For a small ventilation opening in an enclosed retail shop, a very low heat release rate given out by the fire can induce the flashover to occur easily as the criterion for constituting the flashover is low. However, it does not mean that flashover must occur. The oxygen content will be limited in an enclosed shop. Once the oxygen is consumed, flashover will not occur and fire is likely to be extinguished.

If the consumption of air inside the shop is taken into account, the width of the ventilation opening W_v^* (in m) required to acquire the minimum heat release rate for flashover to occur in those shops will be different with W_v. Considering the heat release per unit mass of air consumed in combustion is 3 $MWkg^{-1}$ (air) [Drysdale 1999] and the opening air flow rate for a fire room at uniform temperature is $0.5\,A_v\sqrt{H_v}$ kgs^{-1}, the maximum possible heat release rate in the fire room is $1.5\,A_v\sqrt{H_v}$ MW. W_v^* can be expressed in terms of $A_v\sqrt{H_v}$ as:

$$W_v^* = \frac{A_v\sqrt{H_v}}{H_v^{3/2}} \qquad \ldots (4.7)$$

Taking Shop 19 as an example, Q_{fm} is 1.4 MW if the door is closed with a gap of H_v 0.01 m [Society of Fire Protection Engineers and National Fire Protection Association 2002]. The ventilation factor $A_v\sqrt{H_v}$ required 0.93 for getting 1.4 MW for flashover. For H_v of 0.01 m, W_v^* is equal to 933.33 m for Shop 19. When H_v is 2.3 m, the ventilation factor $A_v\sqrt{H_v}$ becomes 9.6 for getting 14.4 MW for flashover. W_v^* under this ventilation condition is 2.75 m.

The values of W_v^* under the two ventilation conditions V1 and V2 for the 41 retail shops at levels 5 and 7 are illustrated in Figure 4.2. Flashover will be occurred when the door is opened. When the retail shops are enclosed with a gap of 0.01 m, it is unlikely for flashover to occur. However, a fire will be given out when it has consumed the air in the retail shop. In case of fire, the key of whether the retail shop will become a big burning object for the departure hall and arrival hall depends on the materials utilized for the doors of the retail shops. For a door with an adequate FRP, fire will be confined inside the shop though flashover has occurred. Otherwise, the door will be cracked and fire spread to the departure hall and arrival hall of the airport terminal.

4.3 Assessment of fire risks

The fire load of the mechanical plant rooms is considered to be low, such that the fire risk generated is comparatively lower than the places with high fire load, i.e. retail areas and restaurants, as illustrated in Tables 4.2 & 5.1. Retail areas and restaurants can be understood as places with high fire risk as the fire load of the shops and restaurants, i.e. heat release rate given out by the combustibles, are generally high and thus the occupants are under a great risk in case of fire [Chow 2001d; Chow and Ng 2004; Chow and Ng 2002; Ng 2006].

Design fires of 1.3 MW and 5MW, which are similar to burning a soft toy mountain [Garrad and Smith 1999] and a Chinese restaurant in Macau [Ng 2006], are normally utilized as the fire size for the retail shops and restaurants for assessing the fire environment of occupants under the fire condition [Chow and Ng 2004; Chow *et al.* 2002]. Therefore, a detailed investigation on the risks of occupants, property losses and business interruption in retail areas is necessary. This can be achieved by using the software Fire Risk Assessment Method for Engineering (FRAME) version 2.0 to assess the fire risks for those aspects in Chapter 4.4.

The software FRAME [Smet 1998, 1999] is a proving tool for "performance based" fire protection designs. It shows the influence of protective measures and can be used to compare the overall equilibrium of an engineered solution to a Code imposed protection level. It is a fire risk evaluation method that is aimed to manage the risk and reflect the severity, as characterized by the worst possible case. Probability or frequency of occurrence and a magnitude of consequent loss or severity can typify all risks. The higher the frequency rate, the less acceptable. Calculation method of FRAME was originally based on Gretener-method [Smet 1998, 1999]. This method gives an empirical calculation for fire risk assessment of buildings with property, occupants and activities. A systematic evaluation of all major influence factors is given, and the result is a set of values expressing from 0 to 1 [Smet 1998, 1999]. It can be used to study the initial risk, potential risk, acceptance level and protection level in order to determine the fire risk and whether there is an equilibrium between risk and protection for retail shops [Chow and Ng 2004] in Chapter 4.4. Fire risks for small shops and their contents (R), occupants (R_1) and business activities (R_2) would be calculated in Tables 4.3 & 4.4.

The software is applicable to HK situation as there is no default value in the parameters for calculating the initial risk, potential risk, acceptance level, protection level and fire risk of occupants, property and business activities in . All the data can be assigned by the users in the model. Parameters involved in FRAME are shown in Appendix B.

4.4 Fire risk of the selected shops

As the retail shops consist of a large amount of combustibles and will incur a high fire load density and hence a high fire risk of occupants, property losses and business interruption, the fire risk constituted by the retail shops and is taken as an example for illustrating the risk of occupants, property losses and business interruption in the retail areas in Table 4.3. On the other hand, the fire risk of the departure hall and arrival hall will also be included in Table 4.3 so as to assess the safety of occupants, properties and business continuity in the departure level and arrival level.

Four retail shops in the airport terminal were selected in Table 4.2 for further fire risk analysis arbitrarily:

- Shop 4 at arrival level sells books, toiletries, food and bags.
- Shop 17 at departure level sells wines and cigarettes.
- Shop 18 at departure level sells watches, clothes, bags and food.
- Shop 32 at departure level sells books, magazines and stationery.

Dimensions, occupancy, area of static smoke vents, number of accessible directions and vertical distance from the access level of each shop are determined and shown in Table 4.2. The fire load density FLD (MJm^{-2}) can be expressed in terms of the calorific value of contents Q_{ca} (MJ/kg), weight of contents W_{ei} (kg) and floor area of the shop A_f (m^2) as:

$$FLD = \frac{Q_{ca} \times W_{ei}}{A_f} \qquad \ldots (4.8)$$

The heat of combustion will be taken as 18 MJ/kg [Drysdale 1999] in converting the unit to equivalent weight of wood for the combustibles in the retail shops.

Total fire load density, both mobile and fixed, of four shops will be estimated and summarized in Table 4.2.

According to the survey carried out in the 4 retail shops at the airport terminals, the shops which are selling watches, clothes, bags and food, i.e. shop number 18, and books, magazines and stationary, i.e. shop number 32, had a high fire load density due to the goods were placed vertically upward and fully packed inside the shops.

As good housekeeping of the retail shops can reduce the number of combustibles inside the shops and hence reduce the chances of fire and blockage of escape routes, the fire load intensity inside the retail shop shall be monitored by the facility management team of the Airport Authority. A checklist with respect to the heat release rate given out by different types of combustibles and the maximum amount of combustibles allowed to be placed inside the retail shop shall be designed by the team and coordinated with the shop management.

The shop management shall obtain the prior approval of the facility management team of the Airport Authority for the new products to be sold in the retail shop. Periodical and random checking regarding the total fire load density inside each retail shop at the departure level and arrival level of the airport terminals shall be carried out. Warnings will be given to those retail shops when its fire load density exceeds the restricted total fire load density, i.e. 1135 MJm^{-2} [Fire Services Department Hong Kong Special Administrative Region 1998].

When the volume of the combustible materials in a specific shop exceeds the restricted total fire load density of 1135 MJm^{-2}, the fire safety can be improved by applying upgraded fire engineering systems. Drencher system can be utilized to prevent the heat transfer from the fire zone to the adjacent areas, such that it can replace the smoke curtain installed in the opening of the retail shops. On the other hand, the traditional sprinkler system installed inside the retail shops can be replaced by the water mist fire suppression system (WMFSS) to minimize the inefficiency of the sprinklers when they are covered by goods or used for controlling liquid fires. The feasibility of utilizing the drencher system and WMFSS will be further studied in Chapter 11.

FRAME version 2.0 [Smet 1998] was selected to study the initial risk, potential risk, acceptance level, protection level and fire risk in order to determine whether there is an equilibrium between risk and protection in each retail shop of the airport terminal in Table 4.3. Fire risks R, R_1 and R_2 for the building and its contents, occupants and activities are related to their potential risks P, P_1 and P_2, acceptance levels A, A_1 and A_2, and protection levels D, D_1 and D_2.

- Potential risks

  Results of P, P_1 and P_2 for the retail shops are shown in Table 4.3. From the calculation, P_1 of each shop, departure hall and arrival hall is much higher than P and P_2. More attention should be paid on the protection for occupants in retail shops.

- Acceptance levels

Results of A, A_1 and A_2 for the shops are shown in Table 4.3. Value of A of each shop, departure hall and arrival hall is greater than 1, indicating that the provisions are satisfactory. However, A_1 and A_2 are not satisfactory. Low values of A_1 would pose hazards for occupants.

- Initial risks

Initial risks R_o for the four retail shops, departure hall and arrival hall are shown in Table 4.3. Manual fire fighting equipment is sufficient for shops with R_o less than 1. Fire extinguishers, hydrants and hose heel systems are found everywhere in airport terminal. Sprinklers are also installed in each shop to ensure adequate level of protection.

- Protection levels

As shown in Table 4.3, values of D, D_1 and D_2 for the four retail shops, departure hall and arrival hall are the same. Values of D_1 are the lowest among D, D_1 and D_2. Something should be done on providing a better protection for occupants in the retail shops.

- Fire risks

Fire risk is the quotient of potential risk divided by acceptance level and protection level. It is the possibility value for illustrating the risk of the occupants, building and its contents and activities. For a building with adequate fire protection, R, R_1 and R_2 should be less than 1, thus acquiring an equilibrium between risk and protection. Values of R, R_1 and R_2 for the four retail shops, departure hall and arrival hall are shown in Table 4.3. R and R_2 in each shop, departure hall and arrival hall are below 0.1, indicating that the risk of loss of property and business interruption is small and protection is adequate. However, R_1 is much higher than R and R_2. Although R_1 in each shop and departure hall is below 1, it is higher than 1 in the arrival hall, indicating that the occupants are under a great risk in case of fire.

4.5 Comparison with a local shopping mall

The shopping mall with three levels, i.e. G/F, 1/F and 2/F, located in Mong Kok was investigated. Retail areas of those floors are constituted by a number of small shops. Height of each floor and each shop is 3 m and 2.3 m respectively. A survey was carried out for shops on 2/F. The geometric layout of 2/F is shown in Figure 4.3.

Special features of the shopping mall are:

- Four staircases (P1 to P4) are utilized for escape. Each staircase is protected and accessed from each floor to outside. The fire-resisting door of each staircase is linked to fire alarm and detection system. If the door is pushed, alarm will be sounded and a signal is sent to the Fire Communication Centre of Fire Services Department [Fire Services Department Hong Kong Special Administrative Region 1998].

- Three non-enclosed accommodation staircases (S1 to S3) with 1 m wide are used for access. S1 is ascended to G/F and the other two (S2 and S3) are accessed to 1/F. These staircases are protected by the sprinkler system. However, the staircases are too narrow for occupants to evacuate in case of fire.

- The illumination of exit sign is low. It is difficult for people to locate the escape route, especially for those with disabilities.

- Occupants are travelled by means of escalators and accommodation staircases within the shopping mall. Therefore, the disabled persons can access to G/F only and cannot travel to the upper floors without any assistance.

Most of the small shops in 2/F are selling clothes, soft toys, stationery and CDs. The loss of property would be high in case of fire. If the whole floor of shopping mall is destroyed by fire, the total loss of property would be huge, including the cost for refurbishing the shops and also the loss for disturbing the business in other floors. On the other hand, a very poor public image of the mall will be posed for the loss of occupants' lives, hence affect the desire of people to visit and reduce the profitability of the mall.

Two small shops, labelled as A and B were investigated. These shops are selling soft toys and stationery. Geometry layout of Shop A and B is shown in Figure 4.4. The shops are fully packed with soft toys and stationery, leaving only 2.15 m^2 and 2.69 m^2 in Shop A and B for people to walk in. The plastic bags for packing soft toys are combustible. Though there is no suspensed ceiling inside the shops, a large plastic rack is installed under the ceiling for storing goods. Therefore, the ceiling height is reduced from 2.3 m to 2.1 m. As the goods are close to the high power incandescent lamps, heat emitted from the lamps may ignite the plastic bags. Further, smoking is allowed inside the shopping mall. The chance for igniting those soft toys wrapped with plastic bags is high. If fire is occurred, flame spread rate upon the vertical display items [Drysdale 1999] would be very fast. Fire safety management should be done properly in order to minimize the hazards.

Sprinkler system is installed inside the mall. It can protect the life safety by controlling the conflagration of fire [Malhotra 1987]. As the sprinkler heads are covered by a movable plate, this will affect the thermal sensitivity of the sprinklers. On the other hand, sprinklers were not found inside the shops. It is very dangerous that the occurrence of a drastic fire would give a high hot-layer temperature and heat release rate. Large quantities of smoke produced [Chow 1997a] would not only pose a direct hazard to the lives of occupants [Klote and Milke 2002], but also affect the visibility of the occupants when they are evacuated from the shop [Butcher and Parnell 1979; Chow *et al.* 2001]. Even if sprinklers are installed inside the shops, a lot of goods on the top display shelves would block the discharged water spray from reaching the lower shelves. Goods should be rearranged to match the sprinkler positions.

- Fire risk analysis of the selected shops

  FRAME [Smet 1998, 1999] was applied to determine the fire risk of shops A and B [Chow and Ng 2004] and the whole 2/F of the shopping mall. Fire risks for small shops and their contents (R), occupants (R_1) and business activities (R_2) were calculated and shown in Table 4.4. Although the areas of the shops are small, the evacuation of occupants from the shops is not insignificant as it can give us a reference that the occupants may have difficulties to escape due to the high occupant loading and blockage of stocks. On the other hand, the smoke discharged from a small shop fire will affect the movement of occupants and identify the location of staircases in that floor. Those effects will be accounted in FRAME in order to determine the fire risk of the shopping mall in Table 4.4 when a fire is broken out from a small shop.

  R and R_2 in each shop and 2/F of the mall are below 0.1, suggesting that the risk of property and threat of business activities is small. However, value of

R_1 in each shop and the whole 2/F is higher than 1 in Table 4.4, indicating that occupants are under great risks as those shops will constitute a large fire hazard on them.

- Escape routes

Escape routes are affected by many factors, such as origin of fire, number of people involved in evacuation, structure integrity of building and occupant behaviour [Chow and Ng 2003]. The risks of escape routes during evacuation process can be divided into three parts:

Horizontal transportation:

- Any position inside the shop to the shop exit

  Occupants in small shops should be able to locate the exits easily. However, the shops were full of goods and two sides of the exits were hung with soft toys and stationery, giving an accessible width of only 0.5 m. People cannot leave the shops easily in case of fire. Although the travel distance of occupants from the shop to shop exit is short, problems are created by placing many obstacles inside the shops. FIREWIND version 3.5 [2000] was used to simulate the probable fire environment. Results generated during the steady burning period 342 to 1200 s for Shop A and B are shown in Tables 4.5 and 4.6 respectively. Height of the hot layer in both shops was dropped from 2.3 m to 1.1 m within 60 s.

Q_{fm} for flashover to occur in both shops is 1200 kW for the door openings with height 2.3 m. Flashover is occurred at 360 s for both shops when the smoke layer temperature is higher than the flashover temperature 500 ^{o}C. Occupants are at high risk if they cannot evacuate from the shop timely when a fire occurs.

- Shop exit to staircase

For the horizontal route connecting the shop exit to staircase, it is clear of blockage. The accessible width 2.4 m of the route has fulfilled the legal requirement. Although occupants in Shop A cannot travel horizontally to the nearest staircase, travel distance from the shop exit to staircase is short as illustrated in Figure 4.3. Apart from the nearest path for both shops, there is also an alternative route for people to travel from each shop.

Vertical transportation:

- Staircase to final exit

It is the vertical route of travelling down the staircase to final exit. Access for occupants is not allowed in normal period. A protected lobby is connected to each staircase to minimize the risk of smoke and heat from penetrating into the staircase before occupants leave the building. For occupants who are not familiar with emergency routes and location of protected staircases, normal access routes and accommodation staircases will become the preferred escape routes in case of fire. There is a risk that the width of accommodation staircases is not adequate to allow large number of occupants to evacuate simultaneously. Although the staircases are protected by sprinklers, smoke and heat can easily entrain the staircases and endanger the lives of occupants during evacuation [British Standards Institution 1999].

- Escape time

Two components [British Standards Institution 1997b], i.e. response time for occupants to take action and evacuation time to reach a safe place, are involved in the escape time for occupants to evacuate from the shop to final exit.

Response time comprises two parts [Ghosh 1997], i.e. the time for people to realize the danger and take action to evacuate. The responsiveness of occupants depends on many factors, such as the mental and physical conditions, their familiarity with building and the extent to which they feel threat from fire. It is obvious that the response time will be decreased with the shop area. Response time t_{res} (in s) [Ghosh 1997] can be expressed in terms of the shop area A_f (in m^2) and constant β which is equal to 75 for average response time and 22.5 for quick response time.

$$t_{res} = \beta \log (A_f) \quad \ldots (4.9)$$

The equation is applicable to Hong Kong situation. The result obtained is depended on the shop areas and can be taken as a reference for the response time of occupants in the retail shops of Hong Kong.

Evacuation time is the time required for occupants to move from the hazard area to an ultimate place of safety as mentioned in MoE Code [Buildings Department Hong Kong 1996b] when they recognize the danger and start to evacuate. According to BS 7974 [British Standards Institution 2004], the place of safety is a predetermined place in which the occupants have no immediate danger from the fire effects. The place can be inside or outside the building, depending upon the evacuation strategy. In this case, the escape route of occupants will be taken from the furthest position in the shop to the nearest protected staircase and then to the final exit of shopping mall as shown in Figure 4.3. Evacuation time t_{eva} (in s) [Ghosh 1997] can be calculated by the walking pace of occupants k_{walk} (in ms^{-1}) and travel distance d_{trav} (in m).

$$t_{eva} = \frac{1}{k_{walk}} \times d_{trav} \qquad \ldots (4.10)$$

Calculations for the required escape time t_{req} (in s) for two shops are shown in Table 4.7. Required escape time for occupants includes the average response time and evacuation time. Response time of occupants is unlikely to be fast if they have no training on fire safety. Escape time for Shop A and B are 138 s and 135 s respectively. This time may be shorter than the actual value as many factors such as origin of fire and blockage of goods inside the shops are not included. On the other hand, occupants are assumed to use the nearest staircases. Therefore, the escape time can only be used as a reference, and the actual value should be larger.

There are four protected staircases in each level of the mall. Maximum sum of the direct distance from the shop to the shop exit and travel distance from the shop exit to any one of the protected staircases should not exceed 45 m [Buildings Department Hong Kong 1996b]. In fact, the maximum sums of the direct distance and travel distance for Shop A and B are 17 m and 16 m respectively, which fulfilled the legal requirement. Further, the longest separation between those staircases is 38 m, which satisfies the allowed maximum staircase's separation of 48 m [Buildings Department Hong Kong 1996b]. Therefore, the travel distances are acceptable among those escape routes for both shops.

4.6 Fire safety management for retail shops in airport terminal

There are many problems constituted in small shops. Due to the low ceiling, smoke will fill up the shops rapidly. Fast vertical fire growth will be resulted if the ignition source is placed at the bottom of display items. If people cannot evacuate efficiently, their lives will put in jeopardy.

Fire safety aspects of the local shopping mall can act as a reference for the retail areas of airport terminal. In order to minimize the fire risks, proper fire safety management should be considered. Based on the analysis in Chapters 4.4 and 4.5, the followings are the suggestions of the improvement measures that shall be carried out in order to minimize the fire risk and enhance the life safety, property protection and business continuity of the local shopping mall and retail areas of the airport terminals:

- Reduction in fire load

  To avoid the occurrence of flashover in case of a fire, the shops should not store too many goods in order to minimize the heat release rate given out by the combustibles. Combustible items should be kept away from the door sides in order to obtain a clear shop exit for occupants to escape [Her Majesty's Stationery Office 1999]. On the other hand, racks should not be stacked up to ceiling, so as to avoid direct contact of combustibles with the light sources.

- Staff training

  Staff training is a key issue in fire safety management. It is referred to the fire safety training provided for all staff on preventing the occurrence of fire, actions to be taken on discovering a fire, first aid firefighting, placing the barriers and floor markings to the boundary of the site, assisting non-staff members to response to an alarm and escape, identifying the routes for evacuation and procedure for calling the police and fire services department. Regular fire drills are needed to be held.

- Sprinkler system

As illustrated in Table 4.3, the occupants in the retail shops, departure hall and arrival hall are under a great risk in case of a fire. To minimize the fire risk of occupants, sprinklers are required to be installed inside the retail shops. Shelves and stocks should be arranged in order not to affect the system actuation. Moveable plate should not be placed under each sprinkler head so as to avoid the effect in thermal sensitivity.

- Other equipment

Audio and visual systems should be able to give fire warning signals and verbal instructions to people in case of fire. Provision of several portable extinguishers should be located in obvious locations such that the trained staff can put out small fires inside the shops. All exit signs should be illuminated and indicated clearly. It is better to use the pictographic exit signs rather than the traditional one which is indicated by words only. Emergency escape lighting should be provided in the mall, such that escape routes and protected staircases can be clearly indicated.

- Accommodation staircases

The staircases would be too narrow for escape purposes. Therefore, upgrade the fire services installation and increase the width of staircases are the good methods. Protection systems such as smoke curtains can also be installed as they are effective in protecting the smoke from entering the staircases.

- Limitation of occupancy

Without the jamming condition in the escape route, the calculated value of the required escape time of occupants to evacuate from the shops is around 2 min. In real situation, the congestion occurred in the escape route will constitute the waiting time of occupants and hence increase the escape time in case of a fire. Therefore, the numbers of occupants inside the retail shops should be restricted. Besides controlling the occupants, suitable evacuation patterns should also be designed carefully.

4.7 Conclusion

A design fire by burning a soft toy mountain was assigned to study the probable fire environment of retail shops inside the airport terminal, with the two-layer zone model HotLayer [FIREWIND version 3.5 2000] in Chapter 4.2. It is found that smoke would fill up the shop even the smoke layer temperatures are lower than the flashover temperature. Care should be taken for not keeping excessive amount of combustibles inside the retail shops.

Four retail shops, departure hall and arrival hall of the airport terminal, and the selected two shops and 2/F of the local shopping mall were selected for fire risk analysis with FRAME version 2.0 [Smet 1998] in Chapter 4.4. From the results of Tables 4.3 and 4.4, the risks of loss of property and business interruption in those areas are small and protection is adequate. However, the values of fire risk for occupants are higher than 1 in the arrival hall of the airport terminal, the selected two shops and 2/F of the local shopping mall, indicating that the occupants are under a great risk in case of fire. Something should be done to improve the provision for life safety. A good fire safety management plan should be implemented as mentioned in Chapter 4.6 to enhance the fire protection of occupants in retail areas.

Chapter 5 : Chinese restaurant of the airport terminal

There are several restaurants and fast food services provided for passengers in airport terminal, of which, Chinese restaurants are believed to be most troubles. Therefore, fire hazards of Chinese restaurants would be studied in detail in Chapter 5.3. Current regulations for fire safety provisions of Chinese restaurants would be introduced with the associated licensing requirements in Chapter 5.1.

Fire risk analysis of a Chinese restaurant at airport terminal was conducted in Table 5.2. An example was also taken in a local Chinese restaurant in Chapter 5.4 to recognize the fire environment encountered. Proper fire safety management of the Chinese restaurants in airport terminal [e.g. Buildings Department Hong Kong 1995, 1996a, b; Hong Kong Ordinance 1998] will then be identified in Chapter 5.6.

5.1 General features and licensing requirements for Chinese restaurants in Hong Kong

Despite of the economic depression, the Chinese restaurants are usually crowded with people. Adequate fire safety should be provided as mentioned in Chapter 5.6. A Chinese restaurant is characterized by a large luxuriously decorated dining hall, a large kitchen and its crowded condition. From the statistical records, over 250 fires per annum were reported in the late 1980s [Fire Services Department 1990]. A fire can easily be started in the kitchen of a restaurant. Ignition of the large amount of combustibles in dining hall will lead to rapid development of fire. The large undivided space would be filled up with flame and smoke within a short time [Bickerdike Allen Partners 1996].

General features of Chinese restaurants in Hong Kong are very similar though their sizes are different [e.g. Chow 1995a, b]. There is a well decorated dining hall and a large kitchen. Since the rental price is expensive in Hong Kong, floor area has to be utilized effectively. As a result, tables and chairs are closely placed to accommodate customers. They are arranged in rows and separated by paths. Sometimes, a snack stall is placed in the dining hall for serving fried food.

The dining hall is decorated with linings, carpets, crystal hanging lamps and low-voltage lighting to provide a luxurious environment. Small rooms partitioned by flexible timber boards on rails would be provided in bigger restaurants. Those rooms will give private area for social gatherings. Open stairs are constructed to provide internal circulation for restaurants with more than two floors. Escalators and lifts might also be installed.

Kitchen is the major and essential component of a restaurant. Gases, steam and flame generated by dipping fresh food into hot oil with alcohol. A large stove with high thermal power is needed. Diesel stoves, town gas stoves, electrical cooking appliances and working tables are distributed over the kitchen.

Another popular feature is the ‘enclosed design’, i.e. the windows of restaurant cannot be opened. This is due to most restaurants are located in urban district where the view is not attractive. Therefore, windows are often sealed and covered by curtains.

According to Chapter 132 Public Health and Municipal Services Ordinance Part IV, a general license should be issued [Hong Kong Ordinance 1987] before a restaurant is in operation. In order to obtain a license, the design should be complied with hygiene requirement and fire safety standard. The layout plans of restaurants would be examined on passive building design [Buildings Department Hong Kong 1995, 1996a, b; Hong Kong Ordinance 1998] and active fire protection system [Fire Services Department Hong Kong Special Administrative Region 1998]. If the fire safety design is satisfactory and hygiene requirements are fulfilled, a license will be issued.

The passive safety measures of restaurants include the structural design, compartmentation, and means of escape. Fire services installation, usage of fuel, ventilation and means of access for fire fighters would also be assessed for restaurants. Fuel storage and type of fuel used will be controlled to minimize the fire risk [Hong Kong Ordinance 2000]. Normally, town gas, diesel oil and liquefied petroleum gas (LPG) are allowed. If diesel oil is used as fuel, it will be stored in a separate fire resisting chamber [Hong Kong Ordinance 1991]. Possibility of fire spread through ventilation ducts would be examined. A separate ventilation ductwork for kitchen is required. If it is not feasible, a fire damper can be installed in the duct for connecting the kitchen and actuated by means of heat or smoke detector.

5.2 Points of concern for Chinese restaurants

From the statistical records [e.g. Fire Services Department Hong Kong 1990], major causes of fire in Chinese restaurants were due to electric faults of cooking appliances and smoking. Most fires were occurred in kitchens. Over 50% of restaurant fires were originated from the high thermal power stoves operated by either town gas or diesel oil as illustrated in the fire records.

Gas stove would be safer as no fuel storage is needed. However, the stoves constructed might be modified illegally to give higher thermal power by having higher air and gas intake rates. The increased air intake rate will blow up the flame and cause accident. If the combustion chamber of the stove is small, complete combustion would not be occurred and fire is resulted. The fire risk of diesel oil stove is relatively higher as leakage of fuel from pipework and accumulation of diesel oil residue in stoves would also cause fire. Fire caused by ignition of combustible materials is occurred frequently when the cooking equipment placed too near.

Fire would also occur in dining hall due to Dim Sum trolleys, snack stalls, and portable stoves for fire pots. Although the fuel used by these burners has to be complied with the local fire regulation, improper operation of these gas appliances will lead to fire or even explosion.

Fire load can describe the potential heat content inside a building. The higher the value, the more serious the potential fire severity and damage to the structure. In the Chinese restaurants, large amount of combustible materials such as furniture, partitions, carpets and tables clothes are stored. Furnishing materials used in dining halls are always made up of synthetic materials. They are combustible and will give smoke when burning.

Smoke is the major killer in most building fires. Chinese restaurants are usually large and very crowded. Customers are not familiar with the layout of the restaurant and it is difficult for them to locate the escape route. Large amount of furniture stored will block the evacuation path. On the other hand, the exits including protected lobbies are used to store tables, tops, clothes and stacked chairs for banquets.

5.3 Hazard of the Chinese restaurant in airport terminal

A Chinese restaurant at level 8 was selected for further fire risk analysis. Total fire load density of the restaurant was estimated and summarized in Table 5.1. FRAME version 2.0 [Smet 1998, 1999] was selected to determine the fire risk and whether there is an equilibrium between risk and protection.

Fire risks R, R_1 and R_2 for the building and its contents, occupants and activities are related to their potential risks P, P_1 and P_2, acceptance levels A, A_1 and A_2, and protection levels D, D_1 and D_2. Results of those parameters are shown in Table 5.2. P_1 would be the highest among P and P_2, while A_1 and D_1 are the lowest among A & A_2 and D & D_2. On the other hand, R_1 is much higher than R and R_2. Those parameters indicated that the risk of occupants is much higher than property loss and business interruption. Something should be done on the protection for occupants in the restaurant.

5.4 Fire environment encountered in a local Chinese restaurant

An example of a local Chinese restaurant is shown in Figures 5.1 and 5.2. It is a real restaurant in Hong Kong but not located in the airport terminal of Hong Kong. To have an understanding on the fire environment that would be encountered in the restaurant, the two-layer zone model TwoRooms in the fire engineering calculator FIREWIND version 3.5 [FIREWIND version 3.5 2000] is used. As kitchen is the most dangerous area, fire is assumed to be occurred inside. Restaurant of size 45.7 m × 45.7 m and height 3 m, including a kitchen of size 9.1 m × 9.1 m with the same height, is taken as an example. A schedule of the calculation target space, in which necessary conditions for the simulation are clearly indicated, will be shown in Table 5.3. There is no ceiling ventilation inside the kitchen and restaurant. Heat release rate Q_c (in kW) at time t (in s) is assumed to follow NFPA t^2-fire [National Fire Protection Association 2000b], with a cut-off value of 5 MW at time t_{cut}:

$$Q_c = \begin{cases} 1000\left(\dfrac{t}{t_g}\right)^2 & t \le t_{cut} \\ 5000 & t > t_{cut} \end{cases} \qquad \ldots (5.1)$$

Values of t_g are 600 s, 300 s, 150 s and 75 s for slow, medium, fast and ultra-fast t^2-fire respectively. The relative t_{cut} are 1341 s, 671 s, 335 s and 168 s.

As the condition of a Chinese restaurant in Macau is similar to the local restaurant, i.e. both with a ceiling height of 3 m and are sprinklered controlled, the fire size of the Chinese restaurant in Macau is similar to that of Hong Kong and can be taken as a reference for utilizing in Hong Kong situation. A high cut-off value 5 MW, which was applied to the Chinese restaurant of Macau [Ng 2006], is used to assess the consequence under the severe condition. This value was predicted using the software FPEtool version 3.2 [Deal 1995], which is similar to burning 2 groups of frameless foam back chairs with a total weight of 41 kg [National Fire Protection Association 2000b]. Simulations were performed up to 2000 s with transient predicted results shown in Figures 5.3 to 5.5.

It is observed that for a slow t^2-fire in Figure 5.3, average hot layer temperature and ceiling jet temperature during the steady burning period 1341 s to 2000 s inside the kitchen are 182°C and 738°C respectively. Average height of the hot layer is 0.31 m as illustrated in Figure 5.4. At 500 s, smoke layer is dropped to 1.7 m although the hot layer temperature is only 70°C. Therefore, staff inside the kitchen should be able to leave within 500 s after a fire starts. Smoke flow rate 2.18 kgs^{-1} from the kitchen door to the restaurant was predicted during steady burning period in Figure 5.5. From the other extreme of the ultra-fast t^2-fire, the steady-burning period is 335 s to 2000 s. Smoke layer falls below 0.5 m above the ground level during the steady-burning period 500 s in Figure 5.4. From the result of zone model as shown in Figures 5.3 & 5.4, fire effect is not significant with smoke temperature 32°C at the height of 2.8 m above the floor. A possible reason is the large floor area.

5.5 Fire safety provisions

Adequate passive building design and active fire protection system should be provided in Chinese restaurants. In addition to fire resisting construction, three key points have considered in passive building design [e.g. Buildings Department Hong Kong 1995, 1996a, b; Hong Kong Ordinance 1998]:

- Means of escape

  At least two staircases with the maximum travel distance lying between 30 m and 36 m are required in Chinese restaurants [Buildings Department Hong Kong 1996b]. Population density factor of dining hall and kitchen is taken to be 1 m^2 per person and 4.5 m^2 per person respectively [Buildings Department Hong Kong 1996b]. Any openings from kitchen to the exit route should be protected by protected lobby. Staircases used as the escape routes should be constructed of fire resisting material [Buildings Department Hong Kong 1996a]. Doors led to the protected staircase shall be opened in the exit direction. All the doors are required to have a FRP of not less than half an hour [Buildings Department Hong Kong 1996a]. The doors should be self-closed and equipped with a clear exit sign.

- Compartmentation

  A Chinese restaurant is normally divided into dining hall, small rooms and kitchen. The dining hall and small rooms are considered as one compartment since they have the same purpose. Therefore, partition materials of small rooms are not specified to have a certain FRP. However, the compartment should have an FRP of 1 hour when it is smaller than 7000 m^3 [Buildings Department Hong Kong 1996a]. For compartments exceeding 7000 m^3 but less than 28000 m^3, FRP should be 2 hours [Buildings Department Hong Kong 1996a].

Kitchen is considered as a different occupancy with special fire hazard. It should be separated from other areas by fire resisting compartment, which has an FRP of 2 hours; or 4 hours when adjoining to staircase [Buildings Department Hong Kong 1996a]. Dampers are required to prevent fire spread through the air ducts from kitchen.

- Basement

All the combustible partitions, wall and floor should have a certain FRP. For restaurants at basement level, the compartment wall and floor between the basement and above storey should have an FRP of 4 hours [Buildings Department Hong Kong 1996a]. According to the building regulation [Buildings Department Hong Kong 1996a], each compartment in basement should be installed with smoke outlet of not less than 0.5% of the floor area. Although dynamic smoke extraction system is not strictly required, it is recommended to install with at least one smoke outlet for every 3500 m^3 of the compartment volume.

Fire services installations in Chinese restaurants are similar to commercial buildings [Fire Services Department Hong Kong Special Administrative Region 1998; Hong Kong Ordinance 1998]. Automatic sprinkler system, fire alarm system, fire hydrants and hosereels, portable hand-operated appliances such as fire extinguishers and fire blankets are normally required in fire regulations. According to the prescriptive fire codes [Fire Services Department Hong Kong Special Administrative Region 1998], four types of active fire protection systems are required in Chinese restaurants.

- Detection and alarm system

  Smoke detectors and heat detectors are commonly used in the automatic fire detection system. Smoke detector is more sensitive and normally installed in dining hall. Heat detector is preferred in kitchen for eliminating frequent occurrence of false alarm. The fire detection system should be connected to the fire alarm system and Fire Services Communication Centre by direct line in order to produce an early fire warning for people and fire fighters to recognize the occurrence of fire [Fire Services Department Hong Kong Special Administrative Region 1998].

- Suppression system

  Automatic sprinkler system is installed according to the common rules for automatic sprinkler installations as specified in the Fire Services Department Circular Letter [e.g. Fire Services Department Hong Kong 1994]. Sprinkler system of Chinese restaurant should be designed to deal with Ordinary Hazard (OH) I. The normal operating temperature of sprinklers in commercial buildings is 68°C. It is suitable to install in the dining halls of restaurants. However, sprinkler heads with higher actuation temperature such as 79°C; or longer response time index should be considered in kitchens so as to prevent the sprinkler heads above the stove to be actuated by hot gas.

Fire hydrants are usually located inside the staircase enclosure. Occupants can use the hose reels to control the fire at initial stage. Portable appliances such as extinguishers and fire blankets are also provided. Water, carbon dioxide and powder types of extinguishers are commonly used. There is also an increase use of water mist fire suppression system in kitchens [e.g. Chow and Yao 1997; Liu and Kim 1999].

- Smoke management system

In order to prevent the spread of smoke, smoke barriers constructed of non-combustible materials are required. Dampers are required in air ducts as smoke can spread through the air ducts of air-conditioning system. Therefore, air-conditioning system should be automatically shut down to prevent smoke from circulating through the whole compartment in case of fire [Fire Services Department Hong Kong Special Administrative Region 1998].

- Back up system

Emergency lighting is required to provide a minimum illumination level of not less than 2 lx when normal lighting breaks down in case of fire [Fire Services Department Hong Kong Special Administrative Region 1998]. It is required in areas such as staircase and exit route, and should be backed up by the emergency power supply or secondary battery if the building is not equipped with an emergency generator. These systems should be capable of maintaining the stipulated lighting level for a minimum period of one hour. A clear indication of the exit route is needed as customers are normally unfamiliar with the layout of restaurant. Illuminated 'Exit' signs in English and Chinese should also be provided at each exit [Fire Services Department Hong Kong Special Administrative Region 1998].

5.6 Proper fire safety management

Proper fire safety management in Chinese restaurants [e.g. Malhotra 1987; Dailey 2000; National Fire Protection Association 1995a; Della-Giustina 1999; Chow 2001c] should be provided with several fire safety plans, i.e. maintenance plan, staff training plan and fire action plan.

- Maintenance plan

Fire protection systems should be operated effectively to reduce the fire loss. The fire services installations should be maintained in a good condition.

According to the fire regulations, fire services equipment should be checked annually by registered fire contractors. Escape routes should be kept clear, and combustible materials should be separated from ignition sources. Exit doors should be closed and unlocked during business hours. These doors can only be locked when there are no occupants inside. Proper maintenance procedures are required to ensure the fire services installations are in right order.

- Staff training plan

Further training on fire safety should be provided for all staff in Chinese restaurants to ensure that they can respond properly in case of fire.

- Fire action plan

Proper training for using portable fire extinguishers or hose reels should be provided for staff. An evacuation plan should be worked out to help the customers to escape from the Chinese restaurant.

5.7 Conclusion

A Chinese restaurant in the airport terminal was selected for fire risk analysis with FRAME version 2.0 [Smet 1998, 1999] in Chapter 5.3. The results in Table 5.2 illustrated that heed should be paid to improve the provision for life safety. Fire safety aspect of a typical Chinese restaurant was also studied in Chapter 5.4

with the aid of a two-layer zone model [FIREWIND version 3.5 2000]. Simulation results in Figures 5.3 to 5.5 illustrated [Chow 1995a, b; FIREWIND version 3.5 2000] that the fire effect is not too terrible for restaurants with large floor area. However, the fire safety management as mentioned in Chapter 5.6 should be watched carefully to enhance the fire safety protection of occupants in Chinese restaurants.

Chapter 6 : Passenger loading survey

Emergency evacuation in the crowded airport terminal is of great concern. Taking the incident in the airport terminal of Hong Kong in early August 2006 as an example [South China Morning Post 2006], the chaos occurred in the airport terminal under typhoon condition would lead to several thousands of passengers crowded in the departure hall for a long time. The data on occupant loading is important for designing the means of escape. However, there are queries on whether the data specified in the codes are realistic in designing the occupant loading for the airport terminal.

Therefore, the passenger loading in the departure level and arrival level of the airport terminal will be studied in Chapter 6.4. A field survey on the transient occupant loadings of the airport terminal was carried out as illustrated in Chapter 6.2 to justify the maximum allowed loadings specified in the design codes and standards.

6.1 Importance of the occupant loading

Many big fires had occurred since 1996, e.g. the Garley Building fire in Hong Kong [Hong Kong Standards 1996]. Public transport terminals and interchanges are identified to be the areas requiring special consideration. There was an airport terminal fire in Hong Kong before operating [South China Morning Post 1998], underground railway arson fires in Daegu, Korea [The Chosun.Ilbo 2003] and Hong Kong [South China Morning Post 2004b], explosion in trains in Moscow, Russia [CNN Homepage 2004], and underground railway terrorist attack in London, UK [The Standard 2005]. Further, railway stations and airport terminal in the Far East are always crowded with people. The recent snowfall in Zhengzhou (a city linking up several main railway routes), Hanan, China [Shanghai Daily 2006] has resulted in several hundred thousands of passengers crowded in the railway stations. Consequent to so many incidents due to emergency evacuation in crowded areas, even without a fire, emergency evacuation should be studied carefully.

Many public transport terminals and interchanges were constructed with big halls. Such buildings will have difficulties in complying the prescriptive fire codes. Therefore, performance-based design [British Standards Institution 2004] was commonly applied. For example, the number of exits was provided based on typical scenarios. There are concerns that such design may not necessary to allow the occupants to evacuate simultaneously in the worst scenario, such as under very crowded condition. Occupant loading should be considered carefully in studying evacuation.

In studying the crowd movement control in the public transport terminals and interchanges, maximum occupant loadings allowed in the local fire codes are referred to. There are considerations on the accuracy of the specifications and whether it is the worst scenario with the longest evacuation time.

The non-restricted areas of the departure level and arrival level of airport terminal are selected [Chow and Ng 2004] for surveying the occupant loading in

Figures 6.3 & 6.4. The maximum loading of the selected airport was around 100,000 per day as reported [South China Morning Post 1999]. There are also official data announced by the Authority [Hong Kong Airport Internet Homepage 2006] as shown in Figure 6.2. All such data should be justified by field studies during peak seasons. The survey was carried out to evaluate the transient occupant loadings in Chapter 6.2. Results illustrated in Table 6.1 are applied to justify how realistic are the design figures specified in the local codes and other overseas standards such as BS [British Standards Institution 1997a] and NFPA [National Fire Protection Association 2000c].

6.2 The survey

A field survey on occupant loading, i.e. the total number of persons that might occupy a building or portion thereof at any one time [National Fire Protection Association 2000c], was conducted to understand the occupant pattern of the airport terminal. Both the departure and arrival levels were studied. Geometry of the airport terminal [Chow and Ng 2004] is shown in Figure 6.1.

The number of users, scheduled flight information, predicted occupants loading, and etc. have been recorded in detailed by the Airport Authority. For example, the monthly statistical data of the total number of passengers in the departure level and arrival level of the airport terminals from Jan 2002 – Jan 2006 has been extracted from the Hong Kong Airport Internet Homepage [2006] and illustrated as in Figure 6.2. From the pattern, peak loadings were recorded in the months with long holidays, such as August and December.

Peak occupant loadings were estimated and happened on 17 to 23 July 2004, 12 to 18 August 2004, 25 September to 1 October 2004, 23 to 28 December 2004, and 30 December 2004 to 3 January 2005. The daily field survey was carried out from 10:00 a.m. to 9:00 p.m. in those possible periods with peak loadings. Visual observation was also performed on site to estimate the loading. The occupant loadings in normal operating days, such as 12 to 18 June 2004, were also investigated with results taken as reference.

In the survey, the areas in which crowded conditions were always found, i.e. retail areas of the departure level and arrival level, the areas in front of the retail areas of the departure level, check-in counters of the departure hall, waiting areas A and B of the arrival level, would be defined into several parts and shown in Figures 6.3 & 6.4. For the retail areas of the departure level and arrival level, the areas were constituted by all the retail shops in those levels. The total retail areas in the departure level and arrival level were 660 m^2 and 230 m^2 respectively.

On the other hand, the areas in front of the retail areas of the departure level, check-in counters of the departure hall, and waiting areas A and B of the arrival level were divided into several portions, i.e. Area D_{1a}, D_{2a}, D_{3a} and A_{1a}, A_{2a}, A_{3a}, with particular unobstructed areas ranging from 430 to 1700 m^2 as shown in Figures 6.3 and 6.4. For instance, the total area of 2940 m^2 in front of the retail areas of the departure level were divided into 3 portions. One of the portions with an area of 980 m^2, i.e. Area D_{1a}, was selected to determine the floor space factor. A clarification of the areas used in determining the floor space factor is shown in Table 6.2.

The occupants staying in those areas were captured by video cameras at an instantaneous time interval of 1 min, for every 15 min surveying. Observation started from 10:00 a.m. to 9:00 p.m. during the sampling period. The number of occupants staying in each area was counted from the fixed frames extracted from the video footage. Results are used to compile the floor space factor defined [Chartered Institution of Building Services Engineers 2003] to be the minimum area excluding stair enclosures, lifts and sanitary accommodation occupied by each person (in $m^2person^{-1}$).

The floor space factors of the departure hall C_d (in $m^2person^{-1}$), arrival hall C_a (in $m^2person^{-1}$), retail areas in departure level and arrival level, C_{rd} (in $m^2person^{-1}$) and C_{ra} (in $m^2person^{-1}$) are estimated by the following expressions:

Departure hall:

$$C_d = \frac{A_d}{N_d} \quad \dots (6.1)$$

Arrival hall:

$$C_a = \frac{A_a}{N_a} \quad \dots (6.2)$$

Retail areas in departure level:

$$C_{rd} = \frac{A_{rd}}{N_{rd}} \qquad \dots (6.3)$$

Retail areas in arrival level:

$$C_{ra} = \frac{A_{ra}}{N_{ra}} \qquad \dots (6.4)$$

A_d (in m^2) and A_a' (in m^2) are the particular unobstructed area as illustrated in Figures 6.3 & 6.4, i.e. Area D_{1a}, D_{2a} or D_{3a} in the departure hall and Area A_{1a}, A_{2a} or A_{3a} in the arrival hall, while A_{rd} (in m^2) and A_{ra} (in m^2) are the total areas of retail shops in the departure level and arrival level. N_d (in number of persons) and N_a (in number of persons) are the number of occupants occupied that particular area in the departure hall and arrival hall at an instantaneous time interval of 1 min per 15 min; and N_{rd} (in number of persons) and N_{ra} (in number of persons) are the number of occupants in all retail shops at an instantaneous time interval of 1 minute per 15 minutes.

6.3 Methodology

Before surveying the hall and retail areas, the best positions for observation and taking videos at the departure and arrival levels of the airport terminal were decided. The survey was carried out by the candidate and two staff. A team of three staff was positioned in those selected areas where the occupant loading in the congested areas can be observed clearly [Olsson and Regan 2001]. The staff would record the individuals by a handheld video camera without any superimposition [Gwynne et al. 2003].

Occupant loading was recorded at an instantaneous time interval, i.e. 1 min for every 15 min, starting from 10 a.m. to 9 p.m. during the sampling period. The occupant loading of each area would be captured by the staff at a higher level to prevent the overlapping of people in the video. Areas D_{1a} and D_{2a} illustrated in Figure 6.3 were recorded from the restaurant area on level 8. Area D_{3a} and Areas A_{1a} to A_{3a} illustrated in Figures 6.3 & 6.4 were taped from the entrance hall on level 7 and level 6 respectively.

Retail areas of the departure level and arrival level are of 660 m^2 and 230 m^2 respectively. Occupants staying inside the shops could not be recorded from the high level. Therefore, the retail shops on those levels were divided into eight groups and four groups respectively. Each group had three to five retail shops.

Some photos captured from the tape recording for the departure level and arrival level have been illustrated as in Figures 6.3 and 6.4. In order to extract more data from the video footage, templates were created to extract the data in a consistent and coherent manner [Gwynne et al. 2003]. The dynamic number of the airport users staying in Areas D_{1a} to D_{3a} and A_{1a} to A_{3a} as shown in Figures 6.3 & 6.4 was counted in the fixed frames of every video footage [e.g. Chung and Hui 2006] by using a large viewing screen, e.g. a 21” monitor. The number of occupants in each retail shop can also be counted in the frames of the footages. Instantaneous occupant loading of the retail areas on both levels can be determined by summing up the occupants in each retail shop. Average value of the occupant loading in those areas can then be obtained on an hourly basis.

After recognizing the number of occupants in the fixed frames of footages, the floor space factors of occupants in the departure hall, arrival hall and retail areas of the departure level and arrival level on an hourly basis can be analyzed in accordance with the average value of occupants in those areas at four instantaneous time intervals, i.e. every 15 min within an hour, as illustrated in Figures 6.5 – 6.8.

According to the head counting experience in mass gatherings and rallies from Chung and Hui [2006], $\pm 5\%$ is adopted for the counting error for estimating the number of people in the fixed frames of footages. As the case is similar to the field survey of the transient occupant loadings of the airport terminal, it is cited as a reference for our case and the range of values after including the counting error $\pm 5\%$ will be utilized for the comparison of the estimated occupant loading for the several fixed frames of different areas within the departure hall and arrival hall in Figures 6.3 & 6.4.

With regards to the several fixed frames of different areas within the departure hall and arrival hall in Figures 6.3 & 6.4, it is found that there is only about 6 % discrepancy in the estimated occupant loading for the fixed frames due to the uneven density of crowd inside the departure hall and arrival hall. This will not constitute a big difference in the floor space factor. Based on the monthly statistical data of the total number of passengers in the departure level and arrival level as shown in Figure 6.2, the peak loadings of the airport terminal occurred in December. It is similar to the results of the field survey on the transient occupant loadings of the departure level and arrival level during the Christmas period as shown in Figures 6.5 to 6.8. Therefore, the survey result illustrated in Figures 6.5 to 6.8 is considered reliable and can be used to compare with the design figures specified in the local codes [Buildings Department Hong Kong 1996b] and overseas standards [British Standards Institution 1997a; Chartered Institution of Building Services Engineers 2003; National Fire Protection Association 2000c].

The floor space factor in the departure hall and arrival hall would be taken as the average floor space factor of the Areas D_{1a}, D_{2a}, D_{3a} and A_{1a}, A_{2a}, A_{3a} as illustrated in Figures 6.3 & 6.4. Floor space factor of the departure and arrival levels in a selected period, i.e. 30 December 2004 to 3 January 2005, are calculated as in Figures 6.5 and 6.6 to compare with the design figures specified in the local codes.

6.4 Results

In normal operating days, i.e. 12 to 18 June 2004, the average floor space factor in the departure hall and arrival hall were 2.7 $m^2person^{-1}$ and 4.8 $m^2person^{-1}$ respectively. The value of the retail areas on the departure level and arrival level was 2.1 $m^2person^{-1}$. On the other hand, the peak period of the airport terminal occurred before and after the holidays. High occupant loading was resulted. Instantaneous maximum occupant loading was found during the Christmas period, i.e. 24 December 2004 at the departure hall and retail areas of departure level in Figure 6.7 and 30 December 2004 at the arrival hall and retail areas of arrival level in Figure 6.8. Crowd conditions of departure and arrival levels at 4:00 p.m. on 24 December 2004 and 3:00 p.m. on 30 December 2004 are shown in Figures 6.3 and 6.4 respectively.

The average floor space factor of the departure and arrival levels from 10:00 a.m. to 9:00 p.m. on 24 December 2004 and 30 December 2004 was demonstrated in Figures 6.7 and 6.8 respectively. At the instantaneous maximum occupant loading, the average floor space factor were 1.1 $m^2person^{-1}$ at departure hall, 1.4 $m^2person^{-1}$ at arrival hall, 0.9 $m^2person^{-1}$ and 0.5 $m^2person^{-1}$ at the retail areas of departure level and arrival level correspondingly as illustrated in Table 6.1.

Consequent to the earthquake and tsunamis in Southern Asia [Hong Kong Standards 2004; South China Morning Post 2004a], the number of people travelled to overseas was decreased in the period 30 December 2004 to 3 January 2005 as shown in Figure 6.5. The average floor space factor in the departure hall was about 2.3 $m^2person^{-1}$ in that period. However, it was only 1.5 $m^2person^{-1}$ in the period 23 to 28 December 2004. On the other hand, the occupant loading in the arrival level increased in the period 28 December 2004 to 3 January 2005 in Figure 6.6. The average floor space factor in the arrival hall was only 1.6 $m^2person^{-1}$, while 2.1 $m^2person^{-1}$ was identified during 23 to 28 December 2004.

6.5 Discussion

Floor space factors around the holidays were smaller than normal days as illustrated in Table 6.1, provided that the airport terminal would be crowded around holidays and specified evacuation plan should be assigned to occupants in case of an emergency. The floor space factor in the departure hall was smaller than the arrival hall in Table 6.1, no matter in the selected peak periods or normal period. However, the floor space factor in those halls switched over during 28 December 2004 to 3 January 2005 in Figures 6.5 & 6.6, as people were reluctant to travel because of the disaster.

The comparisons of the floor space factors for the halls and retail areas in the airport terminal between different codes [e.g. Buildings Department Hong Kong 1996b; British Standards Institution 1997a; Fire Safety Building Regulation 2000; International Code Council 2003; National Fire Protection Association 2000c] and the field surveys during the peak period and normal period are shown in Table 6.1. The figures specified in the MoE codes and UK codes were close to the average floor space factor obtained at the instantaneous maximum loading during the peak period 23 December 2004 to 3 January 2005, i.e. 1.1 and 1.4 $m^2person^{-1}$ in the departure and arrival halls, and 2.1 $m^2person^{-1}$ at the retail areas of departure and arrival levels during the normal period 12 to 18 June 2004. It is acceptable to utilize the floor space factor allowed in the MoE codes or UK codes to estimate the number of occupants staying in the halls and retail areas of airport terminal in Hong Kong.

The occupant loading of retail areas in real situation would be higher than the figures mentioned in MoE codes [Buildings Department Hong Kong 1996b]. Large amount of people would be staying inside the departure hall and waiting areas of the arrival hall no matter in normal days or holidays. In order to prevent accidents due to crowd movement of occupants [South China Morning Post 1993], passenger loading inside the airport terminal should be controlled within a value by proper fire safety management. Some people, especially the relatives of passengers, should not be allowed to enter the airport terminal once the maximum loadings at the departure hall and arrival hall, i.e. 38836 and 34980, are reached. This can control the crowd movement effectively such that passengers can be evacuated efficiently in case of fire.

Passengers may stay inside the airport terminal for a longer time to carry out the check-in and security procedures in the departure hall and arrival hall. Especially before the security counters, many passengers would be queued up. If a fire occurs, escape routes may easily be blocked. Increasing the number of security counters to be operated can shorten the waiting time of passengers such that the time of occupants staying inside the airport terminal would become shorter.

6.6 Conclusion

The floor space factors in the departure and arrival levels were surveyed through the field studies in the airport terminal as mentioned in Chapter 6.2. The methodology adopted in field surveying in Chapter 6.3 are positioning the staff and video cameras at appropriate positions; dividing the departure level and arrival level into several zones; selecting the particular unobstructed areas with an expected size that the video camera can capture the whole region; capturing the selected areas at an instantaneous time interval; extracting the data from the video footage in a sequential way; determining the number of occupants in the fixed frames of the video footage; and calculating the floor space factor.

The surveyed data was compared with the floor space factor allowed in different codes in Table 6.1. The difference in the floor space factor between the field measurement, and MoE Codes and UK codes is small. Therefore, it is acceptable to utilize the value allowed in the MoE codes or UK codes for designing the occupant loading in the halls and retail areas of the airport terminal in Hong Kong.

From the field survey of those levels in the airport terminal, it is shown that the peak occupant loading occurred at around 4:00 p.m. and 3:00 p.m. in the departure level and arrival level respectively from 30 December 2004 to 3 January 2005 as illustrated in Figures 6.5 & 6.6. Therefore, more attention should be paid to the crowded condition occurred in the retail areas, departure hall and arrival hall of both levels during those periods.

Chapter 7 : Numerical simulations on airport evacuation with different software

In studying evacuation, different components of evacuation time should be realized. These include the evacuation time, Required Safe Egress Time (RSET), Available Safe Egress Time (ASET), pre-movement time, travel time, recognition time, response time, walking time, flow time, queuing time and waiting time. Definitions and calculation methods of those time components will be reviewed as in Appendix C, so as to give us a clear picture with the time involved in the evacuation process. A time line of the fire development and evacuation process would be shown in Figure C.1.

Crowd movement during emergency in dense public transport terminals would give serious consequences. The arrival hall of the airport terminal in Hong Kong is always crowded with people during peak seasons. Detailed scenario analysis for the evacuation of occupants during the crowded condition would be considered in Chapters 7.2 to 7.6. The designed occupant loading is based on the floor space factor, i.e. the usable area per person (in $m^2 person^{-1}$) as illustrated in the local codes [Buildings Department Hong Kong 1996b], i.e. 0.5 $m^2 person^{-1}$ for the halls and 3 $m^2 person^{-1}$ in the retail areas.

Models simulating the evacuation of buildings are commonly used to study the evacuation pattern. The evacuation model used should not only include the part on tracking the instantaneous positions of the persons staying inside a building, psychological factors are also needed to be considered. There are no systematic studies on the human behaviours in an accidental fire in Hong Kong, such that no evacuation model with in-depth validation is applicable to demonstrate the evacuation time of the Hong Kong people. As the evacuation models buildingEXODUS [e.g. Galea and Galparsoro 1994] and SIMULEX [e.g. Thompson and Marchant 1994a, b] are well-validated software and demonstrated to be applicable for the escape movement of large numbers of individuals in many single level or multi-level buildings, both models were selected to study the evacuation time of occupants inside the airport terminal in Figures 7.3 to 7.6.

In simulating evacuation, it is better to apply more than one model and compare the predicted TET and jamming condition of occupants at exits. The two commercial packages, i.e. buildingEXODUS and SIMULEX, can be used to simulate evacuation of occupants under high occupant loadings as mentioned in Chapter 7.1. As observed in the simulations in Figure 7.7, jamming is occurred around the exits inside the arrival level. Although the waiting time for each occupant cannot be explicitly indicated in the simulation results of SIMULEX, the long TET simulated would give some hints on jamming. Therefore, the simulation results of the two models are utilized to study how jamming would affect the TET under crowded conditions in Chapter 7.6. The 'snapshots' of the outputs from the simulations will be provided in Figure 7.7.

Based on the field survey conducted in the airport terminal [Chow and Ng 2006] as mentioned in Chapter 6.2, high occupant loading was recorded in some areas. Four sets of scenarios were assessed for the particular areas to realize the evacuation time of occupants [e.g. Ng and Chow 2004a, b] under fire and normal conditions in Chapter 7.2. The number of staircases and exits, occupant loading in each level and characteristics of occupants such as age group, gender, travel speed and response time had been input to the models. In buildingEXODUS, the hazard parameters such as temperature (in ^{o}C), concentrations of hydrogen cyanide (HCN) (in ppm), carbon monoxide (CO) (in ppm) and carbon dioxide (CO_2) (in %), oxygen (O_2) depletion (in %), visibility (in m^{-1}) and radiative heat flux (in kWm^{-2}), can also be assigned in the model as mentioned in Chapter 7.4.

The results of the evacuation time predicted by the two models are compared in Figures 7.3 to 7.6. In addition to the total evacuation time (TET) (time for the last occupant to leave the hall) simulated by both models, useful parameters such as the maximum number of occupants who can leave the hall, number of occupants leaving the hall at the target time, travel distances, waiting time of occupants and moving time of occupants can be derived in Chapter 7.6 to recognize the evacuation condition of occupants and hence the measures to minimize the evacuation time of occupants.

7.1 Evacuation models buildingEXODUS and SIMULEX

Evacuation pattern can be understood by using simulation programs. The followings are the advantages of utilizing the evacuation models buildingEXODUS and SIMULEX [e.g. Galea *et al.* 1997; Galea and Galparsoro 1994; On-line manual for buildingEXODUS 3.0 2000; Thompson and Marchant 1994a, b, 1995a, b, c; Thompson *et al.* 1996]:

- Both models are verified based on the realistic data from several unannounced fire drills.

- They are demonstrated to be applicable to many single- or multi-level buildings for evacuating large numbers of individuals [e.g. Ashe and Shields 1999; British Standards Institution 1997, 2004; Ng and Chow 2004a, b; Weckman *et al.* 1998].

- Psychological factors, such as the response time of each individual, are also considered in both models [Purser 2003; Sime 1996; Thompson 1995b].

- Personal attributes, such as age, gender, walking speed and response time, can be varied for occupants in each model.

However, the disadvantages of the occupants in the two evacuation models are the characteristics of occupants can only be defaulted as UK people. The reasons are:

- The Hong Kong Airport Terminal is an international airport with passengers coming from different countries. Using the characteristics of people from any one country is sufficient to compare the evacuation pattern simulated by those models.

- There are no systematic studies on the human behaviours in an accidental fire of Hong Kong, such that no evacuation model with in-depth validation is applicable to demonstrate the evacuation time of the Hong Kong people. It is reasonable to use the well-compiled UK characteristics as there is not yet systematic analysis on the characteristics of local people.

In spite of the disadvantages of both models, both models are suitable to study the evacuation time of occupants inside the airport terminal as illustrated in Figures 7.3 to 7.6. Geometries, nodes network, travel speed of occupants, change of direction of occupants and special parameters involved in buildingEXODUS and SIMULEX were listed as follows:

- Geometries

  Region of space in which occupants move is geometry. Geometry of the floor plan of building is similar in buildingEXODUS and SIMULEX, in which CAD drawings can be incorporated into the models. Floors are connected to each other by staircases for a multi-level building in both models.

  Within the buildingEXODUS [Galea *et al.* 1997], geometries are two-dimensional grids. Each location on a grid defines a node. A node will possess an additional attribute, which is known as 'potential'. Potential is a measure of nodes distance from the nearest exit. Once the geometry is constructed and exits defined, buildingEXODUS will automatically create a potential map. The map is used to define and influence global escape behaviour of occupants.

On the other hand, SIMULEX has the flexibility in handling infinite spatial variations and routines for automatic route assessment. The 'distance mapping' technique is employed in SIMULEX, which can assess the building space in terms of travel distance and final exit [Thompson and Marchant 1995a]. A 'contour map' is set up by a fine mesh of spatial nodes which covers the plan area of a building [Thompson and Marchant 1995a]. Numerical value assigned to each node is equal to the optimal 'travel distance' from the centre of that node to the nearest available final exit. This value takes account of all changes in the direction of travel, when occupants are blocked by obstructions such as walls and slower persons which prevent the forward movement. The software can also find the furthest point in a building from any exit, i.e. most remote point, and illustrates the route to exit from this point and the total travel distance [Thompson and Marchant 1995a].

- Network

Movement of each individual in buildingEXODUS is accommodated by stepping one node, i.e. a single and defined area, to the next [Galea *et al.* 1997]. The fine network of nodes is connected by four or eight arcs that define the available path of movement from one position to another. Each node represents a portion of space 0.5 m x 0.5 m and can be occupied by one person only [Galea *et al.* 1997], while the arc represents the actual physical distance between nodes, which is set at 0.5 m. It is possible to use the nodes with special properties, such as seats and obstacles.

In SIMULEX, the size of each spatial block is 0.2 m x 0.2 m. All the blocks are identical. The numerical value assigned to each block is equal to the total travel distance to an exit from that block [Thompson and Marchant 1995a]. For the occupants simulated, the shape of a human body is represented by using three circles (one for main body and two for shoulders). Each person is assigned with different body dimensions, which is dependent on age and gender [Thompson and Marchant 1995c]. Unlike buildingEXODUS, the blocks in SIMULEX are not capable of using with special properties.

Both computer models utilize the particle tracking technique, i.e. seeking the flow of particles which are assumed to follow the fluid, and measuring their movement over a known period of time by tracking the particles among different instantaneous pictures [Agüí and Jiménez 1987; Clayton and Massey 1987]. Instantaneous position of each person in the crowd can be tracked in both models.

- Travel speed

The travel speed S' (ms^{-1}) of occupants in buildingEXODUS [Galea *et al.* 1997] depends on the occupants' initial maximum travel speed T (ms^{-1}), their mobility M and the terrain being travelled over. It will range from 0.3 to 1.5 ms^{-1}. T of an occupant is dependent on the minimum arc length. The time taken for an occupant to traverse any arc would be larger than 1/12 s.

M is ranged from 0 to 1. A reduction in M will cause a decrease in S'. An occupant's travel speed at any point in time is determined by the relation of T and M as:

$$S' = T \times M \qquad \dots (7.1)$$

The value of M arbitrarily given in the equation. On the other hand, speed of occupants is assessed individually at each time step in SIMULEX. During the simulation, each person will be assigned with a random unimpeded speed between 0.8 ms^{-1} to 1.7 ms^{-1}. The speed of an individual is related to the distance between centre co-ordinates of the person and others in the obstruction zone [Thompson and Marchant 1995b].

The inter-person distance is a measure of distance between the center points of the bodies of two individual persons [Thompson and Marchant 1995b]. For a single obstructing person, inter-person distance d' (m) is related to the density D_d (number of person m^{-2}) by:

$$d' = \sqrt{\frac{1}{D_d}} \qquad \dots (7.2)$$

The formula for walking speed v_{walk} was derived in terms of unimpeded walking speed V' (ms^{-1}) and plan body depth b (m):

$$v_{walk} = \left(\frac{V'(d' - b)}{0.87} \right) \qquad \dots (7.3)$$

The speed is assumed to be unimpeded when d’ > 1.12 m. 1.12 m is the ‘distance threshold’ and value of d’ can be adjusted, depending on occupant characteristics such as aggression and familiarity. A special relationship is existed between v_{walk} of an individual and d’ from the individual to the nearest obstructing person [Thompson and Marchant 1995a]. When d’ is smaller than a value, such that (d’-b) is tended to zero, the value of v_{walk} will become very small as there is no clear distance between the individual and obstructing person.

- Change of direction

The movement of occupants in both models will produce a degree of jostling in high density crowds. Occupant would be slowed down if obstructed by another person. Change of direction of occupants would be occurred during the simulation of buildingEXODUS [Galea *et al.* 1997]. For example, five occupants want to enter the same node simultaneously. There would be conflicts between all occupants. This conflict can be solved by a random selection process. Only one occupant can occupy the node at the end. Other occupants should be either waited until that person left or carried out another action such as change the direction of movement and find an alternative node.

In SIMULEX, the program will examine the direction of travel of that person when speed of person is reduced [Thompson and Marchant 1995a]. If there is a significant change in speed, direction of travel would be changed to a new and deviated angle. Overtaking is occurred when there is an enough space available for the person to deviate the route. It will not be applied to the areas when the crowd density is exceeded 2 persons m^{-2} [Thompson and Marchant 1995b]. On the other hand, queuing is occurred when groups of people 'merge' in the corridors or pathway junctions of a building structure. The occupant will become stationary if standing exactly behind another person, and there is no space to move sideways [Thompson and Marchant 1995b].

- Special parameters

Large amount of data, e.g. age, weight, travel distance, response time (RT) (in s), cumulative waiting time (CWT) (in s) and evacuation time of each occupant, would be generated in each simulation. CWT is a dynamic attribute calculated by buildingEXODUS and defined as a measure of the total waiting time encountered on the way to exit the building, i.e. the total amount of congestion that the occupants have to experience and remain stationary after they start to evacuate [e.g. DeCicco 2002]. The waiting time spent in each congestion will be recorded. For example, the waiting time of an occupant is started when an individual starts to congest. It is ended after the person caught in the congestion is free to move again. The magnitude of the first waiting time, i.e t_{wait1}, will be recorded. When next congestion is occurred, the waiting time will then be ended at, say t_{wait2}. For n congestion occurred, CWT is:

$$CWT=\sum_{i=1}^{n} t_{waiti} \qquad \ldots (7.4)$$

Based on the evacuation time (ET), RT and CWT, the moving time (MT) (in s) of occupants can be determined.

$$MT = ET - RT - CWT \quad \ldots (7.5)$$

The waiting and moving components in ET (i.e. MT and CWT) can act as an indicator to identify the time portion in which most of the occupants are likely to spend on queuing and travelling during evacuation.

People moved towards the exits once they started to evacuate in SIMULEX. Under a crowd condition, some occupants will gather around the exits while the others were moved at back [Thompson and Marchant 1995a]. The movement of occupants before the exits was slow due to the high occupant density. When the back persons approached the exit, they will get closer with the front occupants and being blocked. If the back occupants cannot overtake the front occupants, they will jam and need to queue up at the exits [Thompson and Marchant 1995c].

Only the exit evacuation time (EET), i.e. time for the last person to get out of the exit, would be shown in the simulation result of SIMULEX. The number of people through all exits in a period of 5 s would be generated. Waiting time would not be explicitly specified for each occupant. Some of occupants are observed to be stationary during the simulation. The waiting period should be included in the travel time (TT) (in s) of occupants. Evacuation time (ET1) (in s) of occupants in SIMULEX [e.g. Thompson *et al.* 1996;

Spearpoint 2004] is expressed in terms of response time (RTI) (in s) and TT as:

$$ET1 = RT1 + TT \qquad \dots (7.6)$$

Evacuation performance of occupants can be solved by some number distribution functions. As the number of occupants is a function of evacuation time, plotting this relationship can recognize the transient number or percentage of people whom can be evacuated within a specified time interval. Results are useful to judge whether the occupants can be escaped within the target time.

7.2 Evacuation scenarios

Occupant loading in the airport terminal is high in the peak seasons according to the field survey conducted in Chapter 6.2. Passengers would be waiting inside the waiting areas of the arrival level. Evacuation at this level was considered with the layout shown in Figure 7.1. The geometry of the floor plan in Figure 7.1 was simplified in order to incorporate into both models for carrying out the simulation.

Based on the field survey conducted in the airport terminal [Chow and Ng 2006] as mentioned in Chapter 6.2, high occupant loading was observed in some areas such as the retail areas and departure hall in Table 6.1. The floor space factor of those areas was small and close to the values as indicated in the local codes

[Buildings Department Hong Kong 1996b], i.e. 0.5 $m^2person^{-1}$ for the halls, and 3 $m^2person^{-1}$ in the retail areas.

Four scenarios with different fire locations in the arrival level were identified based on the field survey [Chow and Ng 2006] on areas with high occupant loading in Figures 6.3 & 6.4. These are the retail shops, the areas in front of the retail shops, near the exit 3 or staircases 8 and 9 as shown in Figure 7.1. The designed occupant loading at those areas should follow the floor space factor specified in the local codes [Buildings Department Hong Kong 1996b]. Each scenario will be divided into several sub-scenarios. The conditions of different scenarios and sub-scenarios of the arrival level will be summarized as in Table 7.1. The initial locations of occupants in those sub-scenarios will be illustrated as in Figure 7.7.

The evacuation time of occupants under normal condition and fire condition were investigated in these selected areas in Figures 7.3 to 7.6. Normal condition is the case without a fire. Fire condition means a fire occurs near to the direct exit or staircase. The fire effect is needed to be taken into account and the exit or staircase concerned cannot be used in evacuation. Both normal and fire conditions were simulated in buildingEXODUS, while the simulation in SIMULEX could only be carried out under the normal condition.

- Scenario 1: Retail shops of number 1 to 14

Two sub-scenarios 1a and 1b under normal condition were considered in Table 7.1. Sub-scenarios 1a and 1b were simulated by buildingEXODUS and SIMULEX respectively.

- Scenario 2: Areas in front of the above retail areas

Four sub-scenarios 2a, 2b, 2c and 2d were considered in Table 7.1. Sub-scenario 2a was under fire condition and a fire was assumed to occur inside the shop number 9, such that staircase 3 would not be used for evacuation in the simulation. Sub-scenarios 2b, 2c and 2d were under normal condition.

Sub-scenarios 2a and 2b were simulated by buildingEXODUS. In sub-scenario 2a, the selected area was divided into four zones: fire zone, zones A, B and C as in Figure 7.2. It is a diagram for illustrating the fire effect in the selected zone of different scenarios. The correlated hazard parameters of different zones will be shown in Table 7.2. The shop with area 40 m^2 was the fire zone. Shop numbers 5 to 8 were selected as zone A, while shop numbers 10 to 12 were zone B. The areas of zone A and B were 78 m^2 and 62 m^2 respectively. Part of the arrival hall with area 650 m^2, which is in front of those zones, was zone C. No fire was assigned in sub-scenario 2b such that the areas were not divided into zones.

The occupants with the floor space factor as indicated in the local codes, i.e. 0.5 $m^2 person^{-1}$ for the arrival hall, and 3 $m^2 person^{-1}$ in the retail shops, will be located in the selected zone initially. They will be evacuated to the direct exits or staircases in the arrival level randomly after the fire starts, so as to demonstrate the evacuation pattern of occupants towards different exits or staircases in case of fire.

Sub-scenarios 2c and 2d were simulated by SIMULEX. In order to realize the efficiency of evacuation in utilizing the direct exits only, all staircases in sub-scenario 2d were not connected to staircases and occupants could escape through the exits directly. Results of the evacuation time of occupants in sub-scenarios 2c and 2d would be compared in Figure 7.4.

- Scenario 3: Entrance areas near exit 3

Four sub-scenarios 3a, 3b, 3c and 3d were considered in Table 7.1. Sub-scenario 3a was under fire condition. The fire was assumed to occur near to exit 3 in the entrance areas. During the simulation, this exit would be blocked and was not used for evacuation. Sub-scenarios 3b, 3c and 3d were simulated under normal condition.

Sub-scenarios 3a and 3b were simulated by buildingEXODUS. As shown in Figure 7.2, the selected area in sub-scenario 3a was divided into two zones: fire zone and zone A. As the fire occurred near exit 3, the fire zone was located near that exit, with area equal to 36 m^2. The area in front of exit 3 was selected as zone A with area 504 m^2. No fire was assigned in sub-scenario 3b, so zoning was not applied in the areas as in sub-scenario 3a.

Sub-scenarios 3c and 3d were simulated by SIMULEX. Similar to sub-scenario 2d, all the staircases in sub-scenario 3d became the direct exits. Occupants would escape through the exits directly in this case. Results of the evacuation time of occupants in sub-scenario 3c and 3d would be compared in Figure 7.5.

- Scenario 4: Areas near staircases 8 and 9

Four sub-scenarios 4a, 4b, 4c and 4d were considered in Table 7.1. Sub-scenario 4a was under fire condition, with a fire occurred near the staircase 8 and the staircase would not be used in the evacuation. Sub-scenarios 4b, 4c and 4d were simulated under normal condition.

Sub-scenarios 4a and 4b were simulated by buildingEXODUS. In sub-scenario 4a, the selected area was divided into two zones as in Figure 7.2: fire zone and zone A. As fire occurred near the staircase 8, the fire zone would be located at that staircase, with areas equal to 49 m^2. Area between the staircases 8 and 9 of 273 m^2 was selected as zone A. No fire was assigned in sub-scenario 4b, such that the area was not divided into zones.

Sub-scenarios 4c and 4d were simulated by SIMULEX. Exits in sub-scenario 4d were not connected to staircases. Occupants would escape through the exits directly. The staircases 1 to 11 in sub-scenario 4d became the direct exits. Similar to sub-scenario 3d, occupants escaped through the exits directly in this case. Results of the evacuation time of occupants in sub-scenarios 4c and 4d would be compared in Figure 7.6.

7.3 Design objectives

According to the local MoE codes [Buildings Department Hong Kong 1996b], 300 s (5 min) is a figure used to compile the discharge value high rise building egress under total evacuation situation. It is an unique value as quoted by the local codes for the targeted evacuation time for sprinklered buildings. Therefore, 270 s is likely to be adopted as the evacuation target time for the evacuation analysis. Railway terminal is classified as an assembly occupancy in following the NFPA 101 [Coté 2000], i.e. an occupancy gathered of 50 or more persons awaiting transportation, the target evacuation time was assigned as 270 s for many railway stations in Hong Kong.

An airport terminal has a similar occupancy as the railway terminal. The target TET, which is the time for the last occupant to leave the arrival level, would be set at 270 s as mentioned in Appendix C. The selected range of instantaneous response time was from 0 to 30 s in both models to investigate its effect on evacuation time. On the other hand, widths of the exits would be varied for different areas and the flow rate of people in descending the staircases is taken to be 80 persons $m^{-1}min^{-1}$ [Buildings Department Hong Kong 1996b]. The exit-choice will be determined by the random selection process in the models.

7.4 Fire scenarios

Fire scenarios can be studied in buildingEXODUS. The results from fire models such as zone model are used. In respect to the design fire, it can be a slow, medium, fast or ultra-fast NFPA t^2 fire [e.g. National Fire Protection Association 2000a]. The ultra-fast fire is typical for items made from thin plywood, fast burning upholstered furniture and pool fire such as petrol and other flammable liquid fires [e.g. Karlsson and Quintiere 2000]. The fast fire is applicable to retail shops and restaurants [National Fire Protection Association 2000a]. Therefore, a fast t^2-fire was assigned for the fire condition in buildingEXODUS.

The smoke/ fire interaction with evacuees had been considered in the simulations. The effect of smoke/ fire will be designed as the hazard parameters in Table 7.2, i.e. temperature (T) (in ^{o}C), concentrations of hydrogen cyanide (HCN) (in ppm), carbon monoxide (CO) (in ppm) and carbon dioxide (CO_2) (in %), oxygen (O_2) depletion (in %), visibility (V) (in m^{-1}, instead of dBm^{-1}) and radiative heat flux (R_f) (in kWm^{-2}), and input into the model.

Environmental states of the upper level and lower level of room, which are close to the ceiling and floor, are defined at the selected nodes [Galea *et al.* 1997] for the fire zone in the fire scenarios. The building can be divided into different zones with different hazardous conditions. Values of hazards can be obtained by Fractional Effective Dose (FED) toxicity model, experiments or defined by users [Galea *et al.* 1997].

The hazard parameters H' at a given time t are temperature T, concentrations of CO, CO_2 and HCN, O_2 depletion, V and R_f. H can be expressed in terms of the initial value H_o, and constants m' and p [Galea *et al.* 1997] in Table 7.2. The values of H_o, m' and p would be assigned in the hazard sub-model of buildingEXODUS to realize the influence of fire on the evacuation efficiency in the evacuation process [Gwynne *et al.* 1998b].

$$H' = H_o + m' t^p \qquad \ldots (7.7)$$

As shown in Figure 7.2, the selected areas in scenario 2 were divided into four zones: fire zone, zones A, B and C. The areas were divided into two zones: fire zone and zone A as in scenarios 3 and 4. A 1.3 MW fast t^2-fire, which is similar to burning a soft toy mountain [e.g. Garrad and Smith 1999; National Fire Protection Association 2000a], was used to calculate the radiative heat flux R_f (in kWm^{-2}) of different zones in the sub-scenarios 2a, 3a and 4a. The values of m' and p of R_f can thus be predicted [e.g. Gwynne *et al.* 2001] in Table 7.2.

As there is no experimental data on the fire environment for the airport terminal, the other hazard parameters except R_f were assigned from the default values in the software [Galea *et al.* 1997] for testing the fire effects on evacuation. Those parameters were used by Li and Chow [2000] for carrying out the evacuation study in the local atria, for which the architectural features of the atria are similar to the arrival hall of the airport terminal. Therefore, the hazard parameters illustrated in Table 7.2 would be applicable to the fire occurred in the arrival level of the airport terminal.

7.5 Simulation results

- Scenario 1

The first occupant in SIMULEX passed through the exit after 10 s. The number of people leaving the areas at a certain time in each sub-scenario is compared in Figure 7.3. Results are summarized in Table 7.3, while the direct exits and staircases utilized in the evacuation are mentioned in Table 7.4.

- Scenario 2

The number of people leaving the areas at a certain time in each sub-scenario is compared in Figure 7.4. The results of scenario 2 are illustrated in Table 7.3 and the direct exits and staircases utilized in the evacuation are shown in Table 7.4.

- Scenario 3

The number of people leaving the areas at a certain time in each sub-scenario is compared in Figure 7.5. Results are summarized in Table 7.3 and the direct exits and staircases utilized in the evacuation are shown in Table 7.4.

- Scenario 4

  The number of people leaving the areas at a certain time in each sub-scenario is compared in Figure 7.6. Simulation results are shown in Table 7.3, while the direct exits and staircases utilized are shown in Table 7.4.

The 'snapshots' of the outputs from the simulations of buildingEXODUS will be shown in Figure 7.7. In using SIMULEX, some occupants might not be able to leave the hall, giving an infinite long evacuation time. For those scenarios, the time for the last occupant (not all the occupants!) who could get out is then recorded. The number of occupants who could get out would be less than the occupant loading as illustrated in Table 7.3. The average value over all the individual evacuation time of occupants is also shown in Table 7.3.

CWT is a dynamic attribute calculated by buildingEXODUS. It is a measure of the total amount of congestion time experienced for occupants remained stationary after starting to evacuate [e.g. DeCicco 2002]. Counting of the waiting time of an occupant starts when an individual starts to congest, and it ends when the person caught in the congestion is free to move again, taking WT_1 in the first congestion. The magnitude of the first waiting time WT_1 is recorded. When the next congestion occurs, the waiting time will then end at, say WT_2. For a scenario with x congestions, the CWT is given by:

$$CWT = \sum_{i=1}^{x} WT_i \qquad \ldots (7.8)$$

The longest CWT is the maximum waiting time taken by the occupant in the simulation. The results of the number of people escaped, the number of exits utilized, the longest CWT, the longest moving time, the evacuation time of the last occupant to get out in SIMULEX, the TET and average evacuation time are shown in Table 7.3. The time t_{peak} with the maximum number of people N_{max} escaped; and the time interval Δt regarding the number of people equal to or larger than $N_{max}/2$ are also shown in Table 7.3.

As illustrated in Table 7.3, all the occupants will be evacuated in the sub-scenarios simulated by buildingEXODUS, no matter jamming condition occurs or not; while some of the occupants cannot be evacuated in the sub-scenarios of SIMULEX, when congestion is occurred. The difference between the predictions by buildingEXODUS and SIMULEX implies that under a high occupant loading, the TET of occupants can be generated by buildingEXODUS as the cumulative waiting time (CWT) of occupants is a finite time period in the simulation. The jamming condition of occupants will be ended and all the occupants can be escaped finally. However, the TET of occupants cannot be generated by SIMULEX when the crowd density is reached a level that the inter-person distance between occupants is tended to zero. Due to the small inter-person distance, the moving speed becomes very slow such that a large amount of occupants are jammed in front of the exits and cannot be escaped.

As the occupant loading of the airport terminal is high, it is not able for SIMULEX to generate the TET of occupants. Therefore, buildingEXODUS is considered to be a better model for simulating the TET of occupants in the arrival level of the airport terminal.

7.6 Discussion of the results

- Maximum number of occupants leaving the arrival level

  For the sub-scenario 1a and 1b of Figure 7.3, the maximum number of occupants, i.e. 36.7 % and 22.7 %, left the zone at 40 s. For the sub-scenarios 2a and 2b of Figure 7.4, 27.1 % and 26.1 % of the occupants were evacuated at 100 s and 75 s respectively, while 86.2 % and 85 % of the occupants in sub-scenarios 2c and 2d escaped at 50 s.

  The maximum number of occupants leaving the areas in sub-scenarios 3a to 3d of Figure 7.5 was about 14.4 %, 35.2 %, 10.4 % and 20.6 % at 40 s, 30 s, 40 s and 40 s respectively, while 15.2 % in sub-scenario 4a; 23.3 % in sub-scenario 4b; 50.4 % in sub-scenario 4c and 52.5 % in sub-scenario 4d of Figure 7.6 left the areas at 100 s, 100 s, 50 s and 50 s respectively. However, only a few occupants, i.e. 22 persons, were able to escape in sub-scenario 4c.

  All the evacuation times for the maximum number of occupants leaving the areas in different scenarios are within the target TET in Figures 7.3 to 7.6. The time for the maximum number of occupants leaving the arrival level is considered in order to recognize the congestion occurred around the staircases and direct exits. In the peak period, the maximum number of occupants evacuated in each sub-scenario of buildingEXODUS in Figures 7.3 to 7.6 is larger than the sub-scenarios simulated in SIMULEX when the occupants utilized both the staircases and direct exits to evacuate. This is due to much serious congestions occurred around the staircases in the scenarios simulated by SIMULEX.

- Number of occupants escaped within the target TET

As shown in Table 7.3, the TET of sub-scenarios 1a, 3a and 3b simulated by buildingEXODUS, i.e. 50 s, 171 s and 45 s, is shorter than the target TET. For the same scenario simulated by SIMULEX in sub-scenarios 1b and 3c, the TET is infinity. Only 75 and 1002 occupants were able to escape at 100 s and 180 s, i.e. 94.9 % and 92.8 % of all occupants. For sub-scenario 3d, all the occupants had escaped at 100 s, which is shorter than the TET of occupants in the fire condition as simulated in sub-scenario 3a. When a fire occurred near the direct exit or staircase, that exit or staircase could not be used. This would reduce the number of direct exits or staircases for the occupants to escape. TET would be increased as the occupants needed to travel to other direct exits or staircases which might not be the nearest for them.

No matter there was a fire or not, the TET simulated by buildingEXODUS in sub-scenarios 2a, 2b, 4a and 4b of Table 7.3 is exceeded the target time. The TET is increased from 288 s to 363 s (scenario 2) and 284 s to 548 s (scenario 4) under the fire condition in Table 7.3. About 89.1 % and 55.2 %

of the occupants under the fire condition, 97.5 % and 95.8 % of the occupants under the normal condition in scenarios 2 and 4 evacuated within the target TET.

On the other hand, the TET became infinity for the sub-scenarios 2c and 4c simulated by SIMULEX in Table 7.3. Only 29 and 22 occupants could escape at 100 s and 50 s, i.e. around 2.1 % and 3.4 % of all occupants. In sub-scenarios 2d and 4d of Table 7.3, all the occupants had evacuated at 100 s and 45 s, which is shorter than the target TET. It indicated that the occupants escaped more effectively by means of the direct exits in case of a fire, instead of using the staircases. More direct exits should be provided in the arrival level of the airport terminal.

As shown in Figure 7.6, scenario 4, i.e. areas near the staircases 8 and 9, was the worst scenario among all the scenarios. Occupants in this scenario were not able to evacuate within the target TET even without a fire. On the other hand, only 3.4 % of the occupants in sub-scenario 4c of Table 7.3 could escape from the arrival hall of the airport terminal. This is due to the staircases in this area were congested with occupants. No matter there is a fire or not, the occupants seldom utilize the direct exits as the exits are distant from them and they prefer using the staircases to evacuate.

If there is a fire, the situation will become worse as the occupants may have difficulties in evacuation when the radiant heat exposure and smoke density increase in case of fire [British Standards Institution 1988] and result in the decrease in mobility and crawl speed of the occupants in evacuation [Galea *et al.* 1997]. More attention should be paid on the width of the staircases or direct exits as their widths would be further reduced when occupants are bringing their luggage to escape. In order to minimize the blockage of exits, critical width of the staircases and direct exits should be recognized. If the width of the staircases is not capable to allow the occupants to escape simultaneously, increasing the number of staircases or direct exits should be considered in the arrival hall of the airport terminal.

- Travel distances

The travel distance of occupants was not illustrated in the simulation results of SIMULEX. Only the results of the sub-scenarios simulated by buildingEXODUS can be considered. The longest travel distance for sub-scenarios 2a, 3a and 4a was 45 m, 46 m and 53 m respectively, while it was only 37 m, 20 m and 49 m in sub-scenarios 2b, 3b and 4b. It revealed that the travel distance of occupants in the arrival level of the airport terminal was longer when there was a fire occurred.

Under normal condition, the maximum sum of the direct distance and travel distance of occupants inside the retail areas of the arrival level can fulfill the local code requirement, i.e. not exceed 45 m [Buildings Department Hong Kong 1996b]. This means that the occupants in the retail areas need not to travel a long distance to escape. However, only parts of the occupants (about 44.7% to 72%) are able to travel within the target distance, i.e. 36 m, in the arrival hall [Buildings Department Hong Kong 1996b]. More direct exits of width more than 2 m [Buildings Department Hong Kong 1996b] can be provided in the arrival hall to shorten the travel distance of occupants and hence the TET.

Numerous signs would be observed in the airport terminal for efficient evacuation or internal circulation. Occupants may lose sight of the particular signs for staircases or exits if many signs are populated in one place [Filippidis *et al.* 2006]. Therefore, excess signs should be removed from the areas and leaving only a few exit signs to allow the occupants to locate the staircases or direct exits clearly without travelling a long distance in evacuation.

- Waiting time of occupants

The waiting time of occupants was not illustrated in the simulation results of SIMULEX. Therefore, only the results of the waiting time of occupants simulated in the sub-scenarios of buildingEXODUS in Table 7.3, i.e. sub-scenarios 1a, 2a and 2b, 3a and 3b, and 4a and 4b, would be analyzed.

In Table 7.3, the longest CWT of sub-scenarios 1a and 3b was only 7 s and 3 s respectively, which is only 14 % and 6.7 % of the TET and shorter than the longest moving time in those sub-scenarios. The short CWT in sub-scenarios 1a and 3b was due to the lower occupant loading in the evacuation process, i.e. 79, and most of the occupants, i.e. 98.2 %, utilized two direct exits with width 6 m to evacuate. However, the longest CWT of sub-scenarios 2a and 2b, 3a, and 4a and 4b in Table 7.3 was longer than the longest moving time. The CWT of occupants became a large component in TET, where the moving time needed by occupants was comparatively smaller. This is because most of the occupants needed to queue up before the direct exits or staircases and wait for a long time to pass through.

On the other hand, CWT was longer under the fire condition. This can be verified by the sub-scenarios 2a, 3a and 4a in Table 7.3. For instance, the longest CWT was up to 343 s and 531 s in sub-scenarios 2a and 4a respectively. Those waiting times exceeded the target TET and took up 94.5 % and 96.9 % of the TET in those sub-scenarios. Definitively, it is unacceptable and should be reduced!

The CWT in those sub-scenarios can be minimized by providing more direct exits and staircases of adequate width for occupants to escape or by controlling the number of people staying inside the retail areas and arrival hall of the arrival level.

- Moving time of occupants

Same as the waiting time of occupants, only the moving time of the occupants simulated in the sub-scenarios of buildingEXODUS in Table 7.3, i.e. sub-scenarios 1a, 2a and 2b, 3a and 3b, and 4a and 4b, would be analyzed.

The longest moving time in those sub-scenarios of Table 7.3 varied from 20 s to 109 s, i.e. 9.3 % to 44.4 % of the TET.

If the CWT of occupants is shorter in those sub-scenarios, the TET would not exceed the target evacuation time as moving time only occupied a small portion of TET. Therefore, reduction in CWT of occupants is very important to minimize the TET in those scenarios.

7.7 Conclusion

Emergency evacuation in the arrival level of the airport terminal was studied in Chapters 7.2 to 7.6. Scenarios mentioned in Chapter 7.2 with maximum occupant loading as allowed in the local MoE code were simulated by using buildingEXODUS and SIMULEX. Results illustrated in Table 7.4 showed that jamming occurred around the staircases of the arrival hall and the occupants needed to queue up for a long time. The congestion became worse if the arrival hall was crowded with people. Providing more direct exits with adequate width, e.g. more than 2 m [Buildings Department Hong Kong 1996b] would be an effective method in reducing the waiting time of occupants. On the other hand, controlling the occupant loading is also a good solution to solving the problem of long queues inside the arrival level of the airport terminal.

As shown in Figure 7.6, scenario 4, i.e. areas near the staircases 8 and 9, was the worst scenario among all the scenarios. As the occupants in this scenario would not use the direct exits to escape, this created the biggest challenge for the

Airport Authorities in reducing the evacuation time of the occupants. Clear indication of the exit signs should be provided in this area to direct the occupants to use the direct exits to evacuate. Heed should be paid on the critical width of the staircases and direct exits. If the width of the staircases or exits is not capable to allow the occupants to escape simultaneously, it is needed to increase the number of the staircases or direct exits in the arrival hall of the airport terminal to reduce the evacuation time of occupants.

When a direct exit or staircase was blocked by a nearby fire, occupants would use the other direct exits or staircases. The travel distance of occupants would then increase, such that the occupants would need a longer time to travel to the direct exit or staircase. On the other hand, the reduction in the number of exits or staircases would increase the flow time of occupants passing through the exit or staircase as illustrated in Table 7.4. The occupants would need to queue up for a longer time before the staircase or exit, and the waiting time of evacuation would be extended as in Table 7.3, leading to a higher risk.

Travel distance of the occupants is an important issue. This distance should be taken as a reference for the fire safety management team in designing the location of the direct exits and staircases. Other means, such as clear exit signs, should be provided in the retail areas and arrival hall of the arrival level to ensure the occupants can travel to the nearest exits or staircases with a shorter evacuation time.

Chapter 8 : Waiting time on emergency evacuation

The transport terminals were constructed in the Far East with innovative designs and new architectural features. There are difficulties in complying with prescriptive fire codes on providing means of escapes. Public transport terminals are always under crowded conditions during peak seasons. In case of an emergency, jamming would occur around the exits. Therefore, evacuation during emergency is a key issue to study. For the airport terminal, crowded condition under the maximum loading should be considered to cater to the worst scenario.

Evacuation inside the airport terminal will be studied through detailed scenario analysis in Chapters 8.3 & 8.4. Crowded conditions with maximum occupant loading in the departure level are considered in Table 8.3. The maximum floor space factors allowed in the local codes [Buildings Department Hong Kong 1996b] are 0.5 $m^2 person^{-1}$ in the halls and 3 $m^2 person^{-1}$ for retail areas. Two evacuation models buildingEXODUS [e.g. Gwynne *et al.* 2005] and SIMULEX [e.g. IES 2001; Thompson *et al.* 1996] were selected to study the evacuation time of occupants under the fire and normal conditions in Chapters 8.3. The waiting component in the evacuation time can be used to measure the evacuation efficiency and as an indicator on how long occupants would spend on queuing as mentioned in Chapters 8.2.

8.1 Waiting time

A time line on the evacuation process from ignition can be drawn as in Figure 8.1. The response time RT indicated in Figure 8.1 is the coping time required to initiate effective actions [Stahl et al. 1982]. The time begins when the occupants have decided to take which actions, such as identify the escape route, inform others, assist others or fight the fire after recognizing the occurrence of fire [Pauls, 1987; Sime, 1996].

It is observed that the waiting time would be a large component of TET in crowded spaces as illustrated in Table 8.1. Occupants from different areas converge in front of the exit [Thompson and Marchant 1995c]. They will shuffle along slowly when they get closer [Hankin and Wright 1958; Pauls 1987] and then stop when they cannot move [Thompson and Marchant 1995a]. The occupants will queue up until there is room to move forward. The waiting period can be started counting.

Occupants have to remain stationary and standing behind the front person until that person moves [Thompson and Marchant 1995a]. Queuing time was included in travel time. As reported by Fruin [1971], queuing time t_q was involved as a component of the evacuation time t_{eF} and walking time t_{vF}, in which the response time of occupants would not be included in the equation [e.g. Gwynne *et al.* 1998a].

$$t_{eF} = t_{vF} + t_q \qquad \text{... (8.1)}$$

The queuing time includes the waiting period and moving period in the queues [e.g. Fruin 1971; Melinek and Booth 1975; Pauls 1987]. Two components are suggested in t_q, i.e. waiting time for stationary of queue t_{waF} (in s) and moving time t_{mF} (in s) which is the time taken for a person to move in a queue before reaching the exit [Fruin 1971].

$$t_q = t_{waF} + t_{mF} \qquad \ldots (8.2)$$

Waiting and moving of occupants occur repeatedly in the queuing process until the occupant reaches the exit. Values of t_{waF} and t_{mF} would be alternatively generated under crowded condition. Once an occupant approaches a queue and starts to wait, the movement would be restricted with a long waiting time. The waiting period is ended after the person caught in queue is free to move again. After a very short duration, the next jam may occur and the occupant stops moving forward, waiting time starts again. The total amount of congestion that the occupants have experienced before entering the exit comprises the total t_{waF} encountered in a queue.

t_{waF} will be affected by the high crowd density. The high crowd density will have influence in the inter-person crowd pressure, which may endanger the evacuees in the crowd. The crowd density (in number of person m^{-2}) is inversely proportional to the inter-person distance. The shorter inter-person distance will be incurred a reduction in walking speed of occupants and an increment in inter-person crowd pressure. People will become anxiously waiting or competing to enter the exit [Pauls 1987]. As the crushing force between people is increased, panic situation will be occurred [Melinek and Booth 1975]. The evacuation performance of occupants will be affected and hence resulted in a longer evacuation time in leaving the building or entering a safe place.

8.2 Waiting time index (WTI)

A term "Cumulative Waiting Time" (CWT) was defined by Owen *et al.* [1996] as the total amount of time occupants remain stationary as a result of conflicts or queuing due to crowding, i.e. the time that occupants have to occupy in congestion [Gwynne *et al.* 1998a]. A waiting time index (WTI) is proposed to describe the waiting effect of occupants by comparing the response time RT, motion time MT and CWT as in Figure 8.1.

$$\mathrm{WTI} = \frac{\mathrm{CWT}}{\mathrm{TET}} = \frac{\mathrm{CWT}}{\mathrm{RT} + \mathrm{CWT} + \mathrm{MT}} \qquad \text{… (8.3)}$$

To quantify the extent of congestion occurred in a building, WTI of each person can be derived with respect to RT, MT, t_{waF} and t_{mF}. The i^{th} person would move, wait, and move again, say stopping for n_i times. The maximum total waiting time for the i^{th} occupant would be the value summing up all the waiting time for the stop j^{th} $t_{waFi,j}$. The moving time, t_{mFi}, can be estimated. For a space with m_r occupants, t_{waF} and t_{mF} would be given by:

$$t_{waF} = \sum_{i,j=1}^{m_r, n_i} t_{waFi,j} \qquad \text{… (8.4)}$$

$$t_{mF} = \sum_{i=1}^{m_r} t_{mFi} \qquad \text{… (8.5)}$$

The value of WTI is:

$$\mathrm{WTI} = \frac{\sum_{i,j=1}^{m_r,n_i} t_{waFi,j}}{\mathrm{RT} + \mathrm{MT} + \sum_{i,j=1}^{m_r,n_i} t_{qi,j}}$$

$$= \frac{\sum_{i,j=1}^{m_r,n_i} t_{waFi,j}}{\mathrm{RT} + \mathrm{MT} + \sum_{i,j=1}^{m_r,n_i} \left(t_{waFi,j} + t_{mFi}\right)} \qquad \text{… (8.6)}$$

According to equation (8.3), the terms $\sum_{i,j=1}^{m_r,n_i} t_{waFi,j}$ and $\left(\mathrm{RT} + \mathrm{MT} + \sum_{i,j=1}^{m_r,n_i} \left(t_{waFi,j} + t_{mFi}\right)\right)$ are understood to be the CWT and TET of the occupants respectively. The values of CWT and evacuation time of the individuals can be obtained from the simulation of the evacuation models, such as buildingEXODUS 3.0 [2000]. For example, WTI is 0.67 if CWT and evacuation time of an individual are 40 s and 60 s respectively.

Evacuation performance of occupants at different occupant loading can be studied by some number distribution functions in Figures 8.7 to 8.10. Plotting the number of occupants evacuated against WTI as in Figure 8.11 would give some ideas of waiting time at different occupant loadings.

WTI can be estimated from the simulated evacuation times of each occupant as in Table 8.1. The following can be visualized:

- CWT is the considerable component in TET. For the value of WTI between 0 – 0.5, CWT is not a dominant component in TET. All the occupants can be evacuated within a short TET as they are utilizing less than 50% of time in waiting during the evacuation process. Therefore, the value of WTI between 0 – 0.5 is considered to be acceptable.
- If WTI > 0.5, evacuation time is dominated by waiting time. Occupants have to be queued up and wait to pass through the exits.
- For large WTI with value approaching 1, crowd would be formed at the exits during evacuation.
- For low values of WTI, the waiting time would be a small portion. Waiting is not significant in evacuation.

Values of WTI are lying from 0 to 1. No waiting is required when WTI is 0. Long waiting time would give a WTI very close to 1. Value of WTI is small for fast evacuation.

8.3 Numerical simulations

According to the field survey conducted in Chapter 6.2, occupant loading of the airport terminal would be very high in peak seasons. Passengers used to be queued up at the check-in counters of the departure hall at Level 7. Evacuation in this level was considered with layout shown in Figure 8.2. Four scenarios under normal condition and fire condition were simulated as in Tables 8.3 to 8.6. There is no fire in the normal condition. Fire condition means a fire occurs near to an exit that the associated staircase cannot be used during evacuation. The fire zones are shown in Figure 8.3. It is a diagram for illustrating the fire effect in the selected zone of different scenarios. The correlated hazard parameters of different zones will be shown in Table 8.2.

Four scenarios were selected in the areas where high occupant loading was observed in the field survey as in Figures 6.3 & 6.4. The occupants with the floor space factor as indicated in the local codes, i.e. 0.5 $m^2 person^{-1}$ for the arrival hall, and 3 $m^2 person^{-1}$ in the retail shops, will be located in the selected zone initially in Figure 8.3. They will be evacuated to the direct exits or staircases in the arrival level randomly after the fire starts, so as to demonstrate the evacuation pattern of occupants towards different exits or staircases in case of fire. The initial locations of occupants in those scenarios will be shown in Figure 8.4.

On the other hand, the number of evacuees in each exit is not evenly distributed. Differential loading have been considered on different exits. The occupant loading in each exit will be randomly distributed in the simulations of buildingEXODUS and SIMULEX in Tables 8.3 to 8.6.

The four scenarios of the departure level are:

- Scenario 1: Retail areas of shop number 15 to 41.
- Scenario 2: Areas in front of the above retail areas.

- Scenario 3: Entrance areas near exits 3 and 4.
- Scenario 4: Areas near staircases 14 and 15.

In studying the crowd movement in the airport terminal, maximum occupant loadings allowed in the local fire codes are assumed for each scenario to evaluate the longest evacuation time required. The designed figures illustrated in the codes had been justified by the field studies during the peak seasons as shown in Table 6.1. A summary of the input data on each scenario is shown in Table 8.1.

Both buildingEXODUS and SIMULEX were used for studying the evacuation time as illustrated in Tables 8.3 to 8.6. The occupants in buildingEXODUS and SIMULEX were assigned to be the characteristics of UK people. The reason of selecting the UK characteristics is same as Chapter 7.1. Occupants in buildingEXODUS would be simulated under normal and fire conditions in Figures 8.7 to 8.10, while SIMULEX can only be used in normal condition. The fire condition of the departure level in buildingEXODUS is similar as in Chapter 7.2. All hazard parameters would be shown in Table 8.2.

- Scenario 1

Two sub-scenarios 1a and 1b under normal condition were considered using the two software in Figure 8.7. Sub-scenario 1a was simulated by buildingEXODUS, while SIMULEX was utilized in sub-scenario 1b. Results are summarized in Table 8.1, while the direct exits and staircases utilized in the evacuation are summarized in Table 8.3.

Evacuation patterns for random distribution of occupants predicted at time 40 s by buildingEXODUS and SIMULEX are taken as examples and shown in Figures 8.5 and 8.6. The number of people leaving the areas at a certain evacuation time in each sub-scenario is compared in Figure 8.7. Note that the TET in Table 8.3, taken as the time for the last occupant to leave, was infinite long in sub-scenario 1b in using SIMULEX. Some occupants were not able to escape to a safe place.

- Scenario 2

Four sub-scenarios 2a, 2b, 2c and 2d were considered in Figure 8.8. Sub-scenario 2a was under fire condition with a fire occurred inside the shop number 18. Sub-scenarios 2b, 2c and 2d were under normal condition.

Sub-scenarios 2a and 2b were simulated by buildingEXODUS in Figure 8.8. In sub-scenario 2a, staircase 7 was blocked and the selected area was divided into 4 zones: fire zone, zones A, B and C as in Figure 8.3. The fire zone was in the shop with area 56 m^2. Shop numbers 15 to 18 were assigned in zone A and shop numbers 20 to 23 in zone B. The areas of zone A and B were 68.25 m^2 and 50.75 m^2 respectively. Part of the departure hall in front of zones A and B with areas 750 m^2 was zone C. As there was no fire in sub-scenario 2b, the selected areas were not divided into zones.

Sub-scenarios 2c and 2d were simulated by SIMULEX in Figure 8.8. Note that the staircases 1 to 24 in sub-scenario 2d would be changed to the direct exits such that the occupants would escape through the exits directly. Results of the occupants utilizing only the direct exits to escape can be compared with the utilization of both the staircases and direct exits as in sub-scenario 2c in Figure 8.8.

The results of scenario 2 are illustrated in Table 8.1 and the direct exits and staircases utilized in evacuation are shown in Table 8.4. Comparison of the number of people leaving the areas at a certain evacuation time in each sub-scenario was shown in Figure 8.8.

- Scenario 3

Four sub-scenarios 3a, 3b, 3c and 3d were considered in Figure 8.9. A fire near exits 3 and 4 of the entrance areas was assigned in sub-scenario 3a, while the sub-scenarios 3b, 3c and 3d were under the normal condition.

Sub-scenarios 3a and 3b were simulated using buildingEXODUS in Figure 8.9. As shown in Figure 8.3, the selected area in sub-scenario 3a was divided into 3 zones: fire zone, zones A and B. The fire zone was located between exits 3 and 4, with an area of 44 m^2. The corridors connected to the entrance areas was zone A; with areas 472.5 m^2. Zone B was the area of the departure hall connected to the corridors. It is equal to 300 m^2. The exits 3 and 4 were blocked and could not be used for evacuation in case of fire. No fire was assigned in sub-scenario 3b such that zoning would not be applied in the areas as in sub-scenario 3a.

Sub-scenarios 3c and 3d were simulated by SIMULEX in Figure 8.9. The staircases 1 to 24 in sub-scenario 3d were become the direct exits. Occupants would be escaped through the exits directly to identify the difference in evacuation time as in sub-scenario 3c, when the occupants were only utilized the direct exits to escape.

Results are summarized in Table 8.1 and the direct exits and staircases utilized in evacuation are shown in Table 8.5. Comparison of the number of people leaving the areas at a certain evacuation time in each sub-scenario was shown in Figure 8.9.

- Scenario 4

Four sub-scenarios 4a, 4b, 4c and 4d were considered in Figure 8.10. Again, a fire was assigned in sub-scenario 4a, which was near the staircase 15. Sub-scenarios 4b, 4c and 4d were simulated under normal condition.

Sub-scenarios 4a and 4b were simulated by buildingEXODUS in Figure 8.10. In sub-scenario 4a, staircase 15 was blocked and the selected area was divided into 2 zones as in Figure 8.3, i.e. fire zone and zone A. As the fire occurred near staircase 15, the fire zone of areas 40 m^2 would be located near the staircase, while the areas of 871.5 m^2 between exits 14 and 15 was labelled as zone A. No fire was assigned in sub-scenario 4b such that the areas would not be divided into zones.

Sub-scenarios 4c and 4d were simulated by SIMULEX in Figure 8.10. The staircases 1 to 24 in sub-scenario 4d would become direct exits. Similar to sub-scenario 3d, occupants escaped through the exits directly in this case so as to determine the difference in evacuation time as in sub-scenario 4c.

The simulation results were shown in Table 8.1 and the direct exits and staircases utilized were shown in Table 8.6. Comparison of the number of people leaving the areas at a certain evacuation time in each sub-scenario was shown in Figure 8.10.

The crowd density at each exit has been considered in the evacuation simulations. According to the simulation results of buildingEXODUS and SIMULEX for the four scenarios in Tables 8.3 to 8.6, the crowd density at each exit is exceeded 2 persons m^{-2} and the occupants need to wait for a long time before passing through the exit.

All the occupants will be evacuated in the scenarios simulated by buildingEXODUS as illustrated in Table 8.1, no matter jamming condition occurs or not. Large volume of data on age, weight, travel distance, response time (in s), cumulative waiting time (CWT) (in s) and evacuation time of each occupant are generated. On the other hand, some of the occupants cannot be evacuated in the scenarios of SIMULEX in Table 8.1, when congestion is occurred. The difference between the predictions by buildingEXODUS and SIMULEX is similar to the description as mentioned in Chapter 7.5. As the occupant loading of the airport terminal is high, it is not able for SIMULEX to generate the TET of occupants. Therefore, buildingEXODUS is considered to be a better model for simulating the TET of occupants in the departure level of the airport terminal.

From the 95th percentile results (i.e. number of people evacuated are 192, 114, 627 and 2 in sub-scenarios 1b, 2c, 3c and 4c) as illustrated in Table 8.1, the occupants started to jam at the exits at 680 s, 700 s, 84 s and 30 s respectively. The evacuation times of the 99th percentile results (i.e. number of occupants are 200, 118, 653 and 2 in sub-scenarios 1b, 2c, 3c and 4c) in Table 8.1 are 700 s, 760 s, 93 s and 30 s respectively.

8.4 Discussions on WTI

WTI of a building can be evaluated by the waiting time and TET simulated through the evacuation model, such as buildingEXODUS 3.0 [2000]. Results from the scenarios of the departure level as mentioned in Chapter 8.3 would be applied to study the jamming condition of occupants. As waiting time of occupants was not illustrated explicitly by SIMULEX, only the results of the sub-scenarios simulated by buildingEXODUS in Table 8.1 were applied to assess the WTI. Results of the CWT from the simulated sub-scenarios in Table 8.1 can be applied to study the jamming condition of occupants.

WTI depends on the occupant loading. If there are very few occupants, say only 1 people, the waiting time is zero, giving zero WTI. A higher occupant loading will result in a longer waiting time, thus giving a value of WTI closer to 1. Additional scenarios were simulated for sub-scenarios 1a, 2a, 2b, 3a, 3b, 4a and 4b to study the correlation of WTI with the number of occupants in Table 8.7. The number of occupants evacuated is plotted against the WTI in Figure 8.11.

From the simulation in Table 8.7, it is observed that CWT of occupants is a large component of the evacuation time no matter in the fire condition or normal condition. This is due to the overcrowding occurred during the evacuation and occupants needed to wait to enter the direct exits or staircases in those scenarios. Most occupants had to queue up before the direct exits or staircases and waited for a long time to pass through. As illustrated in Figure 8.11, WTI for different occupant loadings varied from 0.05 to 0.96. The value of WTI increased with the number of occupants to be evacuated in Table 8.7. Scenarios with WTI higher than 0.5 should be improved.

WTI was much higher under the fire condition as shown in Figure 8.11. For example, the WTI was up to 0.93 in sub-scenario 3a. The value was only 0.82 in sub-scenario 3b for 1634 occupants to evacuate. Such high value is not acceptable and should be reduced by increasing the number of direct exits and staircases or controlling the number of people staying inside.

For the scenarios with a short CWT as illustrated in Table 8.1, TET for some sub-scenarios, such as 1a and 3b, would not exceed the targeted time. Therefore, reduction in CWT of occupants is very important, so as to minimize the TET in those scenarios.

WTI can be reduced by increasing the number of direct exits and staircases at the departure level. As shown in Table 8.1, the time to utilize the direct exits in sub-scenarios 2d, 3d and 4d are 960 s, 755 s and 110 s respectively, for 1118, 1234 and 370 persons to escape. The number of occupants who were able to escape at 800 s, 100 s and 50 s were 986, 855 and 256 respectively. More occupants could leave in sub-scenarios 2c, 3c and 4c at the same evacuation time, i.e. 800 s, 100 s and 50 s. More effective evacuation can be resulted using the direct exits, instead of staircases.

8.5 Reduction of waiting time

Waiting time can be reduced by selecting the right exits and staircases. Optimal use of all exits and staircases in a building [e.g. British Standards Institution 2004] is important. However, the exits and staircases are difficult to have a simultaneous maximum flow [Thompson and Marchant 1995a]. Selection of exits and staircases depends on the awareness of its existence through visual contact. If the exits or staircases are not visible, occupants may get the information from neighbouring persons and procedural influence such as the alarm system. They would also move to the exits or staircases which they have previous experience [British Standards Institution 2004]. Therefore, the departure hall in the airport terminal should be provided with clear exit signs. On the other hand, appropriate public announcements can ensure the occupants to recognize the location of exits and staircases in case of an emergency.

Inadequate exit width will restrict the flow capacity and result in inconvenience and forming queue [Ando *et al.* 1988; Polus *et al.* 1983]. For a wider exit, crowd density in a queue can be reached to give a shorter waiting time. A narrower exit would constitute a greater flow density but the freedom of movement for occupants in a queue would decrease. Critical value of exit width should be determined to ensure maximum flow rate for minimizing the waiting time.

8.6 Conclusion

Emergency evacuation in the departure level of the airport terminal was studied in Chapters 8.3 & 8.4. Scenarios with maximum occupant loading in following local MoE code simulated by buildingEXODUS and SIMULEX were carried out. Results in Tables 8.3 to 8.6 showed that jamming occurred around the staircases of the departure hall. The maximum number of occupants entering the departure level of the airport terminal should be monitored carefully. Control of the occupant loading would be a good solution for solving the problem of long queues and ensuring the occupants to evacuate efficiently from the retail areas and departure hall in case of fire.

The number and width of exits and staircases in the departure level might not be adequate. People who got into a panic would have longer response time during evacuation. When some staircases were blocked because of a fire occurred nearby, occupants would be evacuated through the other exits. Reducing the number of exits would give a longer time to queue up (if there is still an orderly queue!) in front of the exits and the waiting time for evacuation would be extended as illustrated in Table 8.1. The risk of occupants being subject to fire and smoke would then increase.

WTI can be an index on assessing the evacuation design as mentioned in Chapter 8.2. It is good to evaluate overcrowded conditions inside the existing buildings. WTI can be deduced from the simulation results in Table 8.1. The value of WTI will increase with the number of occupants evacuated in each sub-scenario as illustrated in Table 8.7. In most scenarios of Figure 8.11, values of WTI are approaching 1. This indicated that waiting time occupies a very large portion of TET for airport terminal.

Chapter 9 : Full-scale burning tests for pre-flashover and post-flashover retail shop fires

For assessing the consequences of a fire, possible heat release rates (HRR) (in MW) [e.g. Babrauskas and Grayson 1992; Peacock *et al*. 1994] should be studied experimentally so as to obtain the maximum amount of heat released (in J) upon burning up all combustibles under adequate ventilation and high temperature. A design fire depends on the use of building and the combustibles present [Garrad and Smith 1999]. HRR [e.g. Babrauskas and Grayson 1992; Peacock *et al*. 1994] can be used as input parameters for fire models in Chapter 7.4 to study the fire environment. Value used [e.g. Chow 2001e] is up to 7 MW for terminal halls. It is difficult to decide the accuracy of value as there is no database for local combustibles.

For the small retail shops locate in the departure level and arrival level, only selected combustibles are allowed to store. Examples are newspapers and magazines; cigarettes and tobacco; alcohols up to 75 ℓ; furniture including polyurethane foam sofas or cushions; coffee tables with wood or other timber products and chairs. Flame spreading of the building materials can be controlled as fibreglass composites and flammable aerosols are not allowed.

Full-scale burning tests carried out on some selected shops as in Table 9.1 is necessary to observe the HRR given by those combustibles. Performance of the fire suppression systems such as sprinkler system and water mist fire suppression system on those shops [Chow *et al*. 2003; Chow and Yao 2001] will be demonstrated in Figures 9.8a to 9.9d and 9.15a to 9.17d. Consequences of flashover fires for some dangerous arrangements are also studied in Chapter 9.3.

9.1 Full-scale burning tests

According to the risk assessment of the retail areas of airport terminal in Table 4.3, it is recognized that the retail shops will constitute a high fire risk to occupants. In case of fire, the HRR given out by the combustibles in a retail shop shall be paid attention to. Therefore, a set of full-scale burning tests as illustrated in Table 9.1 will be carried out to study the HRR resulted from burning combustible items in the small retail shops of airport terminal. The aim of the fire tests is to obtain the HRR for the local combustibles in a retail shop and hence identify its impact to the airport terminal with suitable fire models as in Chapter 7.4.

Burning tests of several fire scenarios under flashover condition are performed in a new full-scale burning facility, the PolyU/HEU Assembly Calorimeter [Chow 2001e; Chow *et al*. 2003] as shown in Figure 9.2. The facility is developed as a collaboration project between the Harbin Engineering University (HEU) and The Hong Kong Polytechnic University (PolyU). The role of the candidate in the tests is to develop the experimental procedures for the tests of the pre-flashover and post-flashover retail shop fires, collaborate with the technical and academic staff, supervise and carry out part of the test, investigate the flame spreading over the combustibles and analyze the data, while the calibration of Calorimeter and set up of experiments are performed by the technical specialists of HEU.

The experiments are carried out in Lanxi, a remote area in Harbin, Heilongjiang, China as shown in Figure 9.1. An exhaust hood with a fan-duct system in Figure 9.2 is developed to measure the HRR through the oxygen consumption method [e.g. Babrauskas and Grayson 1992]. The tests are carried out in a room of length 3.6 m, width 2.4 m and height 2.4 m, with a door of height 2 m and width 0.8 m as shown in Figure 9.2. It is built at the experimental hall in Lanxi as shown in Figure 9.3.

As the cotton materials and plastic materials are considered with a high HRR and easily be ignited, the short sleeves T-shirts made of 100% cotton and CDs with boxes in Figures 9.5a & 9.14b are taken as examples. The arrangement of the tests will be in accordance with the real situation of the combustibles in the boutiques and CD shops of the airport terminal. Six fire scenarios in Table 9.1, i.e. B1 to B6, are tested to assess the boutiques as the shops will be contained a large amount of cotton products and may create a high fire hazard for occupants. Those scenarios are the major scenarios for different fire locations, types and conditions of fire, and fire suppression systems. Short sleeves T-shirts made of 100% cotton hanged on an iron clothes hanger are taken as combustibles. On the other hand, three fire scenarios C1 to C3 in Table 9.1 are tested for retail shops selling CDs. The test conditions of the fire scenarios of boutiques and CD shop will be shown in Table 9.1.

The T-shirts hanged on the iron clothes hangers and displayed CDs in Figures 9.5a & 9.14b will be arranged in the test room and under pre-flashover or post-flashover condition. Flashover is set off by burning 4000 ml of gasoline.

This is similar to test the materials by a cone calorimeter [e.g. Babrauskas and Grayson 1992] where the samples are exposed under a radiative heat flux of 20 kWm^{-2}. In pre-flashover condition, fire will only be started manually by an igniter.

9.2 Results of those tests

The followings are the tests carried out for boutique and CD shops as in Table 9.1:

- Test B1: Clothes ignited by an igniter

  Diagram of an iron clothes hanger of length 2.1 m, width 0.7 m and height 1.2 m is shown in Figure 9.4. The hanger is put at the centre of room. There are four iron racks on the clothes hanger. Twenty-four pieces of T-shirts are hanged on each iron rack vertically by iron T-shirts hangers and therefore ninety-six pieces of T-shirts are hanged on the hanger. The T-shirts are same size and each T-shirt is covered by a transparent plastic bag as in Figure 9.5a.

  The layout of clothes is shown in Figure 9.5a. Clothes on rack 1, which are the farthest from the door, are ignited initially. Twenty-two thermocouples are utilized in this experiment. Thermocouples T1 to T6, M1 to M6, C1 to C6 and D1 to D4 are placed at ceiling, left wall, door and door side as in Figure 9.5b.

The graphs of heat flux, room temperature, HRR and oxygen consumption are shown in Figures 9.6a to 9.6d. It is observed that the peak HRR can rise up to 1.2 MW in Figure 9.6c. Values are higher than 1 MW within a burning period of 40 s in Figure 9.6c. Air temperatures are up to 830°C in Figure 9.6b.

- Test B2: Clothes ignited by a gasoline pool fire

The set up of experiment is same as Test B1 in Figures 9.5a & 9.5b, except the clothes are ignited by a pool fire. Gasoline of 4000 ml is placed in a pool of diameter 0.5 m and located in the centre of the room to get flashover. Locations of thermocouples are same as Test B1 in Figure 9.5b. T-shirts are ignited spontaneously by the heat flux given by the flashover fire.

Heat flux, room temperature, HRR and oxygen consumption curves are shown in Figures 9.7a to 9.7d. Note that the maximum HRR of the clothes and gasoline, and gasoline only is up to 2.4 MW and 0.47 MW respectively in Figure 9.7c, which is higher than Test B1. Values of HRR are above 1.5 MW of over 170 s of the burning period in Figure 9.7c. The maximum air temperatures are up to 880°C in Figure 9.7b.

- Test B3: The room installed with water mist fire suppression system (WMFSS)

The experiment set up is similar to Test B2 and illustrated as in Figure 9.5c. A pool fire of 0.5 m diameter with 4000 ml gasoline is used to set the flashover. A WMFSS is installed in the fire test room in Figure 9.5c. The system comprises a water mist nozzle, water tank, pipes and other components. Pressure and flow rate of the system are set at the maximum value, i.e. 15 bars and 0.24 ls^{-1}. Nozzle is installed near the centre of the ceiling. Locations of thermocouples are same as Test B1 in Figure 9.5b. T-shirts are ignited spontaneously. WMFSS is activated manually once clothes are ignited.

Transient results on heat flux, room temperature, HRR and oxygen consumption are shown in Figures 9.8a to 9.8d. As WMFSS is activated manually once clothes are ignited, i.e. about 100s, the maximum HRR of clothes is only up to 1.6 MW in Figure 9.8c. Values of HRR are above 1 MW of over 100 s of burning time in Figure 9.8c, while the maximum air temperature is only up to 720^{o}C as illustrated by thermocouple T2 in Figure 9.8b.

- Test B4: The room installed with sprinkler system

The set up of experiment is similar to Test B1 and illustrated as in Figure 9.5d. Clothes in rack 1 are ignited initially by an igniter. Sprinkler system is installed in the fire test room in Figure 9.5d. Sprinkler head without the sensing element is connected to the pipe sections, water pump and water tank. Pressure and flow rate of the system are set at the maximum value, i.e. 11 bars and 2.9 ls^{-1}. The sprinkler is installed near the centre of ceiling. Locations of thermocouples are same as Test B1 in Figure 9.5b. Although the activation temperature of sprinkler head is set at 68°C, it is not the real actuation temperature. Therefore, a hypothesis is taken such that the sprinkler system will be activated manually with a delay of 30 s after the thermocouple T4 reaches 68°C, i.e. the system is manually actuated when T4 reaches 164°C.

Results of heat flux, room temperature, HRR and oxygen consumption are shown in Figures 9.9a to 9.9d. As clothes are only ignited by an igniter and the sprinkler system will be manually actuated at 125 s, i.e. 30 s later after thermocouple T4 reaches 68°C, maximum HRR and maximum air temperatures are only up to 0.8 MW and 360°C respectively in Figures 9.9c & 9.9b.

- Test B5: Clothes ignite under the hood

The clothes are ignited under the hood in Figure 9.10 by an igniter to realize the HRR under free burning condition. In order to prevent the fire from becoming too vigorous, only eight T-shirts are ignited. The hanger is put at the centre of hood. Photo of hood is shown in Figure 9.10. Eight pieces of T-shirts are hanged vertically together on rack 1. Each T-shirt is covered by a transparent plastic bag. Clothes in the middle of rack 1, will be ignited initially.

HRR and oxygen consumption curves are shown in Figure 9.11a and 9.11b. Although the maximum HRR is only up to 0.4 MW in free burning condition in Figure 9.11a, the predicted maximum HRR will be up to 4.6 MW if ninety-six clothes are burnt. The values are higher than 2 MW within a burning period of 70 s in Figure 9.11a.

- Test B6: Clothes ignite without transparent plastic bags

The set up of experiment is similar to Test B2 in Figures 9.5a & 9.5b, except the clothes are ignited without covered by transparent plastic bags as in Figure 9.5a. Gasoline of 4000 ml is placed in a pool of diameter 0.5 m and located in the centre of room to get flashover. T-shirts are ignited spontaneously. The layout of thermocouples is shown in Figure 9.12. Positions of thermocouples M1 to M6 are changed to the centre of room. For other thermocouples, the locations are same as Test B1 in Figure 9.5b.

Heat flux, room temperature, HRR and oxygen consumption curves will be shown in Figures 9.13a to 9.13d. Note that the maximum HRR is up to 1.9 MW in Figure 9.13c, which is much lower than the value of Test B2 in Figures 9.7c, i.e. 2.4 MW. HRR is above 1.5 MW within a burning period of 120 s in Figure 9.13c. However, the maximum air temperatures in Figure

9.13b will be up to 915^{o}C as measured by thermocouple M3, which is higher than the maximum temperature in Test B2.

- Test C1: The room installed with WMFSS

CD displays of width 1.5 m and height 1.6 m are put at the left and back walls of the room in Figure 9.2. The diagram of display and layout of CDs are shown in Figure 9.14a and 9.14b. There are 10 rows in each display. Each row has an array of 8 x 3 CDs and a total of 240 CDs are put in each display. 480 CDs will be utilized in this experiment. Gasoline of 4000 ml is placed in a pool of diameter 1 m to get flashover. Twenty-two thermocouples will be utilized in this experiment. Thermocouples T1 to T6, M1 to M6, C1 to C6 and D1 to D4 are placed at ceiling, centre of room, door and door side as in Figure 9.12, which have the same positions as those in Test B6. CDs will be ignited by the thermal radiative heat flux.

WMFSS will be installed and operated manually during the experiment. Pressure and flow rate of the system are set at 15 bars and 0.24 ls^{-1} respectively. A water mist nozzle is installed near the centre of ceiling as in Figure 9.5c. The system will be activated and turned off periodically to evaluate the performance of WMFSS in controlling the fire.

Heat flux, room temperature, HRR and oxygen consumption curves are shown in Figures 9.15a to 9.15d. At a short period of about 70 s after the activation of WMFSS, air temperatures are decreased tremendously.

Temperatures of thermocouples M1 to M6 located in the centre of room are decreased from 1000°C to about 60°C in Figure 9.15b. HRR are also reduced to lower values in as in Figure 9.15c. Temperatures and HRR are increased again in Figures 9.15b & 9.15c after the water supply is turning off. However, such increments are not large, i.e. only about 130°C and 0.18 MW.

It is observed that the peak HRR for the CDs and gasoline, and gasoline can up to 4 MW at 290 s and 1.1 MW at 180 s in Figure 9.15c. HRR are higher than 2 MW over 100 s of burning time in Figure 9.15c. The maximum air temperatures in Figure 9.15b also increase to 1130°C as measured by thermocouple M2, which is higher than the highest temperatures measured in Tests B1 to B6.

- Test C2: The room installed with WMFSS

The set up of experiment is same as Test C1 in Figures 9.14a & 9.14b. A pool fire of 1 m diameter with 4000 ml gasoline is used to get flashover. Locations of thermocouples and water mist nozzle, pressure and flow rate of WMFSS are same as Test C1 as in Figure 9.12. WMFSS is actuated manually once a row of CDs is ignited. The mist will be discharged continually until the fire is extinguished.

Results of heat flux, room temperature, HRR and oxygen consumption are shown in Figures 9.16a to 9.16d. As WMFSS is actuated manually once a row of CDs is ignited, heat flux, air temperatures, HRR and oxygen consumption of the experiment are not reached the peak as in Test C1 in Figures 9.15a to 9.15d. Maximum air temperatures and HRR are about 520^oC and 0.7 MW respectively in Figure 9.16b & 9.16c, which is smaller than the values for igniting the gasoline only, i.e. 535^oC and 1.1 MW. Air temperatures and HRR are decreased gradually in Figure 9.16b & 9.16c as the mist is discharged continually.

- Test C3: The room installed with sprinkler system

Set up of the experiment is same as Test C2 in Figures 9.14a & 9.14b. A pool of 1 m diameter and 4000 ml of gasoline is used to give a flashover fire. Sprinkler system will be installed in the fire test room. Pressure and flow rate of the system are set at 11 bars and 2.9 ls^{-1} respectively. A sprinkler head without the sensing element will be installed near the centre of ceiling as in Figure 9.5d. Locations of thermocouples are same as Test C1 in Figure 9.12. CDs are ignited vigorously by the heat flux due to flashover fire. Once a row of CDs is ignited, the system will be activated manually until the fire is put out.

Transient results on heat flux, room temperature, HRR and oxygen consumption are shown in Figures 9.17a to 9.17d. Same as Test C2, sprinkler system is activated once a row of CDs is ignited. Heat flux, air temperatures, HRR and oxygen consumption are lower than Test C1 in Figures 9.15a to 9.15d. Maximum air temperatures and HRR are only about 410^oC and 0.6

MW respectively in Figures 9.17b & 9.17c, which is smaller than the values for igniting gasoline only, i.e. 535°C and 1.1 MW.

9.3 Discussion of the results and observations obtained

Flashover is defined as the transition from a glowing fire to a fully developed fire in which all combustibles in the room are involved in fire [Walton and Thomas 1995]. In normal condition, it is difficult to recognize whether the flashover is happened inside the room. Therefore, three practical criteria will be used to assess the occurrence of flashover. Flashover will be occurred if the following criteria are matched [Society of Fire Protection Engineers and National Fire Protection Association 2002]:

- Upper layer temperature inside the room reaches 550 to 600°C.
- Heat flux at the floor level reaches 20 kWm^{-2}.
- Flame is coming out from the openings of room.

When the flame reaches ceiling, it will be deflected horizontally. Flashover is occurred when the flame of the upper layer become yellow, i.e. temperature of the upper level reaches 550 to 600°C. Radiative heat fluxes in the upper level will be transferred to the lower level and caused the combustibles to reach their ignition temperatures. Heat fluxes will be transferred between combustibles. Finally, all combustibles in the compartment are ignited together.

The amount of gasoline used for setting off flashover is adjusted to 4000 ml. HRR curves for burning the gasoline only are shown in Figures 9.7c, 9.8c, 9.13c and 9.15c. These curves demonstrate that the heat liberate from the pool fire is lower than the shop contents. However, for the experiments of CDs in Tests C2 and C3, HRR curves in Figures 9.16c to 9.17c for burning the gasoline are higher than igniting the CDs. This is due to the WMFSS in Test C2 and sprinkler system in Test C3 is activated once a row of CDs is ignited. Heat liberated by CDs is cooled down by mists or water discharged before reaching its maximum level.

The followings are observed from the full-scale burning tests on boutique:

- As clothes are hanged vertically in Figure 9.5a, flame and hot gases will spread vertically upward when the bottom parts of clothes are ignited. Flame spread rate upon T-shirts will be very fast [Drysdale 1999]. Clothes are burnt completely and cannot be self-extinguished.

- Only T-shirts on racks 1 and 2 will be ignited in Test B1. Flashover occurs at around 195 s when thermocouple T2 reaches 550^{o}C in Figures 9.6b and the flame is come out from door.

- HRR of Test B2 in Figures 9.7c is higher than Test B6 in Figures 9.13c, in which the clothes are not covered by transparent plastic bags as in Figure 9.5a. The difference between the HRR is about 0.5 MW in Figures 9.7c & 9.13c. Locations of thermocouple tree in Figures 9.5b & 9.12 are different in those tests. The tree is located in the centre of room in Test B6 in Figure 9.12, i.e. closer to the pool, maximum temperature measured in Test B6 in Figure 9.13b will be higher than Test B2 in Figure 9.7b.

- In the tests, the heat flux is not measured properly in Figures 9.8a, 9.9a, 9.13a, 9.15a, 9.16a & 9.17a due to the fault in the heat flux meter. As there is no local HRR database for different types of local combustibles, the objective of the tests is to identify the HRR of combustibles in a retail shop in Figures 9.6c, 9.7c, 9.8c, 9.9c, 9.11a, 9.13c, 9.15c, 9.16c & 9.17c and its impact to the airport terminal with suitable fire models. Therefore, the measurement of the heat flux in Figures 9.8a, 9.9a, 9.13a, 9.15a, 9.16a & 9.17a is not the key point such that it is considered to be acceptable.

- As the heat flux meter is covered by burnt clothes at around 170 s in Test B6, heat flux measured is suddenly dropped to 0 kWm^{-2} in Figure 9.13a. The heat flux is normal again in Figure 9.13a at 190 s and risen to its maximum point, i.e. 3.3 kWm^{-2}.

- The burning time of clothes in Test B4 in Figure 9.9c is shorter than Test B3 Figure 9.8c. This is due to the clothes in Test B4 are ignited by an igniter, while the clothes in Test B3 are ignited by pool fire. Water discharged by sprinkler system, i.e. 2.9 ls^{-1}, is higher than the WMFSS, i.e. 0.24 ls^{-1}. Only some T-shirts are ignited in Test B4 as the clothes are wet by large amount of water.

- Clothes are ignited vigorously under free burning condition in Test B5. Although only 8 T-shirts are ignited, HRR is high in Figure 9.11a. As the fire is fuel-controlled, i.e. sufficient air is provided for clothes to burn, HRR will not be affected by the room environment. Little CO is formed as the combustion is near-complete [Gottuk and Roby 1995].

Full-scale burning tests on CD slips:

- CDs and CD boxes are not totally consumed in those experiments. Most of the CDs are not damaged as they covered by CD boxes. As the CDs are made of polycarbonate, they are tough and have a high temperature resistance [Lemaster 1994]. Only a few CDs and CD boxes are broken and melted as illustrated in Figures 9.18a to 9.18c. On the other hand, the CD boxes are made of polystyrene (PS) [Zhang 2003]. They are not able to withstand the temperature as in CDs. Most of the boxes are broken, melted and stuck with other CD boxes.

- Due to the airflow induced by fire, many CDs drop to floor or even the pool. Those CDs are ignited easily. The fire becomes very vigorous in a short period. As CDs and CD boxes are made of plastics, i.e. carbon products, large amount of black soots are given out and spread through the whole environment. The flame is also covered by the 'black' smoke.

- The fire is controlled quickly once the sprinkler system or WMFSS is activated. However, HRR of Test C3 in Figure 9.17c is much lower than Test

C2 in Figure 9.16c. This is because the water discharged by sprinkler system, i.e. 2.9 ls^{-1}, is larger than WMFSS, i.e. 0.24 ls^{-1}, the heat liberate will be easier to absorb and cool down by water in Test C3.

9.4 Conclusion

Possible HRR of combustibles under flashover condition is determined for retail shops in Figures 9.6c, 9.7c, 9.8c, 9.9c, 9.11a, 9.13c, 9.15c, 9.16c & 9.17c. Flashover is obtained by a liquid pool fire with the amount of gasoline adjusted carefully. Once the flashover occurs, i.e. 550°C near the ceiling or 20 kWm^{-2} of radiative heat flux at floor level, pool fire will only be sustained for a short time. The followings can be concluded from the full-scale burning tests carried out:

- Peak HRR for CDs is up to 4 MW in Test C1 in Figure 9.15c, with flame filling up the entire room. If the retail shop is located in a large hall, this 4 MW burning object will give a big thermal plume [Chow 2002a].

- As the HRR for CDs is high as illustrated in Figures 9.15c, 9.16c & 9.17c, the stock of CDs keeping in a CD shop shall be paid heed to. The value of HRR for CDs in Figures 9.15c, 9.16c & 9.17c can be utilized for recognizing the design parameters such as the fire size, flame height, smoke temperature and mass flow rate, and the volumetric flow rate required by the smoke extraction system and make-up air system for a CD shop in the fire engineering study.

- Only one vertical clothes hanger in Figure 9.5a and two vertical CD displays in Figure 9.14b are tested for boutiques and CD shops in the full-scale burning tests. In real situations, large quantities of goods will be kept in a shop. Burning huge amount of combustibles under flashover condition will have a high HRR as in Figures 9.7c, 9.8c, 9.13c, 9.15c, 9.16c & 9.17c. Fire will spread out quickly to the adjacent shops.

- It appears that the sprinkler system is good in suppressing the fire. If the system is activated at right time, fire is probably controlled. However, there may be water damage in discharging excessive water. On the other hand, arrangement of sprinkler heads should be carefully designed. The bottom of sprinkler head shall not be covered by anything to affect its thermal sensitivity. At the same time, the sprinklers cannot be blocked by shelves or stocks to influence the system actuation and the discharged water from reaching the floor.

- Water mist system appears to be useful in suppressing fire. The fire is extinguished within a reasonable time after the water discharged. In the test, the WMFSS will be activated and turned off periodically for every 30 s in Test C1 for evaluating the performance of WMFSS in controlling the fire. During the activation of WMFSS, the fuel surface temperature and HRR will be reduced in Figures 9.15b & 9.15c. However, the fire will not be totally extinguished in Figures 9.15b & 9.15c as the WMFSS is only operated for a short time. Due to the insufficient amount of water mist, the high fuel surface temperature and combustible vapour inside the room will cause the fire to be re-ignited again and HRR increased again in Figure 9.15c once the water supply is cut off. This will not be easily happened for conventional sprinkler system as the fire is probable controlled when the system activated at right time. Therefore, water should be kept on discharging continually for utilizing the WMFSS to control the fire.

Fire safety provisions are normally designed for protection against accidental fires. However, number of arson fires over the world has increased [Chow 2001e; South China Morning Post 2003] in recent years. The hidden fire hazard in the airport terminal is concerned. Obviously, a HRR database for local combustibles should be developed [e.g. Babrauskas and Grayson 1992; Peacock *et al*. 1994]. Fire safety management [Della-Giustina 1999] will also be recommended in Chapter 10.6 based on those studies.

Chapter 10 : Fire safety strategies of airport terminal

Fire safety strategies in the airport terminal were proposed in Chapter 10.3. The possible fire risks of the airport terminal should be recognized to establish the fire safety strategies. Retail areas are identified as places with high fire risk such that the heat release rate of small retail shops is needed to be determined. The fire safety strategies are suggested to have four parts on:

- Passive Building Construction.
- Active Fire Services Installation.
- Fire Safety Management.
- Control of Risk Factors.

These issues are identified by the requirements as illustrated in the local codes [Buildings Department Hong Kong 1995; 1996a, b] and various international publications [Chow 2001a, c; Malhotra 1987] in Chapter 10.3. For the Passive Building Construction mentioned in Chapter 10.4, the building structure, compartmentation, material, travel distance, interaction with FSI, means of access and means of escape in accordance with the local codes which are published by the Buildings Department [Buildings Department Hong Kong 1995; 1996a, b] have been taken into account. On the other hand, the fire services installation mentioned in Chapter 10.5, such as the fire detection and protection system, fire suppression system, emergency lighting system and smoke extraction system, has been based on the FSI Code [Fire Services Department Hong Kong Special Administrative Region 1998] to establish. The fire safety management, i.e. maintenance plan, staff training plan, fire action plan and fire prevention plan, with regards to various international publications [Chow 2001a, c; Malhotra 1987] is worked out in Chapter 10.6, while the risk factors of fire load density and passenger loading in Chapter 10.6 are based on the requirements as mentioned in the prescriptive codes [Buildings Department Hong Kong 1995; 1996a, b; Fire Services Department Hong Kong Special Administrative Region 1998] to consider.

Apart from the above parameters, the possibility of the occurrence of arson fire, terrorist fire and natural disastrous fire, fire safety provisions for those types of fires, the amount of combustibles, i.e. fire load, to be carried by passengers and fire safety provisions for aircrafts; shall be significant for the airport terminal. However, this study is limiting to the occurrence of accidental fire in the retail areas of the non-restricted departure level and arrival level of airport terminal as mentioned in Chapter 1.1. The occurrence of the other types of fires and fire load created by the passengers will not be considered in this Chapter.

10.1 Possible fire risks of the airport terminal

Passengers are only allowed to smoke inside the smoking lounges of the airport terminal. Highly flammable goods, such as kerosene and liquefied petroleum gas (LPG) cylinders are also prohibited to bring into these areas. Therefore, it is unlikely to initiate a fire by the non-extinguished cigarettes inside the rubbish bins at those places.

However, some retail shops are selling alcohols and cigarettes [Chow and Ng 2004] as illustrated in Chapter 4.4. A high fire risk would be posed if those stocks are too large. Fast food service and restaurants with cooking facilities is another concern. The risk can be reduced if gas cookers with portable LPG cylinders are not allowed. As mentioned in Chapter 5.1, very high thermal power stoves operated by either town gas or diesel oil are equipped in the kitchen of the Chinese restaurant at level 8 for ensuring efficient cooking of food. The risk of starting a small accidental fire in kitchen would be high.

In order to provide a spacious shopping and dining environment, a series of extension projects in the arrival hall of the non-restricted areas were commenced. This is another possibility of starting a fire while the refurbishment works were carried out. Process with hot work should be monitored carefully.

Fire risks in passenger terminals were reviewed to include arson, contractors, retail shops and interaction between people and buildings. Note that most of the fire safety provisions are targeted on protecting against accidents. However, protection against 'arson fire' like 'Top One karaoke fire' in Hong Kong [e.g., Chow and Lui 2002]; and 'terrorist attack fire' such as '911 incident on World Trade Centre' in New York, USA [e.g., Chow 2001a], is more than 'safety' problems dealing with accidents. These are 'security' problems!

10.2 Heat release rate of small retail shops

It is obvious that the retail shops in the arrival hall and departure hall are small and packed with goods as illustrated in Tables 4.1 & 4.2. Fire services provisions such as sprinkler system [Fire Services Department Hong Kong Special Administrative Region 1998] and smoke extraction systems [Klote and Milke 2002; Morgan and Gardner 1999; National Fire Protection Association 2000c] mentioned in Chapter 10.5, are required to be installed and designed properly such that they would not give adverse effects. Smoke extraction system is important at the early stage of fire to allow occupants to evacuate in a smoke-free environment. Sprinkler will act in the later stage for suppressing a fire. However, effects on switching on the smoke extraction fan before the operation of sprinklers should be studied carefully.

Heat release rate of burning combustibles in small retail shops should be considered. NFPA t^2-fire [e.g. National Fire Protection Association 2000c] with heat release rate Q_c (in kW) in terms of time t (in s) and constant t_g (in s) is commonly used with an incubation period t_o (in s). Values of t_g for slow; medium; fast; and ultra t^2-fire are 600 s, 300 s, 150 s and 75 s respectively.

$$Q_c = 1000\left(\frac{t - t_o}{t_g}\right)^2 \qquad \text{… (10.1)}$$

Design fires measured by sprinklered calorimeter were reported by Garrad and Smith [1997] and reviewed by Chow [2001d] for the use in retail shops. Most of them can be fitted by a t^2-fire. For example, soft toy mountain fires of total mass up to 46 kg could give a medium t^2-fire with an incubation period of 60 s. Idle pallet fires of about 167 kg and 1325 mm high will give a fast t^2-fire with an incubation period of 120 s. Stacked cardboard boxes fires gave an ultra-fast t^2-fires after a long incubation period. Studies on the real fire scenarios carried out by Ghosh [1997] demonstrated that the fires in video stores will give a heat release rate curve slower than a fast t^2-fire with an incubation period of 70 s. Fires in liquor stores are between the slow and medium t^2-fire.

10.3 Four parts on fire safety strategies

Fire safety strategies in Hong Kong are divided into four areas on fire safety provisions [Chow 2001c, 2002c, Ng and Chow 2001a], in accordance with government departments responsible for that area:

- Passive building construction (PBC) taken care of by the government Buildings Department (BD)

  One of the main objectives of providing PBC is to confine the fire area. The key construction elements should be the fire-resistant wall, door and floor. Providing fire resisting construction is to ensure the fire will be burnt out within the confined area when the combustible materials are consumed. Fire resisting period (FRP) [e.g. Buildings Department Hong Kong 1996a] should be longer than the duration of fire. There should be an evacuation plan for passengers to escape through the means of escape; and firefighters to enter the means of access. Early planning on PBC design is necessary as it is difficult to upgrade after the building is in use.

Local requirements [Buildings Department Hong Kong 1995, 1996a, b] by BD are mainly on providing adequate FRP for specific structural elements; non-combustibility of materials; means of escape, and means of access, while the surface spread of flame over lining materials is requested by local Fire Services Department (FSD) [Fire Services Department Hong Kong Special Administrative Region 1998].

- Fire services installation (FSI) taken care of by the government Fire Services Department (FSD)

Fire engineering systems are installed after the building is constructed. The types of fire can be classified as [e.g. National Fire Protection Association 2000c] Class A solid materials fire, Class B liquid/liquefiable solid fire, Class C gases/electrical fire and Class D metal fire.Hot gases might spread out from the confined area as a result of air leakage, stack effects, or other factors such as the door open. Among all firefighting agents, water is most important as it is non-toxic, cheap, providing a good cooling effect and readily available in Hong Kong. The fire hydrant/hose reel systems and sprinkler systems [Fire Services Department Hong Kong Special Administrative Region 1998] are essential FSI. Others such as fire detection and alarm system; fire extinguishers; smoke extraction system; gas protection system; foam system;

water mist system; and emergency lighting are all specified [Fire Services Department Hong Kong Special Administrative Region 1998].

- Fire safety management (FSM) taken care of by Airport Authority

  This is adopted [Chow 2001a, c; Malhotra 1987] to minimize the fire occurrence, including the fire prevention and actions to be taken in case of fire. Objectives of FSM [Chow 2001a] on managing accidental fires, arson fires, terrorist attack fires or disaster fires should be clarified. FSM should include the staff training, house keeping, fire education for occupants and minimum storage of dangerous or flammable goods.

- Control of risk factors (RF) such as fire load density and passenger loading

  RF should be controlled under the prescriptive codes on fire resisting construction (FRC) [Buildings Department Hong Kong 1996a]; means of escape (MoE) [Buildings Department Hong Kong 1996b] for occupants; means of access (MoA) [Buildings Department Hong Kong 1995] for firefighting, and FSI [Fire Services Department Hong Kong Special Administrative Region 1998].

The reasons of classifying the fire safety strategies into these areas are for easy control, design and implementation under local conditions. PBC is taken care by BD, basically following codes in MoE [Buildings Department Hong Kong 1996b], MoA [Buildings Department Hong Kong 1995] and FRC [Buildings

Department Hong Kong 1996a]. FSI is monitored by FSD under FSI Code [Fire Services Department Hong Kong Special Administrative Region 1998]. FSM is controlled by Airport Authority, while RF is related to the 'fire risks' inside the airport terminal.

10.4 Passive Building Construction

- Building structure

  The structure of airport terminal should be designed, constructed and maintained to protect occupants who are not intimated with the initial fire development for the time they evacuate, relocate or defend in place. Construction and finishing with suitable materials are needed to embody adequate fire resistance under the headings of stability; integrity and insulation.

  Structural elements should be constructed with an adequate FRP [Buildings Department Hong Kong 1996a] such that the occupants and fire-fighters can be evacuated safely. Use of fire retardants on construction and finishing materials is an essential element in strengthening the fire resistance of structure and hence withstanding the high temperatures in case of fire.

- Compartmentation

Adequate compartmentation should be provided in different parts of building to protect the integrity of structure elements and limit the number of people exposed to fire. Building should be subdivided into several compartments by horizontal and vertical barriers such as doors, walls or floors [Buildings Department Hong Kong 1996a]. Those materials should have a FRP to inhibit the spread of fire. Space volume of a single compartment should not be more than 28000 m^3 [Buildings Department Hong Kong 1996a]. However, the compartment of the departure level and arrival level in the non-restricted area will be exceeded 28000 m^3. As the design cannot comply the prescriptive codes [Buildings Department Hong Kong 1996a], FEA shall be applied to the fire safety design of the departure level and arrival level in order to provide a high level of fire protection and enhance the life safety in the airport terminal. Fire dampers should be installed in the supply air ducts of heating, ventilating and air conditioning (HVAC) systems [Fire Services Department Hong Kong Special Administrative Region 1998] so as to prevent the spread of smoke throughout the environment [Fire Services Department Hong Kong Special Administrative Region 1998].

Smoke barriers or smoke screens can give the smoke compartments. According to the FSD requirement [Fire Services Department Hong Kong Special Administrative Region 1998], smoke barriers should be constructed with non-combustible materials and an FRP of 1 hour. These devices should be descended automatically [Beard and Weinspach 1996]. Smoke can be removed by the static or dynamic smoke control systems. As illustrated in Tables 4.3 & 4.4, retail shops have a high fire risk on occupants as the combustibles inside the shops give a high heat release rate in case of fire. Water curtain mentioned in Chapter 11.2 can be installed in front of each retail shop to separate from the other parts of the terminal building.

Parts of the areas in the airport terminal are not supposed to be used as coffee lounge areas and exhibition areas. The fire safety provisions may not be capable to control the fire occurred in those areas. As pointed out by Chow [1996] in Chapter 2.3, the installation of the sprinkler system at high ceiling is not able to suppress the fire. Fire shutters satisfying the criteria of integrity should be installed to separate these areas with the other parts of buildings. However, the best way is to stop using the space as exhibition areas and coffee lounge areas.

- Material

Rubber, plastics and timber should be prevented to use in airport terminal unless flame retardant is added to reduce the heat release rate produced by those materials [Babrauskas and Grayson 1992]. However, environmental effects of some fire suppressants mentioned in Chapter 3.5 should be considered carefully before apply to the materials.

- Travel distance

As illustrated in Chapter 7.6, the travel distance of occupants in the arrival level of the airport terminal becomes longer when a fire occurs. Only some of the occupants are able to travel within the target distance, i.e. 36 m, in the arrival hall [Buildings Department Hong Kong 1996b]. More direct exits of width more than 2 m [Buildings Department Hong Kong 1996b] shall be provided in the arrival hall to shorten the travel distance of occupants. The locations of direct exits should be assessed such that the exits are capable to allow the occupants to escape in case of fire.

- Interaction with FSI

As mentioned by Chow [2001c, 2002c], PBC and FSI should not be monitored separately, though they are controlled by different departments: BD and FSD. Airport Authority should integrate both designs such that the systems can work coherently in case of fire.

An obvious example is the smoke extraction system. Smoke filling process in corridors and halls should be considered. Under a small design fire, the time required to fill up huge space with smoke is long. Flame spreading over combustibles should be watched. Psychological effects and human behaviour under crowded conditions should also be considered. Another Lan Kwai Fong tragedy would be happened if there is no good planning and control on crowd movement [South China Morning Post 1993].

- Means of access

As illustrated in Tables 7.4 and 8.3 to 8.6, the widths of the staircases in the departure hall and arrival hall are only 1.5 m and 2 m. When people escape from fire areas, fire fighters may enter the building at the same time to extinguish the fire. The width of the staircases will be too narrow for the occupants and fire fighters to utilize simultaneously. This will affect the evacuation of occupants and rescuing procedures of firefighters. Both of them will become risky. Therefore, the width of the staircases which are also used as the means of access shall be increased.

- Means of escape

The widths of the staircases in the departure hall and arrival hall are only 1.5 m and 2 m as shown in Tables 7.4 and 8.3 to 8.6. Escape path may not be wide enough to allow occupants to change direction to another exit and firefighters access to the fire area at the same time. As a result, the increment in the width of the escape routes leading to horizontally and vertically escape from any area is significant. On the other hand, adequate provision of exit signs can allow the occupants to evacuate efficiently and reduce the chance of collision with arrival of the fire fighters.

10.5 Fire Services Installation

In Hong Kong, active fire protection systems are regarded as FSI. Provisions of FSI under the FSI code [Fire Services Department Hong Kong Special Administrative Region 1998] are monitored by the FSD.

- Fire detection and protection system

  It is necessary to provide early fire warnings to allow rapid evacuation of the fire zone before reaching the untenable conditions. Fire detection system should be installed in the entrance hall, retail areas of departure and arrival halls in the non-restricted areas of the airport terminal, so as to provide an early notification of the fire occurrence. Fire protection systems, such as special extinguishing systems and smoke control systems, should be activated by fire detectors.

  All equipment rooms should be installed with smoke or heat detectors, portable fire extinguishers and automatic gas flooding system, while the staff areas should also be installed with smoke or heat detectors, portable fire extinguishers and fire hydrants or hose reels. Refuse rooms should be installed with gas protection system. Portable hand operated appliances, such as the portable extinguishers, should be installed in the retail areas of airport terminal.

- Fire suppression system

  - Sprinkler systems

    Fire suppression systems, such as sprinkler system and hose reels, are required in the airport terminal [Fire Services Department Hong Kong Special Administrative Region 1998]. According to the results of the full-scale burning tests in Figures 9.9a to 9.9d and 9.17a to 9.17d, sprinkler system is good in controlling the fire if it is activated at the right time.

    Evacuation should be considered while designing operating conditions for sprinkler system. It is needed to ensure the operation of sprinkler system will limit the fire with minimal failures or unwanted operations due to inappropriate use or poor maintenance [Her Majesty's Stationery Office 1999]. In the passenger terminals, discharge the water too early before evacuation will wet the floor and give a slippery surface. With regard to the results of the evacuation simulations in Tables 7.3 & 8.1, the TET of the occupants in the departure level and arrival is around 5 to 10 min. Therefore, the sprinkler system shall be activated at least 5 min after the ignition of a fire in order to prevent the evacuating occupants being injured by the hot steam produced.

    As mentioned in Chapter 2.3, sprinklers are not applicable to be installed inside the arrival and departure halls due to the high ceiling. In case of fire, smoke plume risen from a fire would spread laterally and interact with sprinklers when it reaches the ceiling. However, the risen smoke plume will draw the air from surroundings and cool the plume. The higher the ceiling, the lower the smoke temperature when it reaches the sprinklers and the activation time of sprinklers is delayed. Water droplets to reach the fire area would be inadequate. In order to design a suitable sprinkler system inside those halls, smoke temperatures at different ceiling levels above a fire should be predicted [National Fire Protection Association 2000c] in the terminal halls.

As demonstrated by the full-scale burning tests in Figures 9.7c, 9.8c, 9.13c, 9.15c, 9.16c & 9.17c, a considerable amount of heat will be given out by the combustibles inside the retail shops in case of fire. Utilization of the WMFSS inside the retail areas [Ng and Chow 2001b] as mentioned in Chapter 11.5 shall be an effective means in controlling or extinguishing the fire.

- Hose reels

Hose reels should be located at conspicuous and accessible places, such as the entrance hall [Her Majesty's Stationery Office 1999].

- Emergency lighting system

Except the toilet accommodation, all escape routes and accommodation have a gross area of not more than 8 m^2 should have an adequate artificial lighting. Emergency lighting for the escape staircases should be on a separate circuit and different from the other parts of escape route [Her Majesty's Stationery Office 1999].

- Smoke extraction system

Smoke spreading from the fire to the whole building should be watched carefully. According to the simulation results of buildingEXODUS and SIMULEX in Tables 7.3 & 8.1, smoke extraction system [Klote and Milke 2002] is required in the departure hall and arrival hall for allowing the occupants to have a longer time to escape. As mentioned in Chapter 3.5, environmental impact such as air pollution due to the smoke generated should be minimized. Air filters can be utilized in the smoke extraction system to separate the toxic particles before extracting the smoke.

The system should enable the air movement to direct away from the protected escape routes and exits [Her Majesty's Stationery Office 1999]. Backlayering of smoke in the egress path should be prevented. The HVAC systems in the airport terminal should be compatible with the smoke extraction system when it is operated under the fire condition [Her Majesty's Stationery Office 1999], otherwise the system should be closed.

10.6 Fire Safety Management

Good implementation of FSM can provide an adequate fire safety for the building even the PBC and FSI are not enough. A good FSM should be considered and implemented properly [Chow 2001a, c; Malhotra 1987] for reducing the hazards. A fire safety plan [Chow 2001c; Malhotra 1987] should be worked out with three parts:

- Maintenance plan

  Good housekeeping is essential to reduce the chances of fire, spreading of fire and smoke and the blockage of escape routes. Housekeeping measures should include the waste control, keeping the combustible materials away from the possible ignition sources, storing flammable liquids, paints and polishes in appropriate containers, recognition of potential hazards, ensuring that escape routes are clear and fire doors are closed.

  Fire prevention and protection systems should be maintained in right order. Planned maintenance procedures should be established and used to ensure the fire protection systems are operated effectively. Routine checking of the emergency systems should be carried out on a regular basis. Maintenance and testing procedures should cover the PBC and FSI as mentioned in Chapters 10.4 & 10.5: alarm system, fire detection system, fixed and portable extinguishing systems, emergency lighting system, compartmentation such as the fire doors and smoke extraction systems.

Potential sources of ignition such as gas, oil and electrical heating installations should also be examined by competent persons on a regular basis. Furniture, particularly sofa, is likely to be ignited. It is found that the poor selection of partition materials, surface lining materials and floor coverings would give a higher heat release rate such that the partitioning materials should be treated with fire retardant.

- Staff training plan

Fire safety training should be provided for all staff on the actions to be taken on discovering a fire, first aid firefighting, assisting non-staff members to response to an alarm and escape, and procedure for calling the fire services department.

For the retail areas of departure and arrival levels at the airport terminal as illustrated in Figure 2.4, simulated incident exercises for the operational staff would be carried out frequently with emergency exercises on fire-fighting and rescue operations, police in controlling the surroundings and access to hospital. Staff is familiarized with the emergency procedures such as inform the police and fire services, placing the barriers and floor markings to the boundary of the site and identify the routes for evacuation.

- Fire action plan

Provision of escape assumes that the building users are able-bodied people, and the essential role of management in a fire is to ensure the calling of fire brigade and carry out a roll call when the evacuation is completed. Presumption of independent capability to use the staircases for egress is inadequate for disabled people. According to the field survey carried out by the candidate as in Chapter 2.2, evacuation involving the assistance to move down (or up) the staircases or the use of suitable lifts is available for the disabled persons in the airport terminal. A communication panel is also installed adjacent to the lifts as a “call point” for the disabled in case of fire.

Staff should undergo proper training on fire prevention and security, including the means to report the fire and actions to be taken in case of fire such as assist the occupants to evacuate to safe places.

For airport terminal, a fourth part, i.e. fire prevention plan, should be included [Chow 2001a, c]. Education is a long term activity on raising the public awareness on fire safety. The education of public on awareness to the risk of fire and deliberate ignition, means of reporting a fire and actions to be taken should be carried out through various safety campaigns such as school talks, displays of posters and public announcements.

In case of fire, other safety aspects such as indoor air quality due to emission of pollutants should be watched. There are two modes of building operation for protecting against an accidental fire as suggested by Chow [2001b]:

- Normal Mode

  Accidental fires started from retail areas; luggage carried by passengers; cooking activities in fast food shops and restaurants; exhibition items and materials, should be watched.

- Refurbishment mode

  Fire safety due to construction activities of expanding the retail areas, major or minor refurbishment inside the passenger terminals should be watched.

10.7 Control of Risk Factors

- Passenger loading

  Based on the simulations of buildingEXODUS and SIMULEX for the departure level and arrival level as in Tables 7.3 & 8.1, the TET of the occupants is long and exceeded the targeted TET under a high occupant loading. In order to reduce the TET of occupants, passenger loading inside the airport terminal should not be too high. People should not be allowed to enter the building once the maximum loading mentioned [Buildings

Department Hong Kong 1996b] is reached, so as to control the crowd movement of passengers. For implementing this strategy, the access control system, e.g. security gates, shall be utilized to control the number of occupants to enter the building.

On the other hand, the staying time of occupants in the departure and arrival halls would be long for carrying out the check-in procedures or waiting for the passengers' arrival. In case of an emergency, the escape route is easily to be blocked. Heed should be paid to the width of escape routes and exits.

- Fire load density

Fire load constituted by the airport terminal would be low if there are no shopping facilities inside the building. However, several retail shops are located inside the terminals such that the fire load density would be high. As illustrated in Figures 9.7c, 9.8c, 9.13c, 9.15c, 9.16c & 9.17c, a high HRR will be given out by the combustibles such as T-shirts and CDs. If a fire occurs in any one of those shops, flame and smoke would spread quickly to other retail shops. Therefore, fire shutters or drencher systems mentioned in Chapter 11.2 should be provided at the entrance of the retail shops to prohibit the spread of fire.

Amount of the combustibles inside each shop should be restricted to the maximum fire load density, i.e. 1135 MJm^{-2} [Fire Services Department Hong Kong Special Administrative Region 1998]. Those combustible items should be kept away from the door sides in order not to block the exit and accelerate the spread of fire. On the other hand, care should be taken in using the hall as exhibition areas and coffee lounge areas.

10.8 Conclusion

In order to improve the fire safety of the airport terminal, the strategies can be implemented by the facility management team of the Airport Authority. The following can be concluded for those strategies:

- Smoke filling the terminal halls due to retail shop fire

  As mentioned in Chapter 2.2, fire protection systems are provided in each retail shop such as the fire detection system and sprinkler system. Performance of the integrated design should be evaluated by the time to detect a fire, time to activate the sprinkler, time for the occupants to escape and impact of passengers outside the shop but still inside the terminal halls. On the other hand, effect of steam generated by water on passengers is another concern.

- Water mist fire suppression system

  The use of WMFSS in retail areas [e.g. Chow *et al.* 2002] should be considered. Water mist system is a good solution for quick fire suppression in a small retail shop as mentioned in Chapter 11.6. However, whether the mist can extinguish a fire rapidly should be considered carefully.

- Drencher system

Water curtain discharged from the drencher system would be effective in blocking the thermal radiation transferred from the fire zone to the adjacent premises [Ng and Chow 2002] as mentioned in Chapter 11.2. Water curtain should be designed at the openings of shop to minimize the heat transmitted to the protected area. For the shops with excessive fire load, it is needed to consider of putting more than one layer of water curtain in the openings.

Chapter 11 : Utilization of modern systems in airport terminal

Utilization of the modern systems, i.e. deluge system, drencher system and water mist fire suppression system (WMFSS) were studied in the departure hall, arrival hall and retail areas in Chapters 11.5 to 11.8, so as to have a recognition of the suitability for utilizing those systems in the terminal building.

Deluge systems can be applied in aircraft hangers, explosive plants and wine storage in which the quick developing fire would be occurred. Codes on specifying the deluge system in different countries were reviewed in Table 11.1. Scientific aspects, such as the size of orifices, response of detectors and heat absorption rate, are discussed in Appendix D. A comparison between the deluge system and automatic sprinkler system is illustrated in Chapter 11.3.

For spaces which are not possible to provide compartmentation, drencher system can be installed to prevent heat transfer from the fire zone to the adjacent areas. Design guides on this system in different countries are reviewed with key features in Table 11.2. Physical quantities of the system were introduced in Appendix F.

Fire load density in small retail shops used to be high [Chow and Ng 2004; Ng and Chow 2001a]. Possible heat release rate would be high at the early stage of fire [Chow 2001d]. Although retail shops are protected by sprinkler systems, the operation of the system would be delayed. Therefore, the utilization of WMFSS in retail shops was considered in Chapter 11.5. Key factors affecting the system performance and potential application strategies were discussed in Chapter 11.6.

11.1 Brief description of deluge system

Water-based active fire protection systems such as sprinkler systems are widely used. Deluge systems are required in Hong Kong for protecting the places where fire spreading is fast such that the sprinkler system would be ineffective. As defined in local codes [Fire Services Department Hong Kong Special Administrative Region 1998], deluge system can discharge water over a considerable fire area in rapid response. It is consisted of open sprinklers and pipework with water controlled by a deluge valve (quick-opening valve). In normal condition, the deluge valve is held in closed position by inert gas, air or liquid pressure.

The system can be activated manually or automatically. For manual operation, the system should be fitted with manual operated points at each deluge valve. When there is a fire, the deluge valve can be opened by the responsible person (e.g. trained staff) to activate the system and discharge the water or foam over the fire area.

The system is activated by means of heat, smoke or flame detecting devices in automatic operation. Detectors are divided into two types: electrical detectors and sprinklers, where the sprinklers should be fast response type if it is used as detectors. In case of fire, the pressure on deluge valve would be reduced and overcome by the upstream water pressure when the detection system is operated. The valve would be opened and water is discharged over the protected area.

Due to the large discharge angle and density of discharge of the deluge system, it is suitable to be utilized in areas with a high ceiling where sprinkler system would be ineffective. This system can be used to control or extinguish the rapid fire spread by water or foam. The extinguishing mechanism is shown in Figure 11.1.

As the heat of vaporization of water is high, combustible and flame can be cooled down. Heat to sustain the flame can be reduced and hence extinguishing the fire. Entrainment of air into the fire area can be prevented by the steam generated. Radiative heat re-entering into the fire zone can be reduced by the formation of fog. For flammable liquids which are soluble in water, the fuel can be diluted rapidly with large flow rate of water. Whereas for insoluble liquids, emulsion can be formed quickly and thus reduce the combustibility [National Fire Protection Association 1996; Society of Fire Protection Engineers and National Fire Protection Association 1995].

Aqueous foam would be a good medium in fighting against the flammable liquids [National Fire Protection Association 1996; Society of Fire Protection Engineers and National Fire Protection Association 1995]. Foam is lighter than any flammable liquids such that it can be floated on liquid and produced an air-insulated, cooling and continuous vapour-sealing layer. However, foam is an unstable air-water emulsion which can be broken down easily by physical or mechanical forces. Therefore, it must be applied in sufficient volume to compensate the loss.

Definitions, activation principles, fire extinguishing mechanisms and applications of the deluge system in UK, USA and Australia are reviewed with a summary shown in Table 11.1. The layouts of the deluge system are shown in Figures 11.2 to 11.4 respectively.

11.2 Brief description of drencher system

Buildings are required to divide into compartments by different structural elements such as walls and floors with a certain FRP to inhibit the spread of fire [Buildings Department Hong Kong 1996a]. Water curtain can be used as an alternative for spaces with problems in compartmentation. It is demonstrated that the thermal radiation can be blocked. As defined in local codes [Fire Services Department Hong Kong Special Administrative Region 1998], drencher system is a system that provides the water curtain for protecting against the internal and external "exposure" to fire. It is an effective means to obstruct the radiant heat transmitted from the fire zone to the adjacent area [Fong and Chan 2001; Fong *et al*. 2001].

Drencher System is composed of nozzles, which can provide a continuous water layer to protect the building when it is exposed to a fire in adjoining premises [Home Office Fire Department 1990]. The drenchers are divided into two types: sealed or unsealed (open). When a fire occurs, the unsealed type drenchers would be operated manually by opening the main valve. Water will then flow into the pipe and a continuous water curtain would be formed to protect against the radiant heat from the fire in adjacent premises. For the sealed drenchers, they are similar to the common sprinkler heads except the shape of deflector plate is different.

Drencher system is used to prevent the spread of fire by reducing the heat transmitted from the fire zone to the adjacent premises as illustrated in Table 11.3. The layout of a typical drencher system in Hong Kong is shown in Figure 11.5. With the activation of drencher system, heat fluxes transferred to the adjoining zone would be decreased. For the energy which is not transmitted, it will be absorbed or diffused back by water droplets [Home Office Fire Department 1990]. Water will be evaporated after absorbing a lot of heat fluxes, thus minimizing the rate of temperature rise in the protected zone [Ravigururajan and Beltran 1989]. However, the mass concentration of water curtain is an important factor in affecting the transmission of radiative heat fluxes. Continuity of water film would be better by reducing the porosity, thus effectively attenuate the transmission of heat fluxes. The discharge pattern of drencher system is shown in Figure 11.6.

Definition, activation principle, fire extinguishing mechanism and application of this system in UK [Home Office Fire Department 1990], USA [National Fire Protection Association 1999, 2000e] and Australia [Australian Standard 1991, 1995b] are reviewed with a summary shown in Table 11.2.

11.3 Comparisons of deluge system with automatic sprinkler system

Hydraulic calculation of deluge system is very similar to automatic sprinkler system. The physical aspects of deluge system are shown in Appendix D. Comparisons of the deluge system and automatic sprinkler system are shown as follows:

- Activation

  For ordinary sprinkler system [Bryan 1997; Building Research Establishment 1978], sprinkler heads are installed in a piping system connected to water supply. It is a 'constant temperature' device which will be activated when a specified operating temperature is reached.

  As illustrated in Table 11.1, open sprinklers are used in deluge system [Home Office Fire Department 1990]. It is connected to a valve and opened automatically or manually. There is a separate detection system installed in the same areas as open sprinklers in automatic operation. Detection system will activate the deluge valve to allow water flowing into the piping system and discharge. For manual operation, the operation points should be located at the deluge valve and taken care by the trained staff.

- Hazard classification

Taking UK as an example, occupancies are classified into three types, i.e. light hazard, ordinary hazard and high hazard [e.g. British Standards Institution 1990]. Automatic sprinkler system is recommended for the occupancies with light or ordinary hazards. Deluge system should be utilized for the occupancies with a high hazard such as aircraft hangers, firework manufacturers and nitrocellulose manufacturers [Australian Standard 1997], where intensive fires with a fast rate of propagation is expected.

- Water discharge

Minimum design discharge densities for light and ordinary hazards should be only 2.5 $mmmin^{-1}$ and 5 $mmmin^{-1}$ respectively for automatic sprinkler system [British Standards Institution 1990]. For high hazard [Australian Standard 1997], building should be completely protected by the deluge system. It is desirable to apply water simultaneously over the fire area with a higher water discharge density. The minimum discharge density should not less than 7.5 $mmmin^{-1}$ for different types of occupancies [Australian Standard 1997].

- Flow rate and pressure required

As the water discharge density of deluge system is higher than automatic sprinkler system, flow rate and pressure required would be higher [Bryan 1997] and discharge angle of deluge system is much larger to give a wider area coverage.

11.4 Suppression mechanisms of water mist fire suppression system

Water mist is defined [e.g. National Fire Protection Association 2000e] as the water particles found in the spray with 99% volume diameter $Dv_{0.99}$ less than 1000 μm. Fire suppression mechanisms of the water mist fire suppression system (WMFSS) include three main mechanisms [Mawhinney *et al*. 1994; Jones and Nolan 1995; Mawhinney and Richardson 1997; Mawhinney and Solomon 1997; Grant *et al*. 2000; Liu and Kim 2000]:

1. Gas phase and fuel surface cooling.
2. Local and global oxygen depletion.
3. Radiant heat blocking to surroundings and fuel surface.

If the systems are designed properly, sufficient water droplets can be discharged to the flame and reduced the heat release. These mechanisms can be divided into direct and indirect flame interaction, depend on whether the mist can reach the flame:

1. Direct flame interaction involves gas phase cooling for fuel and oxidant. Localized oxygen depletion will have a fast suppression.

2. Indirect interaction involves global oxygen depletion and surface cooling. The fire is suppressed by the inadequate air entrained into the compartment.

WMFSS can be used for local application or total flooding. If the entire compartment is covered by WMFSS, these two effects will be acted together. System performance depends on spray characteristics such as mist droplet size and geometry of the compartment [Liu *et al.*2001]. Ventilation plays an important role and should be considered carefully in retail shops.

11.5 Utilization of water mist fire suppression system in retail shops

Retail shops in big halls would be characterized by a low ceiling and open-sided. Without vertical walls, smoke and fire will spread to other places rapidly due to higher thermal radiation feedback. Possible heat release rate in small shops would become larger. Flashover can occur easily in a small shop as mentioned in Chapter 4.2, results in a big burning object with large heat release rate and smoke production rate. Therefore, fire suppression system, such as sprinkler system, is playing a key role. However, sprinkler systems will not work effectively when the sprinklers are covered by goods or used for controlling liquid fires.

Damage due to excessive water discharged is another concern. Alternatives to provide a better fire safety in retail shops should be considered. Feasibility of using WMFSS in retail shops should be investigated.

11.6 Possibility of using water mist system in airport terminal

Sufficient mass flux of water mist should be delivered to fire area. Water mist has a short travel distance because of its size. According to Table 4.1, the ceiling height of retail shops in airport terminal is low, i.e. 2.3 m. Water mist with high downward velocity can overcome the upward plume velocity to reach the flame and fuel surface [Chow and Yao 2001].

Note that the retail shops in a big hall will have opening areas. Smoke temperature, smoke production rate and interaction of water mist and smoke are affected by ventilation. As pointed out by Liu and coworkers [Liu *et al.* 2001], the effectiveness of water mist under forced ventilation was substantially reduced due to strong mass exchange between the room and its surroundings. A total flooding system is not suitable in retail shops with adequate ventilation. Direct interaction of water mist and flame will play a dominant role in fire suppression. Nominal flux density and nominal flow per unit volume should be taken as two key parameters for WMFSS [Mawhinney 1999].

Water mist cannot reach the flame directly if the fire is obstructed. Fire will not be extinguished due to adequate oxygen supply. Indirect interaction would play an important role. When a fire occurs inside the shop, hot smoke layer is formed below the ceiling and the compartment temperature will be increased. Since the ceiling height of the retail shops is low as illustrated in Table 4.1, i.e. 2.3 m, thermal radiation emitted from the smoke layer is significant. The mists will be heated up by hot smoke and evaporate, thus reduce the temperature of the environment significantly.

If the compartment temperature decreases, there will be no thermal damage in the compartment and fire would not spread to the adjacent areas. In addition to compartment temperature, concept of 'Spray Heat Absorption Ratio' (SHAR) can be employed to assess WMFSS efficiency for compartment fires. SHAR is defined as the ratio of thermal energy absorbed by water divided by total heat release rate. As reviewed by Grant *et al.* [2000], the 'Instant extinguishment' was possible at early stages when SHAR was greater than 0.6 and fire was suppressed for typical longer-term SHAR lying between 0.1 to 0.3.

For flashover control at post-flashover stage in a retail shop, high temperature difference between hot gas and water droplet would enhance the convective heat transfer and evaporation [e.g. Grant *et al.* 2000]. Water mist can be effectively used to prevent the combustibles from ignition and radiation attenuation increased with reduction in volume median diameter and increase in water mist concentration.

For some solid combustibles, e.g. toys, which are made of polymeric materials, combustion is incomplete and large amount of soot and toxic gases are produced. In addition to the reduction of thermal damage, water mist can reduce the concentration of toxic gases [Jones and Nolan 1995]. This can minimize the smoke damage and increase the visibility in building such that occupants can evacuate easily.

However, something was considered when using WMFSS for fire protection in small retail shops. Effects of large opening and smoke extraction system on mist performance should be evaluated carefully. Airflow induced by mechanical smoke extraction system will affect the water mist motion and evaporation. For a ventilation-controlled fire, large ventilation factor will result in the increment in heat release rate and smoke production rate. Larger water flux density is required to extract heat. Hot steam generated will endanger the occupants. Spray characteristics of WMFSS should be considered carefully.

11.7 A case study on aircraft hanger

A case study was carried out on an aircraft hanger with length 20 m and width 15 m. Aircraft hangers are classified as high hazard occupancy [British Standards Institution 1990]. For a standard open sprinkler, coverage area is equal to 12 m^2 [Society of Fire Protection Engineers and National Fire Protection Association 1995]. Therefore, 30 open sprinklers are required for the hanger. Fast response type sprinklers with Response Time Index (RTI) 50 $m^{1/2}s^{1/2}$ are selected as the detectors and the response time of deluge valve is less than 20 s after the activation of detectors. Pipe sizes, layout of deluge system and detection system are shown in Figure 11.7.

According to the Australian Standard [1997], minimum design density needed is 7.5 mmmin^{-1}. Diameter of open sprinklers is nominally 15 mm or 20 mm. As a result, the design density and diameter of the open sprinklers are taken as 7.5

$mmmin^{-1}$ and 15 mm respectively. The pressure and flow rate required for each open sprinkler are calculated as in Appendix E.

Pressure P_x and flow rate Q_{wv} at point W as shown in Figure 11.7 are 2.20 bar and 2883.4 $Lmin^{-1}$ respectively. Pressure P_y (in bar) required at the deluge valve can be expressed in terms of P_x and static pressure S_{yx} (in bar) due to the height difference between point x and the valve.

$$P_y = P_x + S_{yx} \qquad \ldots (11.1)$$

where S_{yx} is expressed in terms of ρ, h and gravitational acceleration g (in ms^{-2}) as:

$$S_{yx} = \rho gh \qquad \ldots (11.2)$$

Therefore, pressure required for deluge valve to deliver the flow to the whole deluge system is 2.32 bar.

11.8 Case studies on retail shops of airport terminal

Physical aspects and calculating procedures of the position and area requiring drencher system to protect in three different cases are shown in Appendixes F and G. In Table 11.3, case studies were carried out in the retail shops of the airport terminal to determine the transmitted radiant heat flux I_i in protected zone. The value is used to decide whether the drencher system is needed to be installed inside the retail shop.

Values of I_i of all retail shops are listed in Table 11.3. The total I_i spread to the arrival hall, departure hall and common area of Level 8 are 18.18 kWm^{-2}, 51.45 kWm^{-2} and 26.30 kWm^{-2} respectively. Water curtain should be installed in those shops when I_i is higher than 40 kWm^{-2} [Australian Standard 1995b]. As mentioned in Chapter 2.2, the restaurant areas on Level 8 are constructed with curtain walls. Even the glasses of those walls are treated with special treatment, water curtains should be installed in each side of the shop to prevent large amount of radiant heat intensity transmitting to the common area. Flow rate and pressure required for drencher system are depended on the radiant heat intensity.

The shop, which is selling toys, was used to illustrate the effect of WMFSS. The shop is 6 m long, 4 m wide and 2.3 m high. As reported by Ng and Chow [2001a], an unsprinklered fire will give the heat release rate up to 7.2 MW as illustrated in Table 4.1. An ultrafast design fire can be used in retail shop. The time to flashover is only 196 s. Quick-response type nozzles should be considered in this case to prevent the flashover. To prevent the smoke flowing into the large spaces, smoke curtain and smoke extraction system can also be utilized.

Fire risk in small retail shops is classified into ordinary hazard for non-warehouse fire protection [British Standards Institution 1990]. Discharge water density of sprinkler system is selected as 5 $Lmin^{-1}m^{-2}$ [British Standards Institution 1990]. Water application rate of this shop would be 120 $Lmin^{-1}$. If the application duration is 60 min, the total water volume will be up to 7.2 m^3, which is resulted in water damage.

In WMFSS, closed nozzles with thermal sensitive elements were distributed below the ceiling. A water mist nozzle can protect an area of about 2.5 m × 2.5 m. Six nozzles are used in the retail shop as shown in Figure 11.8. For the discharge density of 2 $Lmin^{-1}m^{-2}$, maximum water application rate in the entire shop is 48 $Lmin^{-1}$. If the application duration is 30 min, the total water volume is only 1.5 m^3; which is lower than the sprinkler system, i.e. 7.2 m^3. Therefore, water damage can be avoided.

For an isolated small retail shop, self-contained modular system can be used. It comprises of detectors, nozzles, water containers, high pressure nitrogen cylinders, pipes and other controlling components. When a fire occurs, detectors will send an electrical signal to control the valve and release high pressure nitrogen to admit water into pipework. WMFSS can be used as a preaction system since water mist nozzles are closed with thermal sensitive elements. Water mist cannot be discharged from nozzles until fire has generated a sufficient quantity of heat to activate the elements.

- Pre-flashover fire protection

    To suppress retail shop fire at early stage, quick-response type water mist nozzles are required. The operation time of nozzle can be predicted by using the National Institute of Standards and Technology program DETACT [Beever 1991]. Assume the ambient temperature is 20°C, RTI is 50 $m^{1/2}s^{1/2}$, design fire is ultrafast and actuation temperature is 68°C, activation time of WMFSS would be 48 s after ignition and the associated heat release rate is

419 kW. The smoke extraction rate required to keep 2.1 m clear height before applying the water mist is 2.2 m^3s^{-1}. As the floor area of the shop is 24 m^2, the average vertical velocity of the smoke layer is only 0.1 ms^{-1}. Water mist movement would not be affected by the smoke movement as the velocity of water mist is high, i.e. 15 ms^{-1}.

The calculated droplet size and velocity of the typical droplets reaching the mean flame height are shown in Table 11.4. Note that the maximum velocity of plume, i.e. 5.7 ms^{-1}, is located at flame mean height. The droplets with large velocity will overcome the plume effect. Droplets will also reach the lower levels, depending on the resultant drag effect of drag, evaporation and droplet trajectories. After suppression, the decrease in plume effect will contribute the smaller droplets in flame cooling and other effects.

Large droplets are used in fuel surface cooling to reduce pyrolysis, while small droplets are used for flame cooling, oxygen displacement and smoke scrubbing. The water density at fuel surface for extinguishing some polymeric materials such as PMMA of 30 kWm^{-2} is less than 0.6 $Lmin^{-1}m^{-2}$ [e.g. Magee and Reitz 1975]. For the WMFSS design of water flux density 2 $Lmin^{-1}m^{-2}$, exit velocity 15 ms^{-1} and volume median diameter 800 μm, at least 50% of larger droplets would have adequate velocities to reach the fuel surface at mean flame height. Fire can be extinguished by sufficient water spray. Other than the larger droplets, smaller droplets can prevent the re-ignition by heat extraction and oxygen displacement.

- Post-flashover fire protection

At post-flashover stage, ventilation factor will affect the WMFSS performance significantly. As the chemistry involved in the combustion process with water vapour is very complicated, a thermal model which is developed by Chow and Yao [2001] is considered to generate several sets of numerical simulation as illustrated in Figures 11.9 – 11.12. In the study, the opening heights were selected as 2.1 m, 1 m and 0.5 m by taking into account the possible positions of smoke curtain. The water flow rates of 2, 4 and 8 $Lmin^{-1}m^{-2}$ and mean droplet diameters of 200, 400 and 800 μm were employed. The initial droplet velocities were 10 ms^{-1}. Steady compartment temperature was estimated before water mist was applied. Note that in this model, the maximum heat release rate correlated with the incoming airflow rate was used to assess the system performance. Heat release rate can be reduced by the combustion reaction of water mist and the temperature decreased more quickly than the estimation by using the maximum value.

The compartment temperature will be decreased after applying the mist in Figures 11.9 to 11.11. For the opening height of 2.1 m in Figure 11.9, the steady compartment temperature before applying the mist was 1623 K due to large ventilation factor and the associated heat release rate. For large droplets, i.e. 800 μm diameter, the compartment temperature decreased a bit due to weak heat and mass transfer between droplets and hot gas, while for small droplets, i.e. 200 and 400 μm diameter, all became water vapour and the compartment temperature decreased significantly. There is no significant difference between the performance of 200 and 400 μm water mist as all of them were evaporated due to high temperature. As shown in Figure 11.9, the temperature was below 800 K in a short time after 8 $\mathrm{Lmin^{-1}m^{-2}}$ applying water mist. As shown in Figures 11.10 and 11.11, the required flux density and compartment temperature decreased to 373 K for a relatively smaller ventilation factor. Under this condition, the remaining fire in the shop would be extinguished by water mist directly.

As shown in Figure 11.12, the mass flow rate of gas increased after applying the water mist. If the smoke temperature was high, the damage would become large. But that does not imply smoke at lower temperature is not detrimental, depending on its effect on human beings and the types of goods stored. Therefore, more attention should be paid to selecting suitable water spray characteristics to achieve suitable suppression performance. Smoke curtain should be released to a relatively low location under fire situations if people have escaped out of the shop, say 1 m above the floor to limit the ventilation factor, compartment temperature and hot gas flow rate. Under this condition, good suppression performance of the WMFSS will be obtained with reduced discharge rate. Further investigation should be conducted to obtain more detailed application principles for fire protection of the small retail shops.

SHAR can be used to assess the suppression efficiency. The calculated values of various opening heights and spray characteristics are shown in Table 11.5. The heat release rate from ventilation-controlled fire would become higher if the opening is higher. With an increment in water density and reduction in droplet diameter, the critical SHAR value for fire extinguishment, i.e. 0.6 or 0.7, can be achieved. Note that the shop was simplified as a ‘well-stirred combustion chamber’ and the effect of induced gas flow by smoke extraction system was not considered. In real case, a larger water density and velocity should be selected to overcome this effect.

11.9 Conclusion

According to Chapter 11.3, deluge system is better than automatic sprinkler system for providing safety in buildings which are classified as high hazard occupancy, such as the aircraft hangers and assembly plants [Australian Standard 1997; British Standards Institution 1997; National Fire Protection Association 1996]. As the terminal buildings are not considered as high hazard buildings, deluge system is only considered to be utilized in the aircraft hangers of the airport terminal instead of the terminal buildings. On the other hand, drencher system can be utilized in buildings with special architectural features, such as the retail shops of the airport terminal [e.g. Ng and Chow 2002] as illustrated in Table 11.3, where desirable sense of spaces and adequate level of fire safety performance should be achieved simultaneously.

In order to prevent smoke and fire spread to the adjacent large open areas from the small retail shops, self-contained and preaction WMFSS would be a good choice in suppressing the fire, reducing the smoke and water damage in retail shops. To supply sufficient water mist, water mist nozzles should not be installed near the exhaust point of the smoke extraction system and adequate momentum should be provided to the water droplet. It is more important for the pre-flashover stage fire as the heat release rate and smoke production rate are smaller and smoke extraction system played a more important role.

Chapter 12 : Conclusion

12.1 Major findings

Aspects of fire safety for the airport terminal in Hong Kong were studied by fire risk models, field surveys, evacuation models and full-scale burning tests in considerable depth. The floor space factor of the departure level, arrival level and retail areas was identified in Table 6.1 through the field surveys to verify the reality of the data specified in the codes in designing the occupant loading for the airport terminal. In order to recognize the times involved in the evacuation process, definitions and calculations of different time components were clarified in Appendix C. By means of the evacuation simulation, the total evacuation time (TET) of occupants under the normal and fire condition could be acquired in Tables 7.3 & 8.1. The waiting time index (WTI) in Table 8.7 would then be estimated from the simulated evacuation time and the severity of the jamming conditions of occupants could hence be realized.

After identifying the minimum heat release rate for flashover to be occurred in Table 4.1, fire risk in Tables 4.3 & 4.4, floor space factor in Table 6.1, TET and WTI of occupants inside the departure level and arrival level of the airport terminal in Tables 7.3 & 8.1 and 8.7, detailed fire safety strategies were then suggested in Chapter 10.3 to have four parts on passive building construction, active fire services installation, fire safety management and control of risk factors. Utilization of the modern systems, i.e. deluge system, drencher system and water mist fire suppression system, was also proposed in Chapters 11.5 to 11.8 for the departure hall, arrival hall and retail areas, so as to improve the fire safety inside the airport terminal.

Major results can be summarized into 5 parts:

- Fire risk analysis
- Passenger loading survey
- Evacuation analysis
- Heat release rate
- Fire safety strategies

12.2 Fire risk analysis

Cabin concept utilized in retail areas was a good design in utilizing more hall space without installing an excessively large smoke extraction system. However, several considerations as mentioned in Chapter 2.3, such as the occurrence of flashover, possibility of the cabin becomes a big burning object and failure of sprinkler system, should be paid heed to. On the other hand, fire safety objectives were proposed for the airport terminal in Chapter 3.5. It was the first step for implementing the performance-based fire safety design in the terminal building. After recognizing the goals and objectives in Chapters 3.1 & 3.2, the fire hazards of the retail areas of the departure level and arrival level were selected for further analysis in Chapter 4.

Fire environments with two different ventilation conditions, i.e. door opened or closed, for retail shops inside the departure and arrival levels of the airport terminal were studied in Table 4.1. Based on the simulation of the two-layer zone model HotLayer of FIREWIND version 3.5 [2000] in Table 4.1, smoke would fill up most of the shops but smoke layer temperature was not too high. Occupants were at high risk if they could not evacuate from the shop efficiently.

Some retail shops were selected to undergo a fire risk analysis with the software Fire Risk Assessment Method for Engineering (FRAME) version 2.0 [Smet 1998, 1999] in Chapter 4.4. The results in Table 4.3 illustrated that the risk of loss of property and business interruption was small in the retail areas of the airport terminal. However, some shops had a higher value on fire risk of occupants, i.e. above 0.7. Attention should be paid on life safety of occupants inside the retail areas of airport terminal.

As Chinese restaurants were regarded as areas with high fire risks, detailed fire risk analysis of a selected Chinese restaurant, i.e. occupants, property and business activities, was carried out in Table 5.2. Although the value on the fire risk of occupants was only 0.25, it was the highest among the fire risks for the loss of property and business interruption. Fire safety management mentioned in Chapter 5.6 should be watched carefully to ensure the life safety of occupants inside the Chinese restaurants of the airport terminal.

12.3 Passenger loading survey

Occupant loading is important for designing the means of escape inside the airport terminal. Therefore, a field survey on the transient occupant loadings inside the departure level and arrival level was carried out to justify the accuracy of the floor space factor specified in the design codes and standards in designing the occupant loading for the airport terminal in Chapter 6.2.

There were several procedures adopting in the field survey to recognize the floor space factor inside the departure level and arrival level of the airport terminal in Chapter 6.3. The surveyed data was compared with the floor space factor allowed in different codes in Table 6.1. It was acceptable to utilize the value allowed in the MoE codes or UK codes [Buildings Department Hong Kong 1996b; British Standards Institution 1997a] for designing the occupant loading in the halls and retail areas of the airport terminal as the difference in the floor space factor between the field measurement and the codes was small.

On the other hand, the surveyed results in Figures 6.5 & 6.6 illustrated that the peak occupant loading occurred at around 4:00 p.m. and 3:00 p.m. in the departure level and arrival level respectively during the New Year period, i.e. 30 December 2004 to 3 January 2005. Attention should be paid to the crowded condition occurred inside the retail areas, departure hall and arrival hall of both levels during the peak period. As mentioned in Chapter 6.5, people except the passengers should not be allowed to enter the airport terminal once the maximum loading at the departure hall and arrival hall were reached.

12.4 Evacuation analysis

Different time concepts involved in fire development and evacuation process [e.g. British Standards Institution 1997b; Fruin 1987; Marchant 1976b; Owen *et al.* 1996; Tanaka *et al.* 2002] were illustrated in Figure C.1. Several time concepts such as the evacuation time, Required Safe Egress Time (RSET) and Available Safe Egress Time (ASET) were studied in-depth in Appendix C. Waiting time is an important factor in affecting the queuing process and hence the evacuation time of occupants. The evacuation of occupants inside the departure level and arrival level of the airport terminal was studied by two different evacuation software, i.e. buildingEXODUS and SIMULEX, under the fire and normal conditions in Chapters 7.2 & 8.3.

The emergency evacuation inside the arrival level of the airport terminal was taken as an example to illustrate the TET of occupants under the design loading as specified in the local codes [Buildings Department Hong Kong 1996b]. Based on the simulations of buildingEXODUS and SIMULEX in Table 7.3, both results illustrated that jamming would be occurred around the staircases of the arrival hall such that the occupants needed to queue up for a long time. As mentioned in Chapter 7.6, providing more staircases and direct exits with critical width, i.e. allowed most of the occupants to escape efficiently, was an effective method in reducing the evacuation time of occupants. On the other hand, clear indication of exit signs and control of occupant loading could also facilitate the occupants to use the direct exits to evacuate and minimize the long queues formed inside the arrival level of the airport terminal respectively.

The waiting time during the emergency evacuation was concerned in Chapter 8.1. WTI was proposed in Chapter 8.2 to quantify the jamming at the direct exits or staircases of the departure hall of airport terminal. It was an index on assessing the evacuation design and evaluating the overcrowded conditions. As illustrated in Figure 8.11, the values of WTI for most scenarios were approaching 1 no matter under the fire condition or normal condition. This indicated that the waiting time was a very large portion in TET for the departure level. The number of occupants entered the departure level should be monitored carefully, so as to ensure the occupants could be evacuated efficiently from the retail areas and departure hall to a safe place in case of fire.

12.5 Heat release rate

Full-scale burning tests for pre-flashover and post-flashover retail shops fires were carried out in the PolyU/HEU Assembly Calorimeter [Chow 2001d; Chow *et al*. 2003] in Figure 9.2. Nine fire scenarios in Table 9.1 were tested for assessing boutiques and retail shops selling CDs. From the results illustrated in Figure 9.11a, it indicated that clothes were ignited vigorously under free burning condition. HRR was high, i.e. 0.4 MW, for only 8 T-shirts. On the other hand, HRR for clothes covered by transparent plastic bags in Figure 9.7c was higher than those without covered by bags in Figure 9.13c. The HRR of plastic bags should not be ignored.

Peak HRR was high for the tests of CDs as illustrated in Figures 9.15c, 9.16c & 9.17c. It gives a big thermal plume [Chow 2002a] if the burning shop is located in a big hall. In those tests, fire was controlled by the sprinkler system. However, the excessive water discharged would cause damage on goods. By the replacement of WMFSS, this situation was improved. However, WMFSS should be kept on discharging water for a period to prevent the increment in HRR as in Figure 9.15c once the water supply was cut off.

12.6 Fire safety strategies

Fire safety strategies were proposed for the airport terminal in Chapter 10.3 to improve life safety, property protection and business continuation after the occurrence of fire. The strategies in Chapter 10.3 were classified into four parts, i.e. passive building construction, active fire services installation, fire safety management and control of risk factors. Those strategies could be taken as a reference for the Airport Authority to improve the fire safety inside the airport terminal.

Detailed analysis of the modern fire services installations, i.e. deluge system, drencher system and WMFSS, were studied carefully inside the departure hall, arrival hall and retail areas of the departure and arrival levels in Chapters 11.5 to 11.8. Deluge system could be applied in special hazards situations such as the quick developing fire occurred inside the large halls. Utilization of drencher system [e.g. Ng and Chow 2002] achieved a desirable sense of spaces and adequate level of fire protection in retail shops simultaneously. WMFSS was good for suppressing fires and reducing smoke and water damage in small retail shops. Those systems could be used to replace the traditional fire suppression system and protection system in buildings with special architectural features, i.e. airport terminal, to improve the fire safety.

12.7 Summary and future works

As a conclusion, fire risk and the minimum heat release rate for flashover to be occurred in retail areas; floor space factor, time concepts involved in the evacuation process, TET and WTI of occupants, HRR of the combustibles in retail shops, fire safety strategies and utilization of the modern fire services installation, were studied inside the departure level and arrival level of the airport terminal in Chapters 4 to 11. From those experimental studies, field surveys and simulations, risks of the airport terminal were revealed. Based on the fire risk analysis in Table 4.3, protections for property and business activities were adequate. However, the provision of life safety should be improved. It could be enhanced by the evacuation design of the airport terminal. Proper fire safety strategies mentioned in Chapters 10.4 to 10.7 should be proposed to enhance the fire safety of the airport terminal to an upper standard. Utilization of the modern fire services installation in Chapters 11.7 & 11.8, i.e. deluge system, drencher system and WMFSS, was also a good solution to increase the fire safety inside the airport terminal.

Last but not least, further investigations on the ability of water curtain in preventing the penetration of smoke and psychological effects of occupants during the evacuation were necessary. Application of the research results in buildings with special architectural features, e.g. railway stations, was another important issue. Therefore, the study could be continued as further higher degree projects. Topics including database development on HRR for different types of combustibles in retail shops; physiological effects of different age groups and sexes of occupants in evacuation; fire spread of combustibles in retail shops and its effect to atrium fire; and studies on smoke spreading prevention and thermal radiation blockage by water curtain are recommended.

Nomenclature

a	Activation factor
a_s	Surface area of droplet (m^2)
A	Acceptance levels for loss of property
A_1	Acceptance levels for threat to people
A_2	Acceptance levels for threat to business
A_{1a}, A_{2a}, A_{3a}	Particular unobstructed area of the arrival hall (m^2)
A_a, A_b	Surface area of a fire (m^2)
A_a'	Unobstructed area of the arrival hall (m^2)
A_d	Unobstructed area of the departure hall (m^2)
A_e	Surface area of element exposed to hot air (m^2)
A_f	Floor area (m^2)
A_{fu}	Fuel area (m^2)
A_o	Total area of openings within a wall or roof (m^2)
A_p	Area coverage by open sprinkler (m^2)
A_r	Aspect ratio
A_{r1}	Aspect ratio in case A1
A_{r2}	Aspect ratio in case A2
A_{r3}	Aspect ratio in case A3
A_{ra}	Total areas of the retail shops in the arrival level (m^2)

A_{rd}	Total areas of the retail shops in the departure level (m^2)
A_s	Total surface area of a single droplet (m^2)
A_t	Total area of the wall (m^2)
A_v	Opening area of the ventilation opening (m^2)
b	Plan body depth (m)
b'	Exit width (m)
B	Width of train door (m)
B'	Width of platform exit (m)
c	Volume number
C	Dimensionless conversion factor
C'	Traffic capacity of occupants (m^2min^{-1})
C_1	Dimensionless conversion factor in case A1
C_2	Dimensionless conversion factor in case A2
C_3	Dimensionless conversion factor in case A3
C_a	Floor space factor of the arrival hall ($m^2person^{-1}$)
C_c	Traffic capacity of occupants moved to a section in corridor (m^2min^{-1})
C_d	Floor space factor of the departure hall ($m^2person^{-1}$)
C_e	Specific heat capacity of thermal sensing element ($Jkg^{-1o}C^{-1}$)
C_M	Momentum coefficient
C_p	Thermal capacity at constant pressure ($Jkg^{-1}K^{-1}$)

C_{ra}	Floor space factor of the retail areas of arrival level ($m^2person^{-1}$)
C_{rd}	Floor space factor of the retail areas of departure level ($m^2person^{-1}$)
C_s	Traffic capacity of occupants moved to a section in staircase (m^2min^{-1})
d	Thickness of water curtain (m)
d'	Inter-person distance (m)
d_f	Dependence factor
d_{trav}	Travel distance (m)
$\frac{dT}{dt}$	Rate of change of temperature between droplet and envelope of cone spray (Ks^{-1})
D	Protection levels for building and its content
D'	Density of flow (m^2m^{-2})
D_1	Protection levels for occupants
D_2	Protection levels for the operation of business
D_{1a}, D_{2a}, D_{3a}	Particular unobstructed area of the departure hall (m^2)
D_c	Diameter of cone spray at the location where water stream is changed to droplets (mm)
D_d	Density (number of person m^{-2})
D_e	Design density of discharge ($mmmin^{-1}$)
D_f	Fire diameter (m)
D_i	Diameter of nozzle (m)
D_l	Limiting distance (m)

D_{l1}	Limiting distance in case A1 (m)
D_{l2}	Limiting distance in case A2 (m)
D_{l3}	Limiting distance in case A3 (m)
D_s	Distance of the radiant heat source away from the protected zone in case A2 (m)
D_{s1}	Distance of the radiant heat source away from the protected zone in case A3 (m)
$Dv_{0.99}$	99% volume diameter (m)
D_w	Diameter of water droplet (μm)
D_x	Mean droplet diameter (mm)
e	Level factor
f	Pressure loss in pipes (bar)
f'	Frictional loss (kPa)
f_1	Flow rate (person $m^{-1}s^{-1}$)
f_p	Flow rate of people moving out the train door (person $m^{-1}s^{-1}$)
f_p'	Flow rate of people passing through the platform exit (person $m^{-1}s^{-1}$)
F	Attenuation factor
F_1	Attenuation factor in case A1
F_2	Attenuation factor in case A2
F_3	Attenuation factor in case A3
F_{ab}	Parameter view factor
F_d	Fire load density (MJm^{-2})
F_o	Structural fire resistance factor

F_r	Fire resistance factor
g	Gravity acceleration (ms^{-2})
g_a	Area factor
G	Constant
h	Height of the opening (m)
h_e	Convective heat transfer coefficient ($Js^{-1}m^{-2o}C^{-1}$)
h_t	Heat transfer coefficient of each droplet ($Wm^{-2}K^{-1}$)
H	Height (m)
H'	Hazard parameter
H_1	Area of horizontal projection of people (m^2)
H_c	Heat of combustion ($kJkg^{-1}$)
H_o	Initial hazard
H_{per}	Equivalent heat (J)
H_v	Height of the opening (m)
i	Fire spread factor
I_i	Transmitted radiant heat flux (Wm^{-2})
I_{i1}	Transmitted radiant heat flux in case A1 (Wm^{-2})
I_{i2}	Transmitted radiant heat flux in case A2 (Wm^{-2})
I_{i3}	Transmitted radiant heat flux in case A3 (Wm^{-2})
I_o	Intensity of radiation incident on a layer of water curtain (Wm^{-2})
I_s	Average radiant heat intensity of the fire source (kWm^{-2})

I_{s1}	Average radiant heat intensity of the fire source in case A1 (kWm^{-2})
I_{s2}	Average radiant heat intensity of the fire source in case A2 (kWm^{-2})
I_{s3}	Average radiant heat intensity of the fire source in case A3 (kWm^{-2})
I_{λ}	Radiant heat flux transfer inside the water curtain (Wm^{-2})
$I^{0}_{\lambda,T}$	Heat flux before entering the water curtain (Wm^{-2})
$I'_{\lambda,T}(\Omega)$	Intensity diffused normally inside the water curtain (Wm^{-2})
k	'k' factor
k_a	Conductivity of air ($Wm^{-1}K^{-1}$)
k_{abs}	Absorption coefficient of water (m^{-1})
k_{ext}	Extinction coefficient of water (m^{-1})
k_s	Shortest distance from the last train door to platform exit (m)
k_{sca}	Scattering coefficient of water (m^{-1})
k_{walk}	Walking pace of occupants (ms^{-1})
K	Constant
l	Equivalent length of pipe and fitting (m)
l'	Length of the flow (m)
L	Length (m)

L_f	Height of flame (m)
L_w	Distance between centres of A_a and A_b (m)
m	Number of floors
m’	Constant
m_a	Rate of mass loss per unit area ($kgs^{-1}m^{-2}$)
m_a’	Mass flow rate of air inflow (kgs^{-1})
m_e	Mass (g)
m_r	Number of occupants in congestion
M	Mobility
M_w	Amount of water injected (kgm^{-3})
n	Number of train doors
n’	Number of drencher nozzles over protected area
n_i	Number of congestions
n_o	Number of openings
N	Number of water droplets per unit volume
N_1	Number of passengers whom can escape through various train doors
N_a	Number of occupants occupied that particular area in the arrival hall
N_{a1}	Total number of passengers inside the train
N_d	Number of occupants occupied that particular area in the departure hall
N_{max}	Maximum number of passengers
N_p	Normal protection factor

N_{ra}	Number of occupants in all retail shops of the arrival level
N_{rd}	Number of occupants in all retail shops of the departure level
Nu	Nusselt number
O_s	Orifice size (mm)
p	Constant
P	Potential risks of building and its content
P_1	Potential risks of occupants
P_2	Potential risks of activities
P_{eo}	Percentage of opening in a wall or roof (%)
P_{eo1}	Percentage of openings in case A1 (%)
P_{eo2}	Percentage of openings in case A2 (%)
P_{eo3}	Percentage of openings in case A3 (%)
P_o	Pressure required to supply the flow for a drencher nozzle (kPa)
P_w	Working pressure for deluge system (bar)
P_w'	Pressure required to deliver the flow (bar)
P_x	Pressure loss (kPa)
P_y	Pressure required at deluge valve (bar)
Pr	Prandtl number
q	Extinction cross-section of a single water droplet (μm^2)
q_f	Fire load factor

q_h	Heat absorption rate by a single water droplet (Ws^{-1})
q_{loss}	Net radiative and convective heat transfer from the upper gas layer (kW)
Q	Minimum flow rate ($Lmin^{-1}$)
Q_a	Average discharge density ($Lm^{-2}min^{-1}$)
Q_{ab}	Radiant heat from A_a to A_b (kW)
Q_c	Heat release rate (kW)
Q_{ca}	Calorific value of contents (MJ/kg)
Q_{con}	Rate of convective heat loss through openings (kW)
Q_{ext}	Extinction efficiency
Q_f	Flow rate ($Lmin^{-1}$)
Q_{fm}	Minimum heat release rate for flashover (kW)
Q_h	Heat absorption rate of the spray of open sprinkler (kW)
Q_i	Discharge density for nozzle ($Lm^{-2}min^{-1}$)
Q_n	Number of occupants
Q_o	Heat loss rate through walls, floor and ceiling by conduction (kW)
Q_r	Radiative heat loss rate through openings (kW)
Q_v	Volume flow rate through unit horizontal area (m^3s^{-1})
Q_{wv}	Flow rate ($Lmin^{-1}$)
Q_x	Flow rate produced by orifice plate ($Lmin^{-1}$)

r	Droplet radius (μm)
r_e	Environment factor
r_p	Parameter of drop size of spray (mm)
R	Fire risk for building and its content
R_1	Fire risk for occupants
R_2	Fire risk for business activities
R_f	Radiative heat flux (kWm^{-2})
R_o	Initial risk
Re	Reynolds number
s	Speed of flow (ms^{-1})
S	Special protection factor
S'	Travel speed (ms^{-1})
S_{yx}	Static pressure due to height difference between point x and valve (bar)
t	Time (s)
t'	Thickness of a person (m)
t_a	Time from detection to notification of occupants (s)
t_{av}	Time required for toxic environment to reach a critical or untenable state (s)
t_{A1}	ASET by Cooper (s)
t_{A2}	ASET by British Standards Institution (s)
t_c	Coping time (s)
t_{cut}	Time at the cut-off value of 5 MW (s)

t_d	Time required to evaluate quality and extent of life threat (s)
t_{de}	Detection time required for sensation of a stimulus from fire environment (s)
t_e	Equivalent duration of the fire (min)
t_{e1}	Evacuation time by Togawa (s)
t_{e2}	Evacuation time by Galbreath (s)
t_{e3}	Evacuation time by Melinek and Booth (s)
t_{e4}	Evacuation time by Smith (s)
t_{e5}	Evacuation time by Pauls (s)
t_{e6}	Evacuation time by Løvås (s)
t_{e7}	Evacuation time by British Standards Institution (s)
t_{eF}	Evacuation time by Fruin (s)
t_{ev}	The evaluation time of recognizing the fire and deciding to take action (s)
t_{eva}	Evacuation time (s)
t_{f1}	Flow time of passengers passing through the exit (s)
t_g	Growth time (s)
t_h	Time of onset of hazardous conditions (s)
t_m	Maximum emptying time (min)
t_{ma}	Margin of safety (s)
t_{mF}	Moving time (s)
t_{mFi}	Moving time of i^{th} person (in s)

t_o	Incubation period (s)
t_p	Elapsed time from ignition to perceive that a fire exists (s)
t_{p1}	Pre-movement time for the first few occupants (s)
t_{p50}	The subsequent distribution of pre-movement times for the population of occupants to begin their travel phase (s)
t_{p99}	Pre-movement time for the last few occupants (s)
t_{peak}	Time with respect to the maximum number of people (s)
t_{ph}	Physical time component (s)
t_{pr1}	Pre-movement time by Pauls (s)
t_{pr2}	Pre-movement time by British Standards Institution (s)
t_{ps}	Psychological time component (s)
t_q	Time taken for entire population to pass through available exits (s)
t_{qf}	Time to queue formation at exits (s)
t_r	Response time of occupants to the warning prior to beginning the evacuation (s)
t_{rc}	Recognition time from people being alerted by a cue (s)
t_{re1}	Time required for escape by Marchant (s)

t_{req}	Required escape time (s)
t_{res}	Response time (s)
t_{R1}	RSET by Pauls (s)
t_{R2}	RSET by Stahl *et al* (s)
t_{R3}	RSET by Sime (s)
t_{R4}	RSET by Buchanan (s)
t_{R5}	RSET by Nelson and Mowrer (s)
t_{R6}	RSET by British Standards Institution (s)
t_s	Walking time of occupants required to travel the staircase (s)
t_{sr}	Walking time for the unimpeded crowd in the r^{th} floor to reach the ground floor (s)
t_{t1}	Travel time needed to reach a safety place (s)
t_{t2}	Travel time by Spearpoint (s)
t_{vF}	Walking time by Fruin (s)
t_{w1}	Walking time of occupants from the last train door to the platform exit (s)
t_{w2}	Walking time for one person to traverse the maximum travel distance (s)
t_{w3}	Walking time of the last few occupants (s)
t_{w4}	Walking time of the first few occupants (s)
t_{wa1}	Waiting time at each queue to exit (s)
t_{waF}	Waiting time for stationary of queue (s)
$t_{waFi,j}$	Maximum total waiting time of the i^{th} occupant for the stop j^{th} (in s)

t_{wait1}	Waiting time of the first congestion (s)
t_{wait2}	Waiting time of the second congestion (s)
T	Initial maximum travel speed (ms^{-1})
T_1	Time (s)
T_a’	Temperature of A_a (K)
T_{at}	Ambient air temperature (K)
T_{flr}	Temperature of the floor (K)
T_g	Temperature of the upper gas layer (K)
T_m	Time for the delaying crowd formed the maximum mass at the platform exit (s)
T_o	Time for the crowd started to form at the exit in platform (s)
T_s	Maximum smoke layer temperature (^oC)
T_w	Temperature of the upper walls (K)
U	Escape factor
U_c	Characteristic plume velocity (ms^{-1})
U_p	Initial droplet velocity (ms^{-1})
v	Venting factor
v_D	Downward component of drop velocity (ms^{-1})
v_1	Walking velocity of the crowd (ms^{-1})
v_{walk}	Walking speed (ms^{-1})
V	Actual windspeed (ms^{-1})
V’	Unimpeded walking speed (ms^{-1})
V_d	Discharge velocity of nozzle (ms^{-1})
V_h	Velocity of hot air in plunge test (ms^{-1})

V_{wind}	Dimensionless windspeed
V'_{wind}	Dimensionless windspeed per unit width
V_x	Mean velocity of droplets inside unit volume (ms^{-1})
w	Width of a person (m)
W	Width (m)
W_e	Weber number
W_{ei}	Weight of contents (kg)
W_{h1}	Height of hall in case A1 (m)
W_{h2}	Height of window areas in case A2 (m)
W_{h3}	Height of building in case A3 (m)
W_s	Water supply factor
W_v	Width of the opening (m)
W_v^*	Width of the opening required to acquire the minimum heat release rate for flashover (m)
W_{w1}	Width of hall in case A1 (m)
W_{w2}	Width of window areas in case A2 (m)
W_{w3}	Width of building in case A3 (m)
WT_1	First waiting time (s)
WT_2	Second waiting time (s)
x'	Distance between sprinkler and floor (m)
y_1	Number of passengers whom are escaping from the train with respect to time T
y_2	Number of passengers whom are flowing out the platform exit.

y_s	Minimum smoke layer interface height (m)
Y	Salvage factor
z_a	Access factor

Greek symbols

χ	Combustion efficiency
ε	Emissivity of the hot gas
ε_a	Emissivity of A_a
α_b	Absorptivity of A_b
σ	Stefan-Boltzmann constant ($Wm^{-2}K^{-4}$)
σ_w	Water surface tension (Nm^{-1})
τ	Time constant (s)
τ'	Duration of delay of movement during queuing (min)
ρ	Density of water (kgm^{-3})
ρ_a	Density of air (kgm^{-3})
ρ_f	Density of fuel vapour (kgm^{-3})
φ	Formula of delaying crowd
β	Constant
δ	Width of the flow (m)
λ	Wavelength
θ	Angle of deflection (radian)
θ_c	Angle of cone spray (radian)

μ_w	Viscosity of water (Nsm^{-2})
Ø	Percentage of the number of passengers gather in one of train doors to the number of those who went to other train doors (%)
Δt	Time period regarding the number of people is equal or larger than $N_{max}/2$ (s)

Abbreviation

ASET	Available Safe Egress Time
BD	Buildings Department
CO	Carbon monoxide
CO_2	Carbon dioxide
CWT	Cumulative waiting time
EET	Exit Evacuation Time
EPBFC	Engineering performance-based fire codes
ET	Evacuation time simulated by buildingEXODUS
ET1	Evacuation time simulated by SIMULEX
FEA	Fire engineering approach
FED	Fraction Effective Dose
FLD	Fire Load Density
FRAME	Fire Risk Assessment Method for Engineering
FRC	Fire Resisting Construction
FRP	Fire Resistance Period

FSD	Fire Services Department
FSI	Fire Services Installation
FSM	Fire Safety Management
HCN	Hydrogen cyanide
HEU	Harbin Engineering University
HRR	Heat release rate
HVAC	Heating, ventilating and air conditioning
LPG	Liquefied petroleum gas
MoA	Means of Access
MoE	Means of Escape
MPFR	Minimum period of fire resistance
MT	Moving time
O_2	Oxygen
OH	Ordinary Hazard
PA	Public Address
PBC	Passive building construction
PolyU	The Hong Kong Polytechnic University
PS	Polystyrene
RF	Risk factors
RSET	Required Safe Egress Time
RT	Response time in buildingEXODUS
RT1	Response time in SIMULEX
RTI	Response Time Index
SAR	Special Administrative Region
SHAR	Spray Heat Absorption Ratio

SI	Safety Index
T	Temperature
TET	Total Evacuation Time
TT	Travel time
V	Visibility
WMFSS	Water mist fire suppression system
WTI	Waiting Time Index

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Table 2.1: Dimensions of different zones in the airport terminal building

Level	Name of Level	Zones	Zones (Restricted Area*)	Width (m)	Length (m)	Height (m)
Roof	Roof	-	-	-	-	-
8	Non-Restricted Mezzanine Level	Restaurant Area		80	28	10
7	Departure Level	Entrance Hall		330	40	12.3
		Departure Hall		330	95	12.3
		Retail Area		120	28	2.3
			East Hall	-	-	-
6	Boarding Level		North Concourse	-	-	-
			South Concourse	-	-	-
			East Hall	-	-	-
			Central Concourse	-	-	-
			West Hall	-	-	-
			Northwest Concourse	-	-	-
			Southwest Concourse	-	-	-
5	Arrival Level	Arrival Hall		330	53	8
		Retail Area		48	10	2.3
			Pre-Immigration Hall	-	-	-
			North Concourse	-	-	-
			South Concourse	-	-	-
			Central Concourse	-	-	-
			West Hall	-	-	-
			Northwest Concourse	-	-	-
			Southwest Concourse	-	-	-
4	Apron	Apron / Plant Platform		-	-	-
3	Not Applicable	Stores		-	-	-
2	Not Applicable	Baggage Hall / Plantrooms		330	120	10
1	Station Platform / Tunnel	Station Platform / Tunnel		-	-	-

* The dimensions of restricted areas cannot be observed.

Table 2.2: Fire protection measures for airport terminal

(1)	Fire protection measure (2)	Primary Contribution (3)	Secondary Contribution (4)
Passive	1. Fire resisting construction The new airport terminal is divided as restricted area and non-restricted area with different FRP requirements.	• Life safety.	• Conflagration prevention. • Property protection.
	2. Protected lobbies	• Life safety.	• Property protection.
Active	1. Central control room • The room is separated from the other part of the building by walls having a minimum FRP of 1 hour. • Large enough to accommodate equipment and recorders. • Ancillary to the fire protection systems installed in the building.	• Life safety.	• Property protection. • Conflagration prevention.
	2. Communication systems: both Audio advisory system and visual advisory system	• Life safety.	-
	3. Emergency lighting	• Life safety.	-
	4. Exit signs	• Life safety.	-
	5. Fire alarm systems	• Life safety.	• Property protection. • Conflagration prevention.
	6. Fire detection systems	• Life safety.	• Property protection. • Conflagration prevention.
	7. Fire hydrant/ hose reel systems	• Property protection.	• Life safety. • Conflagration prevention.
	8. Portable fire extinguishers	• Property protection.	• Life safety. • Conflagration prevention.
	9. Smoke control provisions	• Life safety.	• Property protection.
	10. Sprinkler systems	• Property protection.	• Life safety. • Conflagration prevention.
	11. Water supplies for fire-fighting	• Property protection.	• Life safety. • Conflagration prevention.
	12. Ventilation/air conditioning control systems	• Life safety.	• Conflagration prevention.
	13. Smoke extraction system	• Life safety.	• Conflagration prevention.

Table 3.1: Fire safety goals, objectives and strategies in different countries

	USA [Meacham 1998; National Fire Protection Association 1995b; Society of Fire Protection Engineers 2000; Tubbs 1999]	UK [British Standards Institution 1999, 2004; Chartered Institution of Building Services Engineers 1997; Lillicrap 2000]	New Zealand [Buchanan 1998, 1999]	Japan [Bukowski and Tanaka 1991; Koya *et al.* 1998; Tanaka 1989, 1991, 1994a, b, 1995, 1998, 1999, 2000; Tanaka *et al.* 1996]	Hong Kong [Buildings Department Hong Kong 1995, 1996a, b; Chow 1999, 2002b, 2004; Wong and Chow 1997]
Goals	Established first before ascertaining the objectives. It is put into 4 categories: • Life safety • Property protection • Business protection • Environmental concerns	Not mentioned.	Not mentioned.	The goals established are: • Prevent the fire or retard its growth. • Protect the occupants from the fire effects. • Minimize the impact of fire. • Support the fire -service operations.	Under review at the moment.
Objectives	To meet the goals, stakeholder objectives or functional objectives should be defined. These objectives would be achieved through the design objectives or performance requirements.	The fire safety objectives are: • Life safety of frequent and infrequent users, disabled persons and firefighters • Prevention of conflagration • Property protection	Objectives considered are: • Outbreak of fire • Means of escape • Spread of fire • Structural stability	The corresponding objectives of the goal are: 1. Prevent the fire or retard its growth - Control fire properties of combustible items. - Provide adequate compartmentation.	Fire safety objectives in the prescriptive codes are: • Saving lives of people • Preventing loss of property • Ensuring fire resisting construction • Structural integrity of buildings

	USA [Meacham 1998; National Fire Protection Association 1995b; Society of Fire Protection Engineers 2000; Tubbs 1999]	UK [British Standards Institution 1999, 2004; Chartered Institution of Building Services Engineers 1997; Lillicrap 2000]	New Zealand [Buchanan 1998, 1999]	Japan [Bukowski and Tanaka 1991; Koya *et al.* 1998; Tanaka 1989, 1991, 1994a, b, 1995, 1998, 1999, 2000; Tanaka *et al.* 1996]	Hong Kong [Buildings Department Hong Kong 1995, 1996a, b; Chow 1999, 2002b, 2004; Wong and Chow 1997]
Objectives				- Provide for suppression of the fire. 2. Protect the occupants from the fire effects - Provide timely notification of the emergency. - Protect escape route. - Provide areas of refuge where necessary. 3. Minimize the impact of fire - Provide separation by tenant, occupancy, or maximum area. - Maintain the structural integrity of building. - Provide for continued operation of shared properties.	

	USA **[Meacham 1998; National Fire Protection Association 1995b; Society of Fire Protection Engineers 2000; Tubbs 1999]**	**UK** **[British Standards Institution 1999, 2004; Chartered Institution of Building Services Engineers 1997; Lillicrap 2000]**	**New Zealand** **[Buchanan 1998, 1999]**	**Japan** **[Bukowski and Tanaka 1991; Koya *et al.* 1998; Tanaka 1989, 1991, 1994a, b, 1995, 1998, 1999, 2000; Tanaka *et al.* 1996]**	**Hong Kong** **[Buildings Department Hong Kong 1995, 1996a, b; Chow 1999, 2002b, 2004; Wong and Chow 1997]**
Objectives				4. Support the fire -service operations - Provide for identification of fire location. - Provide reliable communication with areas of refuge. - Provide for fire department access, control, communication, and water supply.	
Strategies	After defining the goals and objectives. The next step is to develop the design criteria and fire scenarios.	Not mentioned.	Not mentioned.	The followings are the strategies: • Explicitly defining the fundamental requirements. • Expressing technical standards in performance terms to the extent possible.	Not mentioned, but big organizations would work out fire safety strategies.

	USA **[Meacham 1998; National Fire Protection Association 1995b; Society of Fire Protection Engineers 2000; Tubbs 1999]**	**UK** **[British Standards Institution 1999, 2004; Chartered Institution of Building Services Engineers 1997; Lillicrap 2000]**	**New Zealand** **[Buchanan 1998, 1999]**	**Japan** **[Bukowski and Tanaka 1991; Koya *et al.* 1998; Tanaka 1989, 1991, 1994a, b, 1995, 1998, 1999, 2000; Tanaka *et al.* 1996]**	**Hong Kong** **[Buildings Department Hong Kong 1995, 1996a, b; Chow 1999, 2002b, 2004; Wong and Chow 1997]**
Strategies				• Providing calculation methods and computer models for predicting fire-related behaviours.	

Table 4.1: Minimum heat release rate for flashover under different ventilation conditions

Level	Shop number	Width W (m)	Length L (m)	Height H (m)	W_v (m)	Ventilation conditions						T_s (^oC)	y_s (m)
						V1 (H_v = 2.3 m)			V2 (H_v = 0.01 m)				
						A_v (m^2)	Q_{fm} (MW)	W_v* (m)	A_v (m^2)	Q_{fm} (MW)	W_v* (m)		
5	1	3.5	2.5	2.3	2.5	5.8	3.6	0.69	0.025	0.4	266.67	376	0.6
	2	2	4	2.3	1.3	3	2	0.38	0.013	0.3	200.00	416	0.5
	3	2	6	2.3	2	4.6	3.1	0.59	0.020	0.5	333.33	325	0.8
	4	**3**	**6.5**	**2.3**	**3**	**6.9**	**4.5**	**0.86**	**0.030**	**0.6**	**400.00**	**267**	**1.0**
	5	2	6	2.3	2	4.6	3.1	0.59	0.020	0.5	333.33	325	0.8
	6	6	5	2.3	6	13.8	8.7	1.66	0.060	0.9	600.00	244	1.5
	7	2	3	2.3	2	4.6	2.9	0.55	0.020	0.3	200.00	346	0.8
	8	3	6	2.3	3	6.9	4.5	0.86	0.030	0.6	400.00	269	1.0
	9	4	10	2.3	3.5	8.1	5.7	1.09	0.035	1.1	733.33	243	1.2
	10	2	4	2.3	1	2.3	1.6	0.31	0.010	0.3	200.00	462	0.2
	11	5.5	2	2.3	1	2.3	1.7	0.32	0.010	0.4	266.67	243	1.2
	12	5.5	3	2.3	3	6.9	4.5	0.86	0.030	0.6	400.00	238	1.3
	13	6	6	2.3	4	9.2	6.2	1.18	0.040	1.0	666.67	246	1.3
	14	2.5	2	2.3	2.5	5.8	3.5	0.67	0.025	0.2	133.33	301	0.9
7	15	1.5	7	2.3	1.5	3.5	2.4	0.46	0.015	0.5	333.33	246	1.3
	16	3.5	2.5	2.3	2.5	5.8	3.6	0.69	0.025	0.4	266.67	376	0.6
	17	**2.5**	**2**	**2.3**	**2**	**4.6**	**2.8**	**0.54**	**0.020**	**0.2**	**133.33**	**301**	**0.9**
	18	**7**	**7**	**2.3**	**8.5**	**19.6**	**12.3**	**2.35**	**0.085**	**1.3**	**866.67**	**351**	**0.8**
	19	7	8	2.3	10	23	14.4	2.75	0.100	1.4	933.33	229	1.7
	20	3	3	2.3	2	4.6	3	0.57	0.020	0.4	266.67	224	1.7
	21	6	3	2.3	5.5	12.7	7.8	1.49	0.055	0.6	400.00	335	0.8
	22	3.5	2.5	2.3	2.5	5.8	3.6	0.69	0.025	0.4	266.67	256	1.5
	23	4	6	2.3	9	20.7	12.4	2.37	0.090	0.7	466.67	301	0.9
	24	5	3	2.3	4.5	10.4	6.4	1.22	0.045	0.5	333.33	239	1.7
	25	3	3	2.3	2	4.6	3	0.57	0.020	0.4	266.67	265	1.4
	26	2	3	2.3	2	4.6	3	0.57	0.020	0.4	266.67	335	0.8
	27	28	4.5	2.3	4	9.2	8.3	1.59	0.040	3.1	2066.67	346	0.8
	28	4	4	2.3	3.5	8.1	5.1	0.97	0.035	0.5	333.33	179	1.3
	29	4	3	2.3	4	9.2	5.6	1.07	0.040	0.4	266.67	271	1.2
	30	2.5	7	2.3	9.5	21.9	13	2.48	0.095	0.6	400.00	241	1.7
	31	3.5	2.5	2.3	2.5	5.8	3.6	0.69	0.025	0.3	200.00	301	0.9
	32	**6**	**3**	**2.3**	**8**	**18.4**	**5.1**	**0.97**	**0.080**	**0.5**	**333.33**	**245**	**1.7**
	33	3	6	2.3	1.5	3.5	2.6	0.50	0.015	0.6	400.00	344	0.6
	34	4	9	2.3	2	4.6	3.6	0.69	0.020	1	666.67	273	0.7
	35	4	4	2.3	6	13.8	8.3	1.59	0.060	0.5	333.33	255	1.5
	36	4	6	2.3	5	11.5	7.2	1.38	0.050	0.7	466.67	253	1.4
	37	10	6	2.3	1.5	3.5	3.5	0.67	0.015	1.5	1000.00	257	0.5
	38	6	10	2.3	6	13.8	9.3	1.78	0.060	1.5	1000.00	226	1.5
	39	6	3	2.3	7.5	17.3	10.4	1.99	0.075	0.6	400.00	247	1.6
	40	2.5	2	2.3	2	4.6	2.8	0.54	0.020	0.2	133.33	351	0.8
	41	3.5	2.5	2.3	2.5	5.8	3.6	0.69	0.025	0.4	266.67	301	0.9

Table 4.2: Summary of the four retail shops

Shop number	Level	Width (m)	Length (m)	Height (m)	Materials of shop				Vent area of static smoke systems (m^2)	Number of accessible directions	Vertical distance from the access level to the upper or lower floor level	Occupancy	Total mass of combustible (kg)	Total fire load density (MJm^{-2})	Below the upper limit of the fire load density?*	Recommendation
					Wall	Floor	Roof	Windows								
4	5	3	6.5	2.3	Wood and metal	Concrete	Metal	-	0	3	8 m below the access level	20	1014	1079	Yes	The fire load density shall be monitored periodically
17	7	2.5	2	2.3	Wood and metal	Concrete	Metal	-	0	3	0 m	5	22.5	102	Yes	The fire load density shall be monitored periodically
18	7	7	7	2.3	Wood and metal	Concrete	Metal	-	0	3	0 m	12	795	334	Yes	The fire load density shall be monitored periodically
32	7	6	3	2.3	Wood and metal	Concrete	Solid plastic	-	0	3	0 m	10	1235	1235	No	Warning shall be given to the retail shop

* The upper limit of the fire load density as indicated in the local fire codes [Fire Services Department Hong Kong Special Administrative Region 1998] is 1135 MJm^{-2}

Table 4.3: FRAME results for the four retail shops

Items	Shop number				Departure Hall	Arrival Hall
	4	17	18	32		
Potential risk						
P	0.37	0.12	0.44	0.33	0.48	0.39
P_1	3.29	1.93	2.10	2.23	2.56	3.58
P_2	0.22	0.08	0.29	0.20	0.37	0.32
Acceptance level						
A	1.19	1.09	1.19	1.19	1.15	1.17
A_1	0.59	0.40	0.49	0.60	0.53	0.55
A_2	0.90	0.80	0.90	0.80	0.80	0.90
Initial risk						
R_o	0.17	0.06	0.20	0.17	0.17	0.17
Protection level						
D	9.15	9.15	9.15	9.15	9.15	9.15
D_1	6.05	6.05	6.05	6.05	6.05	6.05
D_2	8.94	8.94	8.94	8.94	8.94	8.94
Fire risk						
R	0.03	0.01	0.04	0.03	0.05	0.04
R_1	0.92	0.80	0.70	0.62	0.80	1.08
R_2	0.03	0.01	0.04	0.03	0.05	0.04

Table 4.4: FRAME results of small shops

Items	Shop A	Shop B	2/F of the Local Shopping Mall
Potential risk			
P	0.23	0.23	0.24
P_1	3.08	3.08	3.36
P_2	0.15	0.15	0.16
Acceptance level			
A	1.14	1.15	1.15
A_1	0.64	0.65	0.66
A_2	0.90	0.90	0.90
Initial risk			
R_o	0.13	0.13	0.13
Protection level			
D	3.73	3.73	3.73
D_1	3.19	3.19	3.19
D_2	3.70	3.70	3.70
Fire risk			
R	0.05	0.05	0.06
R_1	1.50	1.49	1.60
R_2	0.05	0.05	0.05

Table 4.5: FIREWIND results of Shop A

Time (s)	Heat release (kW)	Height of hot layer (m)	Height of neutral plane (m)	Hot layer temperature (^{o}C)	Smoke layer through opening (kgs^{-1})	Ceiling jet temperature (^{o}C)	Ceiling jet optical density (dBm^{-1})	Radiation from hot layer (kWm^{-2})
0	0	2.3		25	0	25	0	0
60	40	1.1	1.6	75	0.25	84	1.54	0.09
120	160	1	1.3	166	0.63	158	3.76	0.96
180	360	0.5	1.1	254	0.89	301	6.54	3.57
240	640	0.3	1	372	1.03	566	7.7	9.08
300	1000	0.1	1	496	1.08	900	9.11	19.38
360	1300	0	1	584	1.09	900	9.11	30.11
420	1300	0	1	585	1.08	900	9.11	30.12
480	1300	0	1	585	1.08	900	9.11	30.12
540	1300	0	1	585	1.08	900	9.11	30.12
600	1300	0	1	585	1.08	900	9.11	30.12
660	1300	0	1	585	1.08	900	9.11	30.12
720	1300	0	1	585	1.08	900	9.11	30.12
780	1300	0	1	585	1.08	900	9.11	30.12
840	1300	0	1	585	1.08	900	9.11	30.12
900	1300	0	1	585	1.08	900	9.11	30.12
960	1300	0	1	585	1.08	900	9.11	30.12
1020	1300	0	1	585	1.08	900	9.11	30.12
1080	1300	0	1	585	1.08	900	9.11	30.12
1140	1300	0	1	585	1.08	900	9.11	30.12
1200	1300	0	1	585	1.08	900	9.11	30.12

Table 4.6: FIREWIND results of Shop B

Time (s)	Heat release (kW)	Height of hot layer (m)	Height of neutral plane (m)	Hot layer temperature (^oC)	Smoke layer through opening (kgs^{-1})	Ceiling jet temperature (^oC)	Ceiling jet optical density (dBm^{-1})	Radiation from hot layer (kWm^{-2})
0	0	2.3		25	0	25	0	0
60	40	1.1	1.6	72	0.23	84	1.53	0.09
120	160	1	1.3	163	0.63	158	3.76	0.93
180	360	0.5	1.1	249	0.89	299	6.53	3.41
240	640	0.3	1	363	1.03	563	7.71	8.57
300	1000	0.1	1	480	1.08	866	9.14	17.68
360	1300	0	1	568	1.09	900	9.19	27.8
420	1300	0	1	567	1.08	900	9.19	27.72
480	1300	0	1	567	1.08	900	9.19	27.72
540	1300	0	1	567	1.08	900	9.19	27.72
600	1300	0	1	567	1.08	900	9.19	27.72
660	1300	0	1	567	1.08	900	9.19	27.72
720	1300	0	1	567	1.08	900	9.19	27.72
780	1300	0	1	567	1.08	900	9.19	27.72
840	1300	0	1	567	1.08	900	9.19	27.72
900	1300	0	1	567	1.08	900	9.19	27.72
960	1300	0	1	567	1.08	900	9.19	27.72
1020	1300	0	1	567	1.08	900	9.19	27.72
1080	1300	0	1	567	1.08	900	9.19	27.72
1140	1300	0	1	567	1.08	900	9.19	27.72
1200	1300	0	1	567	1.08	900	9.19	27.72

Table 4.7: Calculations on evacuation time

Shop	Floor area	Travel distance					Response time $t_{res} = \beta \log (A_f)$		Evacuation time $t_{evai} = \frac{d_{travi}}{k_{walk}}$					Total evacuation time	Required escape time
	A_f (m^2)	d_{trav1} (m)	d_{trav2} (m)	d_{trav3} (m)	d_{trav4} (m)	d_{trav5} (m)	β	t_{res} (s)	t_{eva1} (s)	t_{eva2} (s)	t_{eva3} (s)	t_{eva4} (s)	t_{eva5} (s)	t_{eva} (s)	t_{req} (s)
A	5.4	3.36	12	11.5	6	8.5	75 22.5	55 16	6.72	24	23	12	17	83	138 99
B	6.25	3.54	8.5	11	6	8.5	75 22.5	60 18	7.08	17	22	12	17	75	135 93

Table 5.1: Summary of the restaurant

Level	Width (m)	Length (m)	Height (m)	Materials of shop				Vent area of static smoke systems (m^2)	Number of accessible directions	Vertical distance from the access level to the upper or lower floor level	Occupancy	Total mass of combustibles (kg)	Total fire load density (MJm^{-2})	Below the upper limit of the fire load density?*	Recommendation
				Wall	Floor	Roof	Windows								
8	10	28	10.3	Glass wall with metal Frame	Concrete	Metal	-	28	1	2.3 m above the access level	50	570	40	Yes	The fire load density shall be monitored periodically

* The upper limit of the fire load density as indicated in the local fire codes [Fire Services Department Hong Kong Special Administrative Region 1998] is 1135 MJm^{-2}

Table 5.2: FRAME result of the restaurant

Items	
Potential risk	
P	0.25
P_1	0.63
P_2	0.16
Acceptance level	
A	1.04
A_1	0.42
A_2	0.80
Initial risk	
R_o	0.21
Protection level	
D	9.15
D_1	6.05
D_2	8.94
Fire risk	
R	0.03
R_1	0.25
R_2	0.02

Table 5.3: Schedule of the calculation target space

Item	Type	Opening dimension		Area (m^2)
		Width (m)	Height (m)	
1	Staircase	2.5	-	-
2	Double leaf door	2.4	2	4.8
3	Staircase	1.2	-	-
4	Single leaf door	1	2	2
5	Single leaf door	0.8	2	1.6
6	Single leaf door	0.8	2	1.6
7	Single leaf door	1.2	2	2.4
8	Single leaf door	1.2	2	2.4

Table 6.1: Comparisons of the floor space factor for the airport terminal

	Floor space factor ($m^2 persons^{-1}$)		
	Departure hall	**Arrival hall**	**Retail areas**
Hong Kong(1) [Buildings Department Hong Kong 1996]	0.5	0.5	3
UK(2a & 2b) [British Standards Institution 1997a; Fire Safety Building Regulation 2000]	0.5	0.5	4
USA(3) [International Code Council 2003; National Fire Protection Association 2000]	9.3 (Concourse areas) 1.4 (Waiting areas)	9.3 (Concourse areas) 1.4 (Waiting areas)	2.8 (Basement and ground floor) 5.6 (Other floors)
Field survey (Maximum value during the peak period – 23 December 2004 to 3 January 2005)	1.1	1.4	0.9 (Departure level) 0.5 (Arrival level)
Field survey (Maximum value during the normal period – 12 to 18 June 2004)	2.5	4.5	2.1 (Departure level) 2.1 (Arrival level)

(1) Hong Kong [Buildings Department Hong Kong 1996]

Table 1

Intended use of storey	Factor representing usable floor area in m^2 per person
(a) Assembly halls, auditoria and stadia without seating or with movable seating	0.5
(b) Areas accessible to the public in viewing galleries, banking halls, betting centres and places where public service counters are provided	0.5

(2a) UK [Fire Safety Building Regulation 2000]

Table 4.1 Floor space factors recommended in UK

Type of accommodation	Floor space factor / (m^2 per person)
	UK (ADB and STS*)
Bars, standing spectator areas (concentrated use without fixed seating)	0.3
Amusement arcade, assembly hall, bingo hall (less concentrated use without fixed seating)	0.5

* ADB: Approved Document B(2); STS: Scottish Technical Standards(3)

† For retail premises the Scottish Technical Standards and BS 5588(4) suggest a floor space factor of 4 m^2/person where the actual maximum occupancy is unknown

(2b) UK [British Standards Institution 1997a]

Table 2 — Suggested floor space factors[a]

Description of room or storey	Floor space per person, excluding stair enclosures, lifts and sanitary accommodation m^2
Retail premises where the occupancy is not known or the floor space factor cannot be ascertained by reference to similar premises	4.0

(3) USA [International Code Council 2003]

TABLE 1004.1.2
MAXIMUM FLOOR AREA ALLOWANCES PER OCCUPANT

OCCUPANCY	FLOOR AREA IN SQ. FT. PER OCCUPANT
Airport terminal	
Baggage claim	20 gross
Baggage handling	300 gross
Concourse	100 gross
Waiting areas	15 gross
Mercantile	
Areas on other floors	60 gross
Basement and grade floor areas	30 gross
Storage, stock, shipping areas	300 gross

For SI: 1 square foot = 0.0929 m^2.

Table 6.2: Areas utilized for determining the floor space factor in the departure level and arrival level

	Location	**Total Areas (m^2)**	**Number of portions**	**Areas utilized for determining the floor space factor (m^2)**	**Name of the area**
Departure Level	In front of the retail areas	2940	3	980	D_{1a}
	Check-in counter J of the departure hall	3180	2	1590	D_{2a}
	Check-in counter D of the departure hall	1500	3.5	430	D_{3a}
	Retail areas (27 shops)	660	1	660	Retail shop areas
Arrival Level	Waiting area B of the arrival hall	5900	3.5	1700	A_{1a}
	Waiting area B of the arrival hall	5900	4	1480	A_{2a}
	Waiting area A of the arrival hall	4600	4	1150	A_{3a}
	Retail areas (14 shops)	230	1	230	Retail shop areas

Table 7.1: The conditions of different scenarios and sub-scenarios of the arrival level

Scenario	Selected area	Sub-scenario	Condition	Location of fire	Evacuation model	Remarks
1	Retail shops of number 1 to 14	1a	Normal	-	buildingEXODUS	-
		1b	Normal	-	SIMULEX	-
2	Areas in front of the above retail areas	2a	Fire	Inside the shop number 9.	buildingEXODUS	Staircase 3 will not be used in evacuation.
		2b	Normal	-	buildingEXODUS	-
		2c	Normal	-	SIMULEX	-
		2d	Normal	-	SIMULEX	Only direct exits are utilized in evacuation.
3	Entrance areas near exit 3	3a	Fire	Near the exit 3 in the entrance areas.	buildingEXODUS	Exit 3 will not be used in evacuation.
		3b	Normal	-	buildingEXODUS	-
		3c	Normal	-	SIMULEX	-
		3d	Normal	-	SIMULEX	Only direct exits are utilized in evacuation.
4	Areas near staircases 8 and 9	4a	Fire	Near the staircase 8.	buildingEXODUS	Staircase 8 will not be used in evacuation.
		4b	Normal	-	buildingEXODUS	-
		4c	Normal	-	SIMULEX	-
		4d	Normal	-	SIMULEX	Only direct exits are utilized in evacuation.

`

Table 7.2: The hazard parameters of different zones

			Upper Level			*Lower Level*		
Zone	**H**		**H_o**	**m**	**p**	**H_o**	**m**	**P**
Fire Zone	T (^oC)		25	0.2	2	25	0.2	2
	HCN (ppm)		5	1	1	5	1	1
	CO (ppm)		1000	200	1	1000	200	1
	CO_2 (%)		2	0.133	1	2	0.133	1
	O_2 Depletion (%)		19	-0.133	1	19	-0.133	1
	Visibility (m^{-1})		0.2	0.001	2	0.2	0.001	2
	R_f (kWm^{-2})	2a	0	0.05	1	0	0.05	1
		3a	0	0.033	1	0	0.033	1
		4a	0	0.033	1	0	0.033	1
Zone A	T (^oC)		25	2	1	25	0.03	1
	HCN (ppm)		1	0.5	1	0	0	1
	CO (ppm)		500	200	1	0	0	1
	CO_2 (%)		0.5	0.03	1	0	0	1
	O_2 Depletion (%)		20.5	-0.03	1	21	0	1
	Visibility (m^{-1})		0.1	0.001	2	0.05	0.001	2
	R_f (kWm^{-2})	2a	0	0.033	1	0	0	1
		3a	0	0.017	1	0	0	1
		4a	0	0.017	1	0	0	1
Zone B	T (^oC)		25	2	1	25	0.03	1
	HCN (ppm)		1	0.5	1	0	0	1
	CO (ppm)		500	200	1	0	0	1
	CO_2 (%)		0.5	0.03	1	0	0	1
	O_2 Depletion (%)		20.5	-0.03	1	21	0	1
	Visibility (m^{-1})		0.1	0.001	2	0.05	0.001	2
	R_f (kWm^{-2})	2a	0	0.033	1	0	0	1
Zone C	T (^oC)		25	0.7	1	25	0.0001	1
	HCN (ppm)		0.1	0.005	1	0	0	1
	CO (ppm)		250	50	1	0	0	1
	CO_2 (%)		0.3	0.01	1	0	0	1
	O_2 Depletion (%)		20.7	-0.01	1	21	0	1
	Visibility (m^{-1})		0.08	0.0005	2	0	0	1
	R_f (kWm^{-2})	2a	0	0.017	1	0	0	1

Table 7.3: Summary of results

		Input data			Results											
Scenario	Sub-scenario	Floor space factor ($m^2 person^{-1}$)	Floor area (m^2)	Maximum occupant loading	Computing time (s)	Number of people escaped	Number of exits utilized		Longest cumulative waiting time (s)	Longest moving time (s)	Time of the last occupant to evacuate in SIMULEX (s)	Total evacuation time (s)	Average evacuation time (s)	t_{peak} (s)	N_{max}	Δt (s)
							Staircases	Direct exits								
1	1a	3	231	79	180	79	4	0	7	22	-	50	32	30	29	29
	1b	3	231	79	30	75	5	0	-	-	100	Infinity	-	50	17	38
2	2a	0.5 and 3	881	1379	600	1379	10	0	343	49	-	363	130	100	374	148
	2b	0.5 and 3	881	1379	600	1379	11	0	264	43	-	288	114	100	360	193
	2c	0.5 and 3	881	1379	7200	29	9	0	-	-	100	Infinity	-	50	25	55
	2d	0.5 and 3	881	1379	59	1379	0	11	-	-	-	175	-	50	1172	53
3	3a	0.5	540	1080	300	1080	6	2	132	46	-	171	59	40	156	66
	3b	0.5	540	1080	300	1080	6	2	3	20	-	45	24	30	380	29
	3c	0.5	540	1080	2700	1002	4	2	-	-	180	Infinity	-	40	104	91
	3d	0.5	540	1080	56	1080	0	7	-	-	-	100	-	40	223	44
4	4a	0.5	322	644	900	644	3	1	531	51	-	548	250	100	98	520
	4b	0.5	322	644	900	644	4	0	265	55	-	284	134	100	150	246
	4c	0.5	322	644	2700	22	6	0	-	-	50	Infinity	-	50	22	25
	4d	0.5	322	644	4	644	0	6	-	-	-	45	-	50	644	25

Table 7.4: Utilization of staircases and direct exits in those scenarios

Scenario	Exit/ staircase	Width of the corridor connected to exit/ staircase (m)	Width of the exits (m)	Number of people passed through the door				Evacuation time of the first occupant (s)				Evacuation time of the last occupant (s)			
				Sub-scenario				Sub-scenario				Sub-scenario			
1				*1a*		*1b*		*1a*		*1b*		*1a*		*1b*	
	Staircase 1	2.5	2	14		0		21		0		48		0	
	Staircase 2	2.5	2	6		24		17		20		43		80	
	Staircase 3	-	2	30		33		13		20		50		100	
	Staircase 4	-	2	29		4		13		25		48		45	
	Staircase 5	2.5	2	0		14		0		30		0		55	
	Overall			**79**		**75**		**13**		**20**		**50**		**100**	
2				*2a*	*2b*	*2c*	*2d*	*2a*	*2b*	*2c*	*2d*	*2a*	*2b*	*2c*	*2d*
	Staircase 1	2.5	2	237	235	3	2	15	15	30	25	244	240	45	40
	Staircase 2	2.5	2	275	162	0	149	14	14	0	5	363	205	0	70
	Staircase 3*	-	2	0	280	1	150	0	8	15	5	0	287	15	65
	Staircase 4	-	2	350	295	7	76	8	8	20	10	345	288	75	65
	Staircase 5	2.5	2	5	5	4	53	22	22	30	15	42	42	40	45
	Staircase 6	-	1.5	143	144	1	114	16	16	25	5	154	154	25	45
	Staircase 7	-	1.5	88	64	6	166	18	18	15	5	101	79	100	45
	Staircase 8	-	1.5	126	48	3	134	15	15	15	5	138	63	20	45
	Staircase 9	-	1.5	90	79	0	173	17	17	0	5	104	96	0	55
	Staircase 10	-	1.5	54	57	2	199	18	18	20	5	71	71	20	175
	Staircase 11	-	1.5	11	10	2	163	18	18	15	5	45	45	20	75
	Overall			**1379**	**1379**	**29**	**1379**	**8**	**8**	**15**	**5**	**363**	**288**	**100**	**175**
3				*3a*	*3b*	*3c*	*3d*	*3a*	*3b*	*3c*	*3d*	*3a*	*3b*	*3c*	*3d*
	Staircase 6	-	1.5	22	5	11	104	20	22	30	20	50	44	145	65
	Staircase 7	-	1.5	60	2	7	24	19	32	40	20	79	34	50	50
	Staircase 8	-	1.5	124	3	0	0	21	32	0	35	143	41	0	50
	Staircase 9	-	1.5	155	4	0	2	20	20	0	20	171	39	0	70
	Staircase 10	-	1.5	78	1	36	94	19	44	30	20	96	44	180	70
	Staircase 11	-	1.5	27	4	15	156	19	21	25	20	49	41	40	70
	Exit 1	-	6	0	0	0	0	0	0	0	0	0	0	0	0
	Exit 2	-	6	300	0	0	0	5	0	0	0	86	0	0	0
	Exit 3*	-	6	0	1043	1	699	0	3	35	5	0	45	35	100
	Exit 4	-	6	314	18	932	1	5	7	5	40	88	34	130	40
	Overall			**1080**	**1080**	**1002**	**1080**	**5**	**3**	**5**	**5**	**171**	**45**	**180**	**100**
4				*4a*	*4b*	*4c*	*4d*	*4a*	*4b*	*4c*	*4d*	*4a*	*4b*	*4c*	*4d*
	Staircase 3	-	2	82	81	0	0	16	16	0	0	96	96	0	0
	Staircase 4	-	2	6	6	0	0	18	18	0	0	42	42	0	0
	Staircase 5	2.5	2	0	0	0	0	0	0	0	0	0	0	0	0
	Staircase 6	-	1.5	0	0	8	120	0	0	15	5	0	0	50	45
	Staircase 7	-	1.5	0	0	3	110	0	0	15	5	0	0	30	40
	Staircase 8*	-	1.5	0	279	2	109	0	13	15	5	0	281	15	40
	Staircase 9	-	1.5	553	278	2	110	9	9	15	5	548	284	20	40
	Staircase 10	-	1.5	0	0	2	111	0	0	15	5	0	0	15	40
	Staircase 11	-	1.5	0	0	5	83	0	0	15	5	0	0	20	45
	Exit 1	-	6	0	0	0	0	0	0	0	0	0	0	0	0
	Exit 2	-	6	3	0	0	0	31	0	0	0	36	0	0	0
	Overall			**644**	**644**	**22**	**644**	**9**	**9**	**15**	**5**	**548**	**284**	**50**	**45**

* Staircase 3, exit 3 and staircase 8 were blocked and could not be used for evacuation in sub-scenarios 2a, 3a and 4a respectively

Table 8.1: The input data and results of each scenario

Scenarios	Sub-scenario	Input data			Results								
		Floor area (m^2)	Floor space factor ($m^2person^{-1}$)	Maximum occupant loading	Number of exits utilized		Computing time required (s)	Number of people escaped	Average evacuation time (s)	Evacuation time (s)	TET (s)	Longest CWT (s)	Longest MT (s)
					Staircases	Direct exits							
1	1a	672	3	224	6	0	300	224	45	98	98	72	38
	1b	672	3	224	7	0	60	203	-	720	Infinity	-	-
2	2a	1422	0.5 and 3	1724	6	0	1200	1724	230	666	666	640	85
	2b	1422	0.5 and 3	1724	7	0	1200	1724	202	524	524	504	49
	2c	1422	0.5 and 3	1724	7	0	2700	120	-	800	Infinity	-	-
	2d	1422	0.5 and 3	1724	0	8	3000	1118	-	960	Infinity	-	-
3	3a	817	0.5	1634	2	0	600	1634	123	255	255	237	109
	3b	817	0.5	1634	2	2	600	1634	63	138	138	113	52
	3c	817	0.5	1634	4	2	1800	660	-	100	Infinity	-	-
	3d	817	0.5	1634	0	6	1800	1234	-	755	Infinity	-	-
4	4a	912	0.5	1823	1	0	1200	1823	249	490	490	468	72
	4b	912	0.5	1823	2	0	1200	1823	123	281	281	261	68
	4c	912	0.5	1823	1	0	1800	3	-	50	Infinity	-	-
	4d	912	0.5	1823	0	3	1800	370	-	110	Infinity	-	-

Table 8.2: The hazard parameters of different zones

			Upper Level			*Lower Level*		
Zone	**H**		**H_o**	**m**	**p**	**H_o**	**m**	**P**
Fire Zone	T (^oC)		25	0.2	2	25	0.2	2
	HCN (ppm)		5	1	1	5	1	1
	CO (ppm)		1000	200	1	1000	200	1
	CO_2 (%)		2	0.133	1	2	0.133	1
	O_2 Depletion (%)		19	-0.133	1	19	-0.133	1
	Visibility (m^{-1})		0.2	0.001	2	0.2	0.001	2
	R_f (kWm^{-2})	2a	0	0.05	1	0	0.05	1
		3a	0	0.033	1	0	0.033	1
		4a	0	0.033	1	0	0.033	1
Zone A	T (^oC)		25	2	1	25	0.03	1
	HCN (ppm)		1	0.5	1	0	0	1
	CO (ppm)		500	200	1	0	0	1
	CO_2 (%)		0.5	0.03	1	0	0	1
	O_2 Depletion (%)		20.5	-0.03	1	21	0	1
	Visibility (m^{-1})		0.1	0.001	2	0.05	0.001	2
	R_f (kWm^{-2})	2a	0	0.033	1	0	0	1
		3a	0	0.017	1	0	0	1
		4a	0	0.017	1	0	0	1
Zone B	T (^oC)		25	2	1	25	0.03	1
	HCN (ppm)		1	0.5	1	0	0	1
	CO (ppm)		500	200	1	0	0	1
	CO_2 (%)		0.5	0.03	1	0	0	1
	O_2 Depletion (%)		20.5	-0.03	1	21	0	1
	Visibility (m^{-1})		0.1	0.001	2	0.05	0.001	2
	R_f (kWm^{-2})	2a	0	0.033	1	0	0	1
		3a	0	0.008	1	0	0	1
Zone C	T (^oC)		25	0.7	1	25	0.0001	1
	HCN (ppm)		0.1	0.005	1	0	0	1
	CO (ppm)		250	50	1	0	0	1
	CO_2 (%)		0.3	0.01	1	0	0	1
	O_2 Depletion (%)		20.7	-0.01	1	21	0	1
	Visibility (m^{-1})		0.08	0.0005	2	0	0	1
	R_f (kWm^{-2})	2a	0	0.017	1	0	0	1

Table 8.3: The summary of results in scenario 1

Staircase	Width of the corridor connected to staircase (m)	Width of the staircase (m)	Number of people passed through the door		Evacuation time of the first occupant (s)		Evacuation time of the last occupant (s)	
			Sub-scenario		*Sub-scenario*		*Sub-scenario*	
			1a	*1b*	*1a*	*1b*	*1a*	*1b*
1	2.5	2	1	Nobody used	30	-	30	-
2	6.2	2	58	57	9	25	54	720
3	2.9	2	35	14	6	25	49	50
4	14.4	2	Nobody used	20	-	30	-	65
5	14.4	2	77	56	4	30	92	135
6	-	2	Nobody used	22	-	30	-	65
7	3.8	2	49	31	16	35	98	95
8	2.5	2	4	3	37	45	55	55
			Total: 224	**Total: 203**	**Minimum: 4**	**Minimum: 25**	**Maximum: 98**	**Maximum: 720**

Table 8.4: The summary of results in scenario 2

Staircase	Width of the corridor connected to staircase (m)	Width of the staircase (m)	Number of people passed through the door				Evacuation time of the first occupant (s)				Evacuation time of the last occupant (s)			
			Sub-scenario				*Sub-scenario*				*Sub-scenario*			
			2a	*2b*	*2c*	*2d*	*2a*	*2b*	*2c*	*2d*	*2a*	*2b*	*2c*	*2d*
1	2.5	2	36	36	15	285	25	23	30	10	60	62	55	110
2	6.2	2	293	293	5	136	11	11	30	10	209	292	40	960
3	2.9	2	421	422	2	191	7	7	30	15	375	369	35	75
4	14.4	2	Nobody used	Nobody used	11	214	-	-	35	10	-	-	50	80
5	14.4	2	679	335	4	7	13	13	40	20	666	346	85	40
6	-	2	8	8	Nobody used	81	11	11	-	10	36	36	-	115
7*	3.8	2	Nobody used	600	64	28	-	10	35	15	-	524	800	55
8	2.5	2	287	30	19	176	25	25	25	15	320	67	60	90
			Total: 1724	**Total: 1724**	**Total: 120**	**Total: 1118**	**Minimum: 7**	**Minimum: 7**	**Minimum: 25**	**Minimum: 10**	**Maximum: 666**	**Maximum: 524**	**Maximum: 800**	**Maximum: 960**

* Staircase 7 was blocked and could not be used for evacuation in sub-scenario 2a

Table 8.5: The summary of results in scenario 3

Exit/ *Staircase*	Width of the corridor connected to exit/ staircase (m)	Width of the exit/ staircase (m)	Number of people passed through the door				Evacuation time of the first occupant (s)				Evacuation time of the last occupant (s)			
			Sub-scenario				*Sub-scenario*				*Sub-scenario*			
			3a	*3b*	*3c*	*3d*	*3a*	*3b*	*3c*	*3d*	*3a*	*3b*	*3c*	*3d*
3*	4.5	3	Nobody used	425	312	234	-	6	5	10	-	113	75	65
4*	4.5	3	Nobody used	407	315	301	-	5	10	15	-	113	100	95
17	-	2	Nobody used	Nobody used	9	172	-	-	25	20	-	-	40	70
18	-	2	855	443	14	286	9	9	25	5	255	138	65	755
19	-	2	779	359	4	129	10	10	25	10	223	110	40	175
20	-	2	Nobody used	Nobody used	6	112	-	-	25	10	-	0	45	60
			Total: 1634	**Total: 1634**	**Total: 660**	**Total: 1234**	**Minimum: 9**	**Minimum: 5**	**Minimum: 5**	**Minimum: 5**	**Maximum: 255**	**Maximum: 138**	**Maximum: 100**	**Maximum: 755**

* Exits 3 and 4 were blocked and could not be used for evacuation in sub-scenario 3a

Table 8.6: The summary of results in scenario 4

Staircase	Width of the corridor connected to staircase (m)	Width of the staircase (m)	Number of people passed through the door				Evacuation time of the first occupant (s)				Evacuation time of the last occupant (s)			
			Sub-scenario				*Sub-scenario*				*Sub-scenario*			
			3a	*3b*	*3c*	*3d*	*3a*	*3b*	*3c*	*3d*	*3a*	*3b*	*3c*	*3d*
8	2.5	2	Nobody used	Nobody used	Nobody used	190	-	-	-	35	-	-	-	110
14	-	2	1823	1013	3	56	8	9	30	5	490	281	50	30
15*	-	2	Nobody used	810	Nobody used	124	-	8	-	5	-	184	-	95
			Total: 1823	**Total: 1823**	**Total: 3**	**Total: 370**	**Minimum: 8**	**Minimum: 8**	**Minimum: 30**	**Minimum: 5**	**Maximum: 490**	**Maximum: 281**	**Maximum: 50**	**Maximum: 110**

* Staircase 15 was blocked and could not be used for evacuation in sub-scenario 4a

Table 8.7: Summary of results on WTI for the additional scenarios

Scenario	Sub-scenario	Maximum occupant loading	Number of the additional scenarios	Additional scenarios	
				Number of occupants	*WTI*
1	1a	224	2	100	0.35
				224	0.73
2	2a	1724	9	200	0.27
				400	0.48
				600	0.62
				800	0.7
				1000	0.77
				1200	0.82
				1400	0.87
				1600	0.92
				1724	0.96
	2b	1724	9	200	0.25
				400	0.45
				600	0.6
				800	0.68
				1000	0.75
				1200	0.81
				1400	0.87
				1600	0.91
				1724	0.96
3	3a	1634	8	200	0.13
				400	0.24
				600	0.33
				800	0.42
				1000	0.5
				1200	0.59
				1400	0.71
				1634	0.93
	3b	1634	8	200	0.05
				400	0.13
				600	0.21
				800	0.3
				1000	0.4
				1200	0.49
				1400	0.61
				1634	0.82

Scenario	Sub-scenario	Maximum occupant loading	Number of the additional scenarios	Additional scenarios	
				Number of occupants	***WTI***
4	4a	1823	9	200	0.46
				400	0.61
				600	0.7
				800	0.76
				1000	0.81
				1200	0.84
				1400	0.87
				1600	0.9
				1823	0.96
	4b	1823	9	200	0.23
				400	0.36
				600	0.46
				800	0.55
				1000	0.63
				1200	0.71
				1400	0.77
				1600	0.83
				1823	0.93

Table 9.1: Test conditions of the fire scenarios for assessing boutiques and CD shops

(a) Fire scenarios for assessing boutiques

Test	Location	Type of clothes	Number of clothes	Covered by	Ignited by	Type of fire	Condition of fire	Extinguished by
B1	Inside the room	Short sleeves T-shirts	24	Transparent plastic bag	Igniter	Ventilation controlled fire	Pre-flashover fire	Nil
B2	Inside the room	Short sleeves T-shirts	24	Transparent plastic bag	A 4000 ml gasoline pool fire	Ventilation controlled fire	Post-flashover fire	Nil
B3	Inside the room	Short sleeves T-shirts	24	Transparent plastic bag	A 4000 ml gasoline pool fire	Ventilation controlled fire	Post-flashover fire	Water mist fire suppression system (WMFSS)
B4	Inside the room	Short sleeves T-shirts	24	Transparent plastic bag	Igniter	Ventilation controlled fire	Pre-flashover fire	Sprinkler system
B5	Under the hood	Short sleeves T-shirts	8	Transparent plastic bag	Igniter	Fuel controlled fire	Pre-flashover fire	Nil
B6	Inside the room	Short sleeves T-shirts	24	Nil	A 4000 ml gasoline pool fire	Ventilation controlled fire	Post-flashover fire	Nil

(b) Fire scenarios for assessing CD shops

Test	Location	Number of CD display	Total number of CD	Ignited by	Type of fire	Condition of fire	Extinguished by
C1	Inside the room	2	480	A 4000 ml gasoline pool fire	Ventilation controlled fire	Post-flashover fire	WMFSS (Activated and turned off periodically)
C2	Inside the room	2	480	A 4000 ml gasoline pool fire	Ventilation controlled fire	Post-flashover fire	WMFSS (Discharged continually)
C3	Inside the room	2	480	A 4000 ml gasoline pool fire	Ventilation controlled fire	Post-flashover fire	Sprinkler system

Table 11.1: Comparison of deluge systems in UK, USA, Australia and Hong Kong

Definitions	**UK**	It is defined as an open sprinkler system controlled by a quick-opening valve and activated by means of heat detectors or sprinklers installed in the same region as the open sprinklers [British Standards Institution 1988; Home Office Fire Department 1990].
	USA	It is a system that the sprinklers are open all the time and the deluge valve is activated by the fire-detecting device [Bryan 1997].
	Australia	It is defined as a system of dry pipes fitted with open sprinklers [Australian Standard 1995a].
	Hong Kong	It is a system requiring a discharge of water over a considerable area in rapid response to a fire [Fire Services Department Hong Kong Special Administrative Region 1998].
Activation principles	**UK**	A separate detection system is provided for automatic operation [Chartered Institution of Building Services Engineers 1997].
	USA	Heat-detecting devices are commonly used to activate the system [National Fire Protection Association 1992, 1996].
	Australia	The system can be activated manually or automatically [Australian Standard 1997]. For manual operation, the system would be fitted with manual operated points at each deluge valve. For automatic operation, the system can be activated by means of heat, smoke or flame detecting devices installed in the same area as the open sprinklers.
	Hong Kong	Not mentioned.
Extinguishing mechanisms	**UK**	Extinguishing mechanism of the system is similar to the automatic sprinkler system but with bigger water discharge area and faster activation time [Home Office Fire Department 1990; Chartered Institution of Building Services Engineers 1997]. This system is used to control or extinguish the rapid fire spread by water or foam where the fire is unlikely to be controlled by the automatic sprinkler system.

	USA	The system is suitable to be utilized in areas with a high ceiling by discharging large spray angle and high density, when the automatic sprinkler system might not be effective [National Fire Protection Association 1996; Society of Fire Protection Engineers and National Fire Protection Association 1995].
	Australia	Extinguishing mechanism of using water in the system is similar to that in UK and USA [Australian Standard 1997].
	Hong Kong	Not mentioned.
Applications	**UK**	It can be used in the wine storage and large areas such as aircraft hangers, where high-hazard fire is likely to be occurred [British Standards Institution 1997].
	USA	It is suitable for various extra-hazard occupancies, exposure, aircraft hangers and assembly plants [National Fire Protection Association 1996].
	Australia	It is suitable for aircraft hangers, ammunition filling plants, chemical manufacturers or processors, paint, varnish manufacturers (solvent based), petrochemical processing plants, resin and turpentine manufacturers, explosive manufacturers, fireworks manufacturers, tar distilleries and nitrocellulose manufacturers or processors [Australian Standard 1997].
	Hong Kong	Not mentioned.

Table 11.2: Comparison of drencher systems in UK, USA, Australia and Hong Kong

Definitions	**UK**	It comprises drenchers, which can provide a continuous water layer to protect the building from damage [Home Office Fire Department 1990].
	USA	It is known as outside sprinkler system, which is used to provide a window curtain to protect the window openings [National Fire Protection Association 1992].
	Australia	It is defined as a system of water pipes fitted with drencher heads, which are heat-sensitive or open discharge devices [Australian Standard 1991].
	Hong Kong	It is a system that provides a water curtain for protection against internal and external exposure to fire, and/or large openings [Fire Services Department Hong Kong Special Administrative Region 1998].
Activation principles	**UK**	Drenchers are divided into 2 types: sealed or unsealed [Home Office Fire Department 1990]. For sealed type, the drencher is activated in the same way as the sprinkler head, except the shape of the deflector plate is different. For the unsealed type, the drenchers would be operated manually by opening the main valve.
	USA	The drencher system can be operated manually or automatically by means of sprinkler system [National Fire Protection Association 1992]. The drencher can provide a continuous fan-shaped or quarter-spherical water curtain, for providing the desired protection.

	Australia	The drencher systems are divided into 2 types: sealed wall wetting sprinkler systems and open wall wetting sprinkler systems [Australian Standard 1995b]. For the sealed system, the operation of the system is similar to the automatic sprinkler system except the shape of deflector plate is different from normal sprinkler head. In the open system, water supply would be controlled by a deluge valve. The system would be activated by means of fire detectors or sealed drenchers installed in the same areas as the open drenchers.
	Hong Kong	The drencher system can be operated automatically or manually [Fire Services Department Hong Kong Special Administrative Region 1998]. For the automatic system, it can be activated by the operation of the sprinkler system. For the manual system, the fire signal from the smoke detectors, flow switches and breakglass unit would be investigated by a responsible person to determine the reality of the fire. If there is a real fire, the drencher control valve would be switched on to activate the system.
Restrictions	**UK**	The minimum pressure of drenchers should be at least 34 bar [Home Office Fire Department 1990]. The controlling valve should be at reachable positions. Less than 72 drenchers would be controlled by a single valve.
	USA	Large volume of water is required to supply the water curtain [National Fire Protection Association 1982, 1992]. Drencher should be provided a discharge of 37 $Lmin^{-1}m^{-1}$ of water curtain or not less than 56.8 $Lmin^{-1}$ for each sprinkler. Water pressure should not be less than 48 kPa.

	Australia	The sealed drenchers should be operated within 10 or 30 mins when exposed to the heat flux of 10 or 30 kWm^{-2} respectively [Australian Standard 1995b]. The average density of discharge of the protected area should not be less than 5 $Lm^{-2}min^{-1}$. The nominal thread size of drenchers should be either 10 or 15 mm. The pressure on drenchers should not be less than 70 kPa for light hazard system, 35 kPa for ordinary hazard system and 50 kPa for high hazard system, while the pressure should not be more than 1 MPa for all systems. The rated pressures for piping, pumps, valves and fitting should not be less than 1.4 times the maximum working pressure of the system.
	Hong Kong	The water flow rate should not be less than 10 $Lmin^{-1}m^{-2}$ [Fire Services Department Hong Kong Special Administrative Region 1998]. The deluge valve should be installed close to the inlet of the drencher system. An independent water tank should be provided such that the drencher system is able to operate for at least 30 mins.
Discharge patterns	**UK**	The radiative heat fluxes would be controlled by using a curtain of free-falling water droplets to absorb and scatter the heat, so as to reduce the heat flux transmitted from the fire zone to the protected area [Home Office Fire Department 1990].
	USA	The discharged water curtain would reduce the heat fluxes received inside the protected area [Ravigururajan and Beltran 1989]. For the higher droplet concentration, the transmission of heat fluxes would be attenuated effectively due to the better continuity of the water curtain.
	Australia	The control mechanism is similar to that of UK and USA. The ability of the system in blocking radiant heat would be affected by the concentration of the water droplets inside the water curtain [Australian Standard 1995b].

	Hong Kong	The radiative heat transmitted to the protected zone would be reduced while passing through the water curtain. More heat would be blocked if the pressure and flow rate are increased, or smaller droplets being discharged [Fire Services Department Hong Kong Special Administrative Region 1998].
Applications	**UK**	The drenchers would be placed on roofs, windows or external openings to protect the building exposed to a fire in adjacent premises [Home Office Fire Department 1990].
	USA	It is installed to protect the window openings in brick wall or combustible cornices from radiant heat in adjacent premises [National Fire Protection Association 1992].
	Australia	It can be used to provide external protection to windows, doors and walls. For the sealed systems, they are suitable to use where there are more than one possible source of hazards; while for the open systems, they are suitable to use when there is a potential for sudden radiant heat such as in flammable liquid storage [Australian Standard 1995b].
	Hong Kong	The system can be installed on all refuge floors inside a building to cover all the external wall openings [Fire Services Department Hong Kong Special Administrative Region 1998].

Table 11.3: Transmitted radiant heat intensity for all retail shops inside non-restricted areas of airport terminal

Level	Shop number	Limiting distance D_l (m)	Conversion factor C	Aspect ratio A	Attenuation factor F	Total area of wall A_t (m^2)	Radiant heat intensity of fire source I_s (kWm^{-2})	Percentage of opening in wall P	**Transmitted radiant heat intensity I_i (kWm^{-2})**
5	1	2	0.93	0.87	0.27	40.6	1.87	81.5	**0.41**
	2	2	0.93	0.87	0.27	56.2	1.82	100	**0.49**
	3	3	1.14	0.77	0.20	75.8	1.59	100	**0.32**
	4	2	0.93	0.87	0.27	56.2	1.82	100	**0.49**
	5	6	1.62	0.38	0.1	96.8	1.65	100	**0.17**
	6	2	0.93	0.87	0.27	30.4	2.68	100	**0.72**
	7	3	1.14	0.77	0.2	70.5	1.66	100	**0.33**
	8	4	1.32	0.58	0.16	136.3	1.13	100	**0.18**
	9	2	0.93	0.87	0.27	41.3	1.65	62.5	**0.28**
	10	4	1.32	0.58	0.16	66.5	1.05	31.2	**0.05**
	11	6	1.62	0.38	0.1	118	1.24	83.3	**0.1**
7	12	1.5	0.81	0.65	0.32	56.6	1.82	100	**0.58**
	13	3.5	1.23	0.66	0.18	39.3	2.34	90	**0.38**
	14	2.5	1.04	0.92	0.23	26.1	2.98	100	**0.68**
	15	7	1.74	0.33	0.09	142.8	1.47	76	**0.1**
	16	7	1.74	0.33	0.09	158	1.46	83.3	**0.11**
	17	3	1.14	0.77	0.2	41	2.07	83.3	**0.35**
	18	6	1.62	0.38	0.1	64.7	2.16	100	**0.22**
	19	3.5	1.23	0.66	0.18	39.3	2.34	90	**0.38**
	20	4	1.32	0.58	0.16	73.3	2.20	100	**0.35**
	21	5	1.47	0.46	0.13	56.4	2.19	100	**0.29**
	22	3	1.14	0.77	0.2	41	2.07	83.3	**0.35**
	23	2	0.93	0.87	0.27	30.4	2.68	100	**0.72**
	24	28	3.49	0.1	0.02	483.2	0.54	17.9	**0**
	25	4	1.32	0.58	0.16	60.7	1.88	100	**0.3**
	26	2.5	1.04	0.92	0.23	56.8	2.74	100	**0.63**
	27	3.5	1.23	0.66	0.18	39.3	2.34	90	**0.38**
	28	6	1.62	0.38	0.1	59	2.49	100	**0.25**
	29	3	1.14	0.77	0.2	73.9	1.21	63.4	**0.15**
	30	4	1.32	0.58	0.16	127.2	0.91	62.5	**0.09**
	31	4	1.32	0.58	0.16	55	2.34	93.8	**0.35**
	32	4	1.32	0.58	0.16	82.5	1.74	62.5	**0.17**
	33	10	2.09	0.23	0.06	190.1	0.58	19	**0.01**
	34	6	1.62	0.38	0.1	179.8	1.13	100	**0.11**
	35	6	1.62	0.38	0.1	60.1	2.43	100	**0.24**
	36	2.5	1.04	0.92	0.23	26.1	2.98	100	**0.68**
	37	3.5	1.23	0.66	0.18	39.3	2.34	90	**0.38**
8	38	10	0.99	0.97	0.25	728.8	6.87	100	**1.72**
	39	10	0.99	0.97	0.25	449	7.26	100	**1.82**
	40	20	1.39	0.52	0.15	480.3	7	100	**1.05**
	41	40	1.97	0.26	0.07	1556.8	5.17	100	**0.36**

Table 11.4: Droplet velocity and diameter reaching mean flame height (HRR: 419 kW)

Initial Diameter (μm)		500	600	700	800	900	1000
Initial Velocity 10 ms^{-1}	Velocity (ms^{-1})	N/A	0.1	3.61	5.17	6.12	6.78
	Drop Size (μm)	N/A	341	532	664	782	894
Initial Velocity 15 ms^{-1}	Velocity (ms^{-1})	2.89	6.95	8.84	10.02	10.85	11.46
	Drop Size (μm)	317	474	596	709	818	925

Note: N/A means that the droplet cannot overcome the plume effect to reach mean flame height.

Table 11.5: Calculated Spray Heat Absorption Ratio (SHAR) for various opening heights and spray characteristics (50 s after water mist application)

SHAR		H_d: 2.1 m	H_d: 1 m	H_d: 0.5 m
M_w: 8 $Lmin^{-1}$ m^{-2}	D_m: 800 μm	0.179	0.321	0.466
	D_m: 400 μm	0.561	0.665	N/A
	D_m: 200 μm	0.561	0.762	N/A
M_w: 4 $Lmin^{-1}$ m^{-2}	D_m: 800 μm	0.099	0.191	0.290
	D_m: 400 μm	0.336	0.556	0.615
	D_m: 200 μm	0.336	0.724	0.704

Note: N/A means that all the heat release from fire is absorbed by water spray.

List of Figures

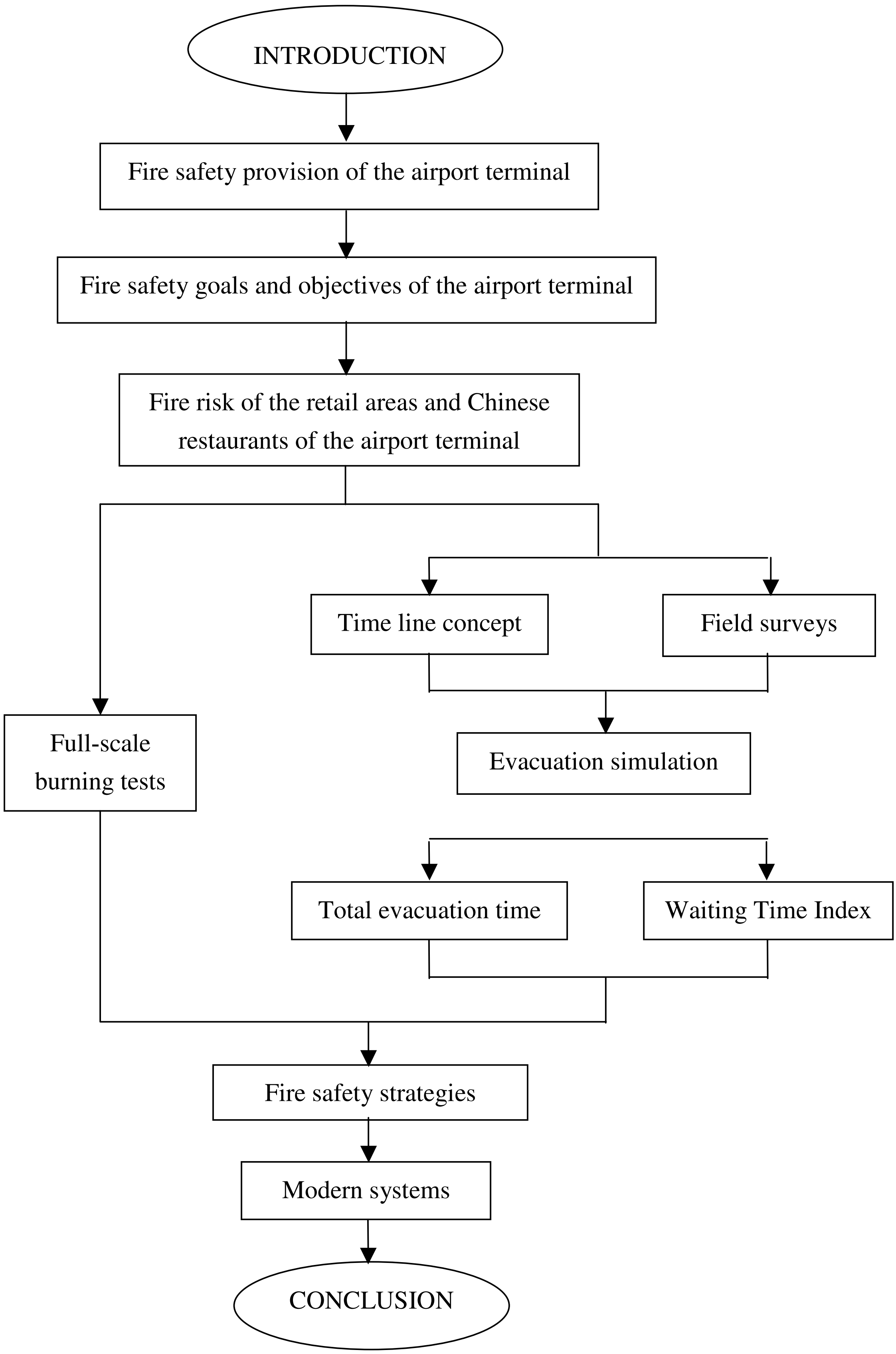


Figure 1.1: Flowchart of this study

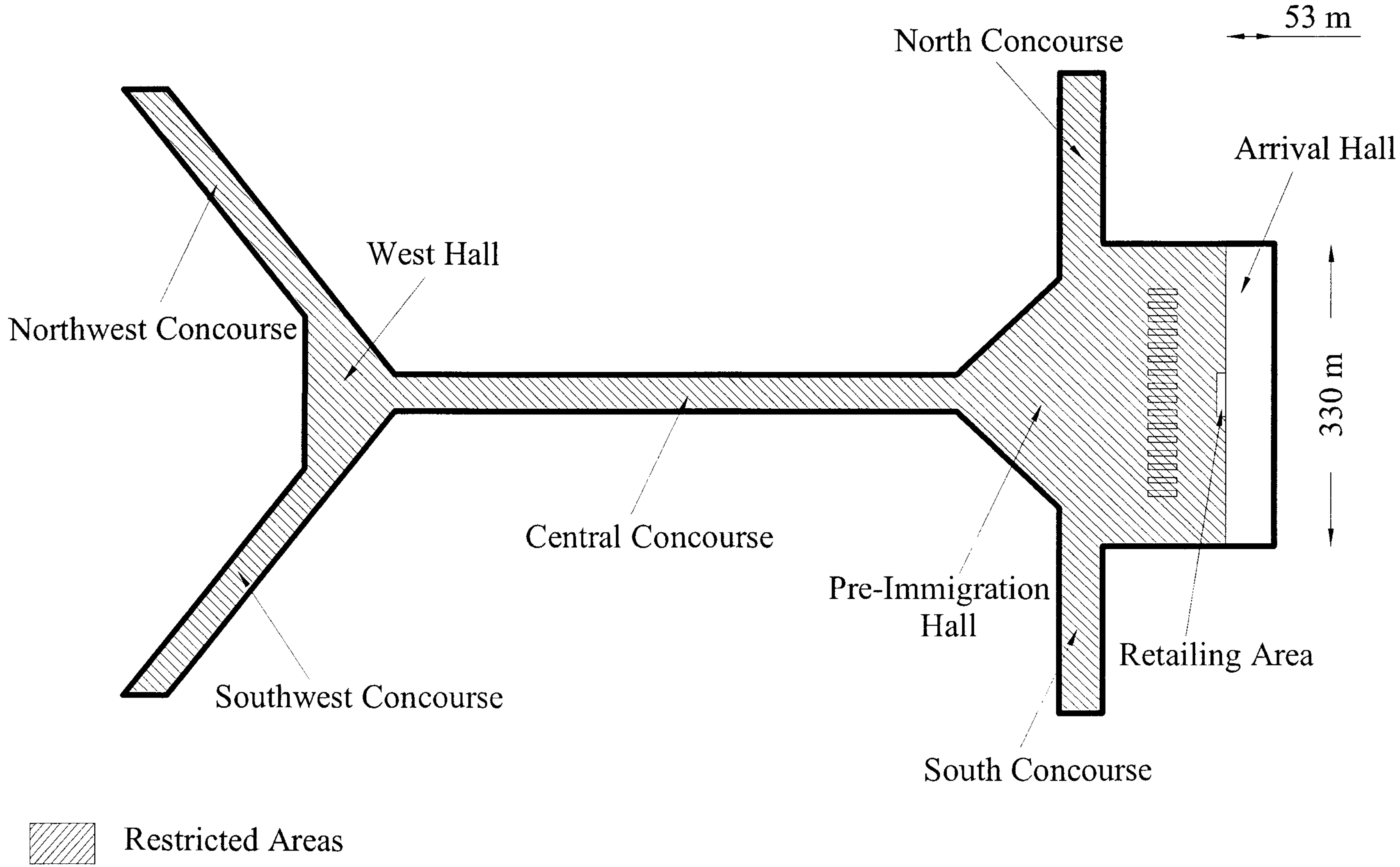


Figure 2.1: Layout of level 5 of airport terminal building

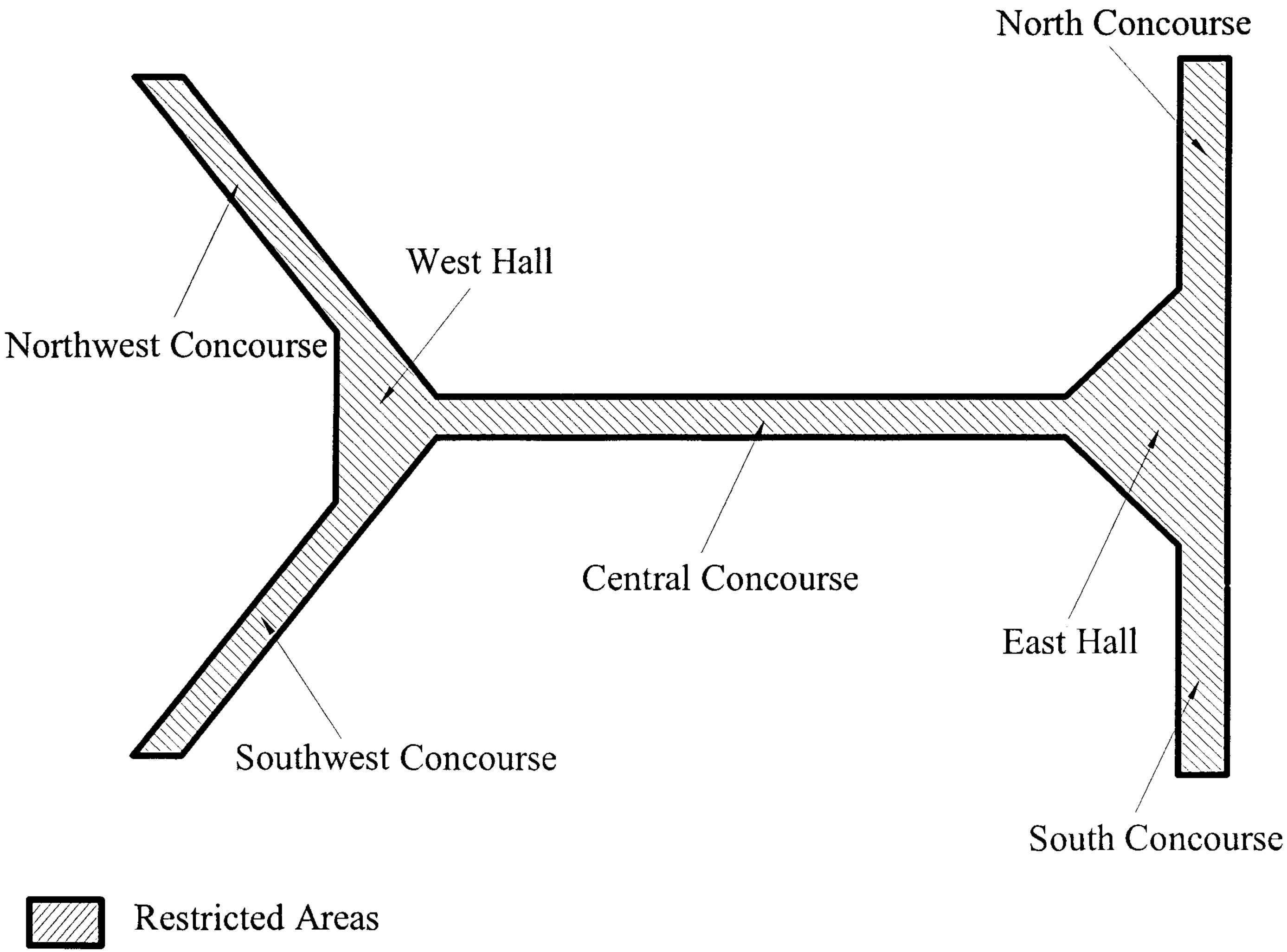


Figure 2.2: Layout of level 6 of airport terminal building

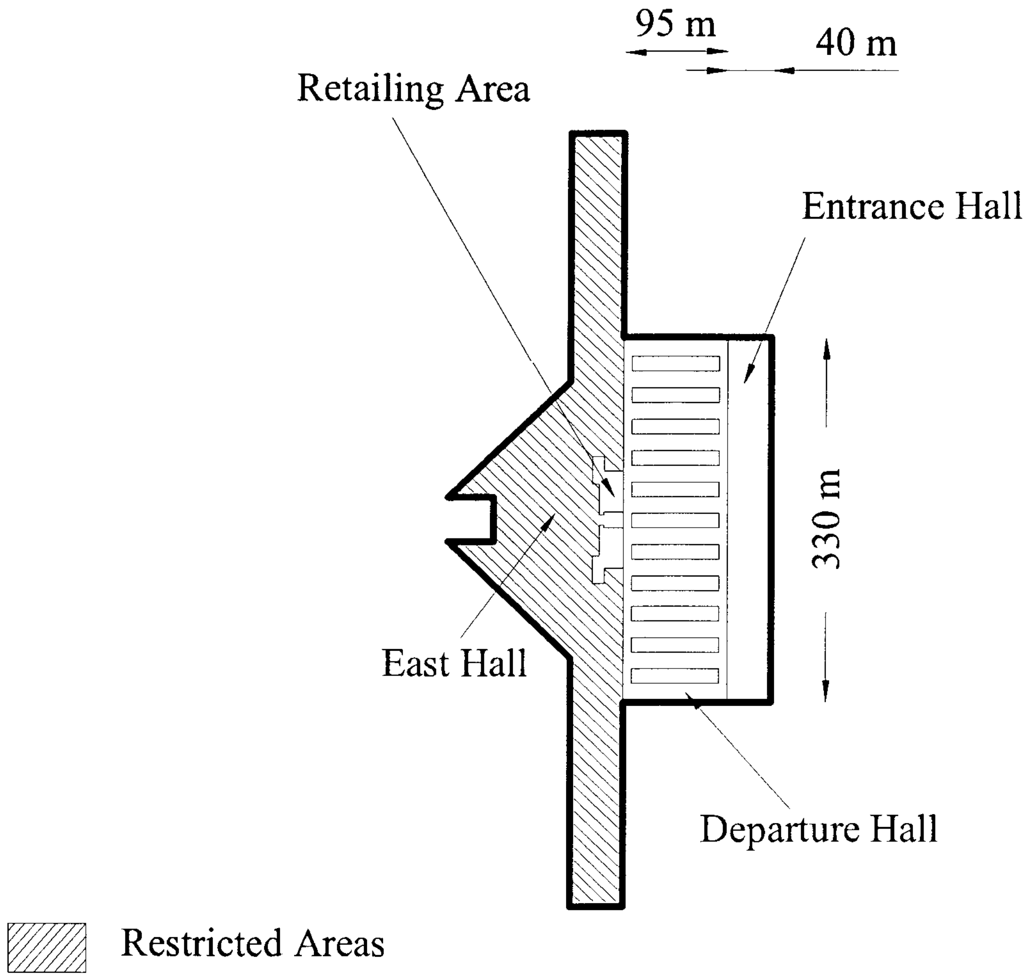


Figure 2.3: Layout of level 7 of airport terminal building

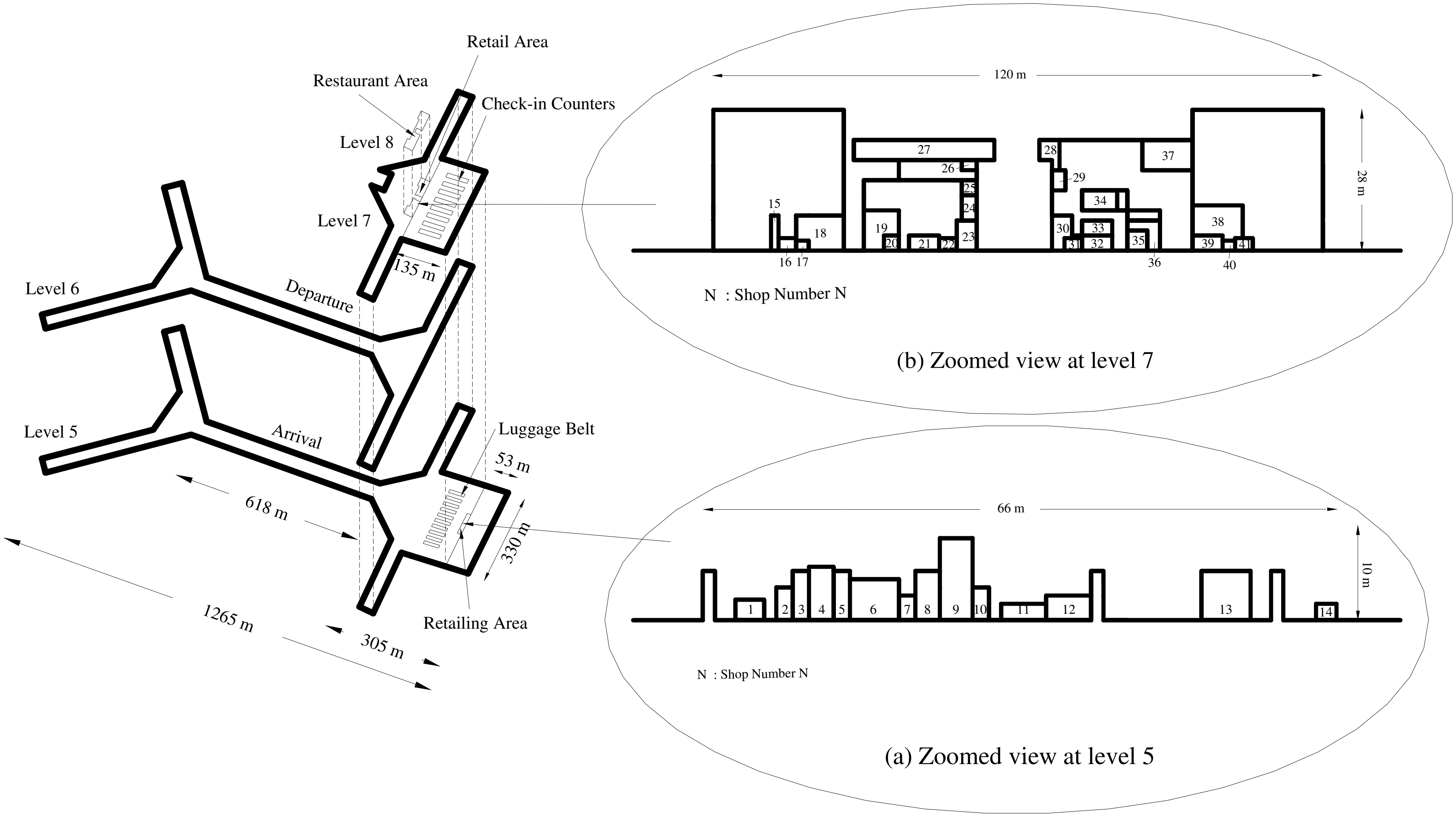


Figure 2.4: Layout of retail areas in the non-restricted areas of airport terminal

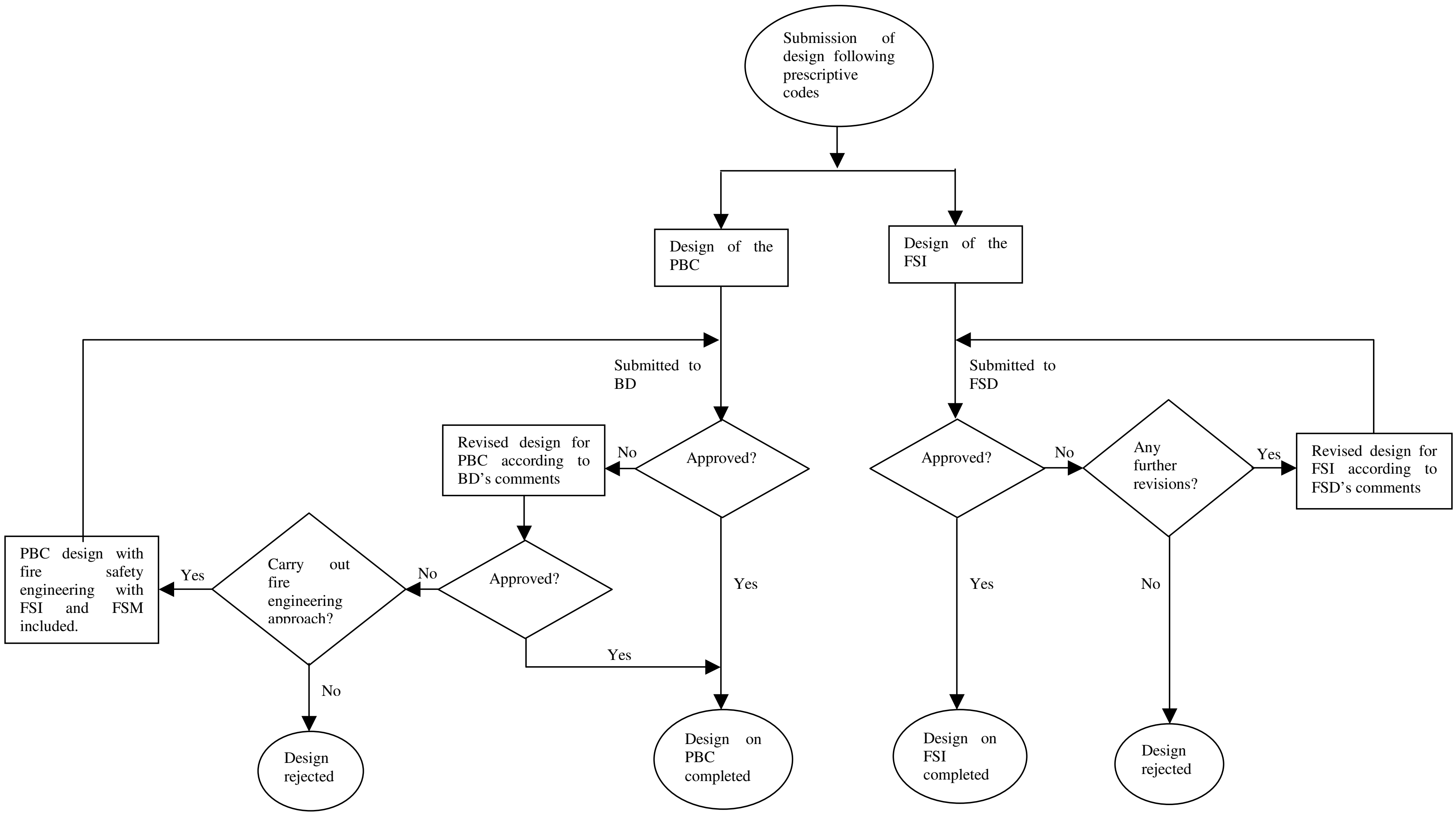


Figure 3.1: Application procedures of the fire safety design in Hong Kong [Chow 2002]

1. Defining the goals [Society of Fire Protection Engineers 2000]
    - Protection of life
    - Protection of property
    - Protection of mission (continuity of operations)
    - Protection of environment from the unwanted effects of fire and fire control.

↓

2. Defining the fire safety objectives [Society of Fire Protection Engineers 2000]
- Life safety of staff and occupants
- Life safety of fire fighters
- Property protection
- Minimum disturbance to the normal operation
- Environmental concerns

↓

3. Developing the performance criteria [Society of Fire Protection Engineers 2000]

↓

4. Developing the fire safety strategies (PBC, FSI, FSM, RF)
- Passive Building Construction (PBC) Strategy
- Fire Services Installation (FSI) Strategy
- Fire Safety Management (FSM) Strategy
- Strategy on controlling Risk Factors (RF)

Figure 3.2: Proposed performance-based design procedures for fire safety in Hong Kong

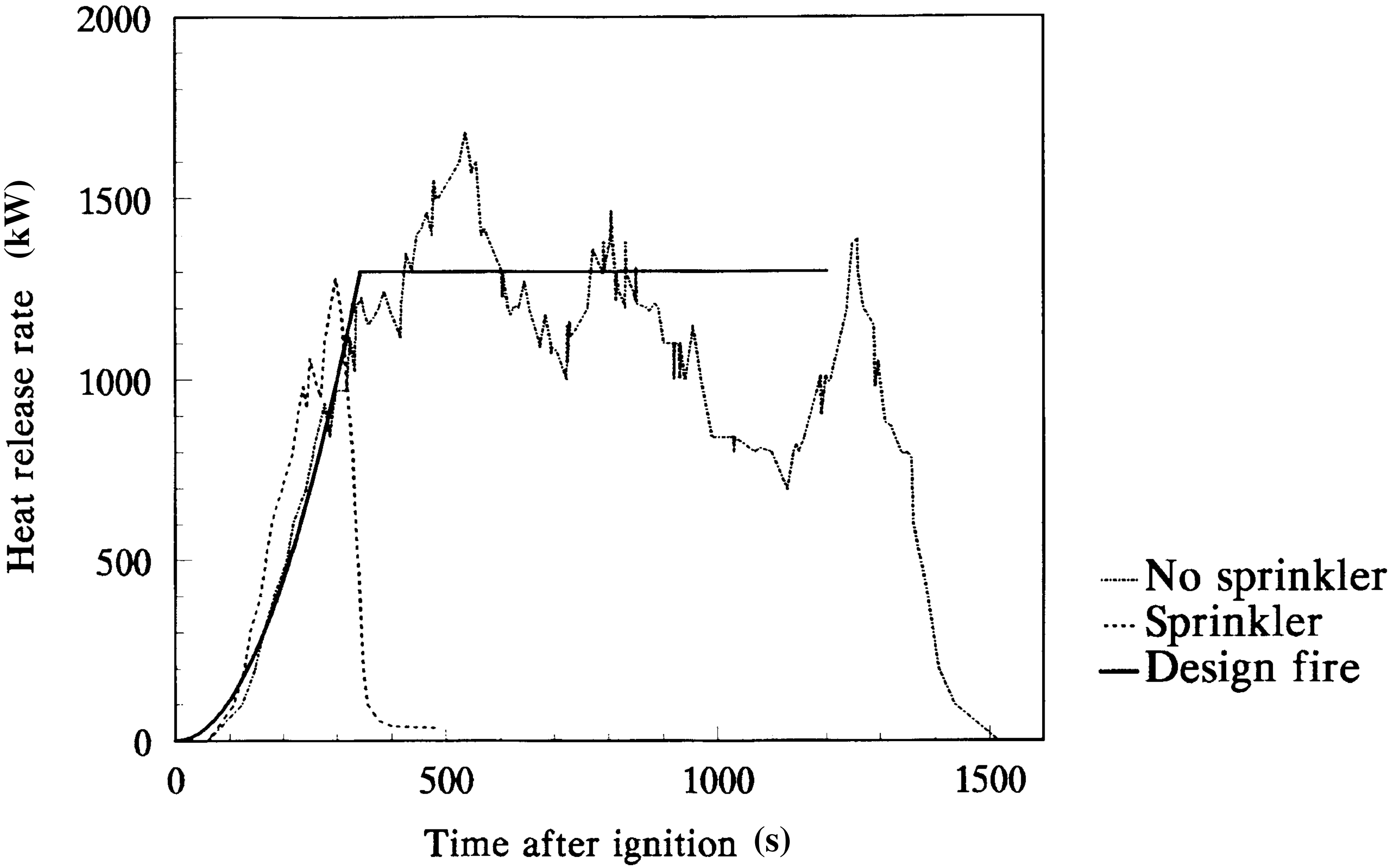


Figure 4.1: Design fire for retail shops

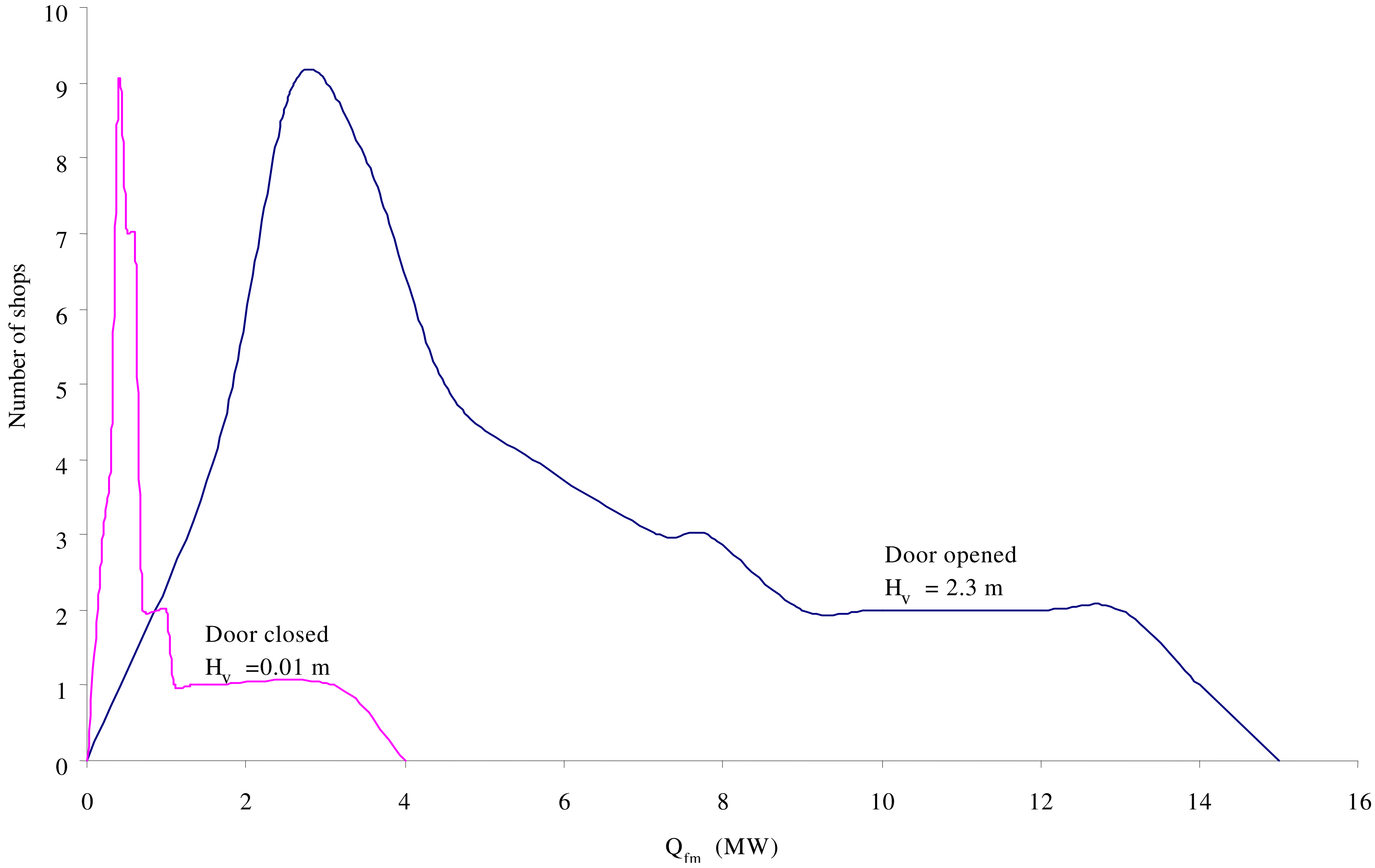
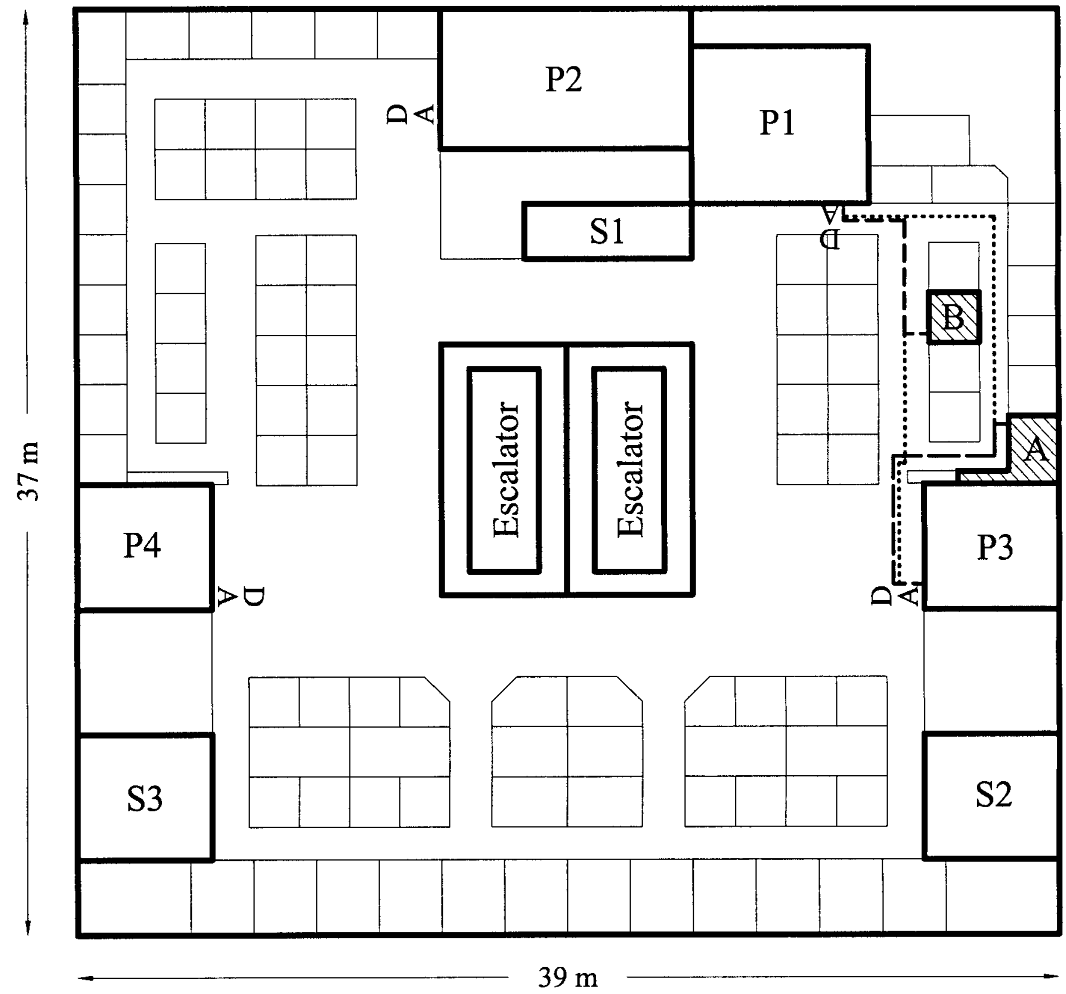


Figure 4.2: Minimum heat release rate for flashover in the forty one retail shops



Selected Shops

P1 - P4 Protected Staircases

S1 - S3 Accommodation Staircases

A Alarm

D Detector

Short Route

Long Route

Figure 4.3: Geometrical layout of the second floor in shopping mall

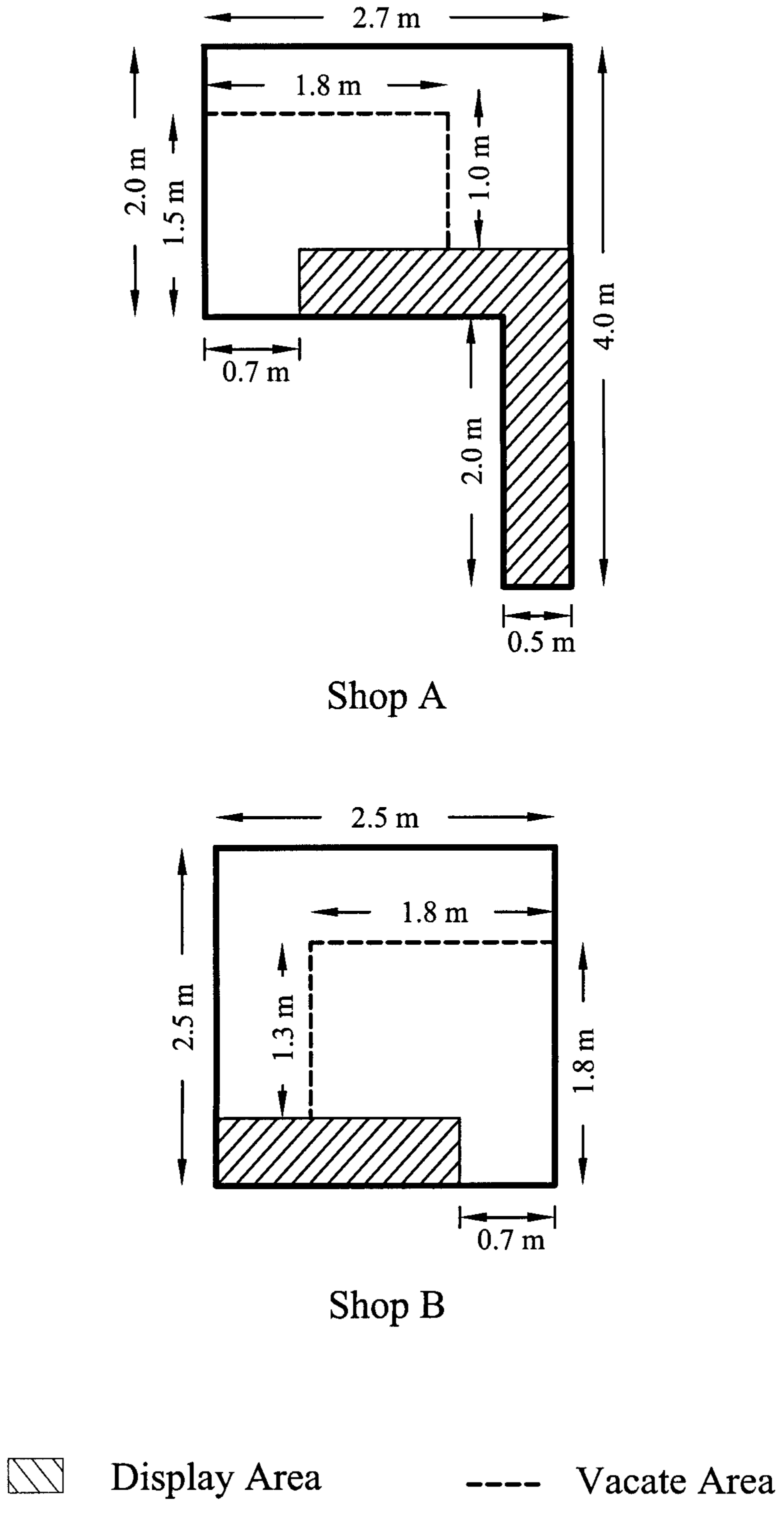


Figure 4.4: Geometrical layout of two selected shops

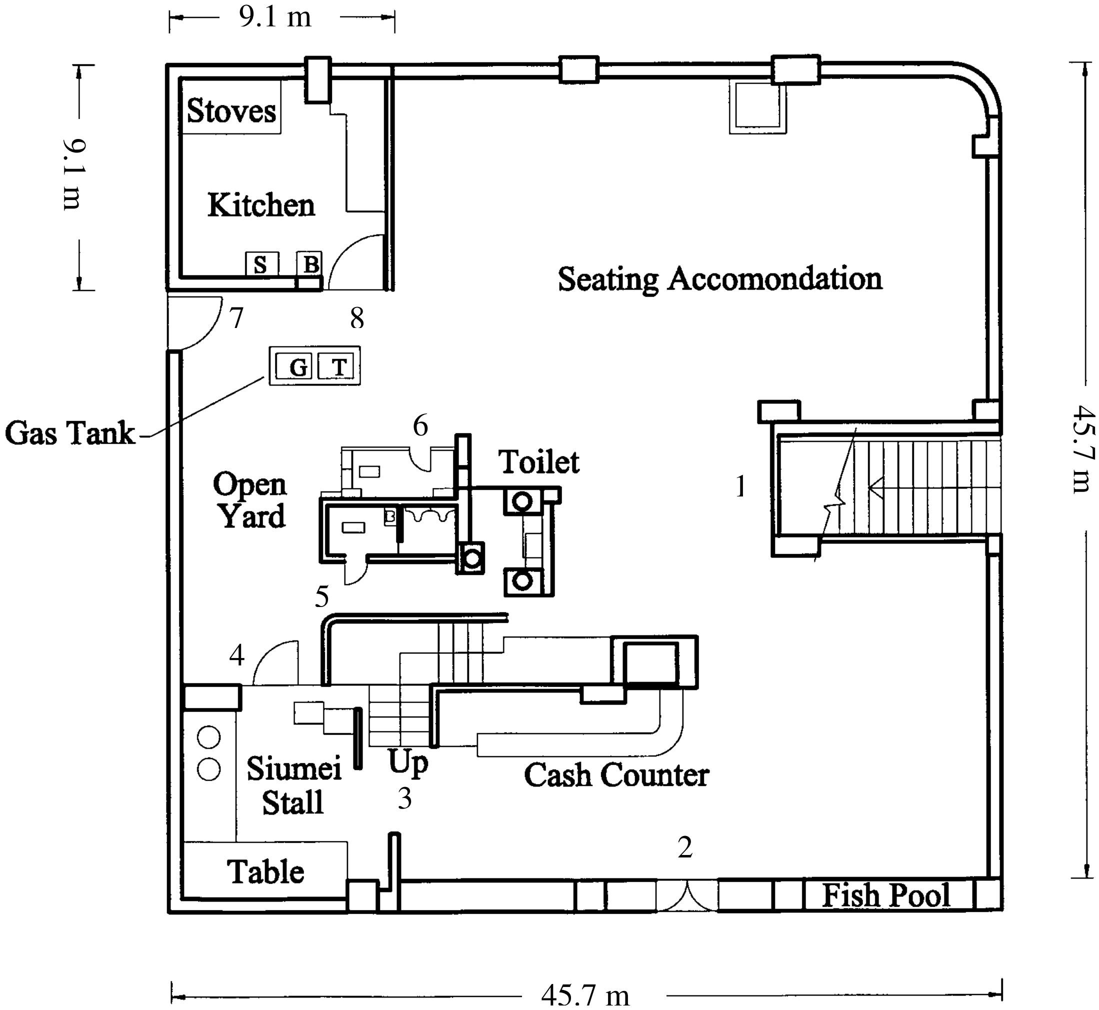


Figure 5.1: A typical Chinese restaurant

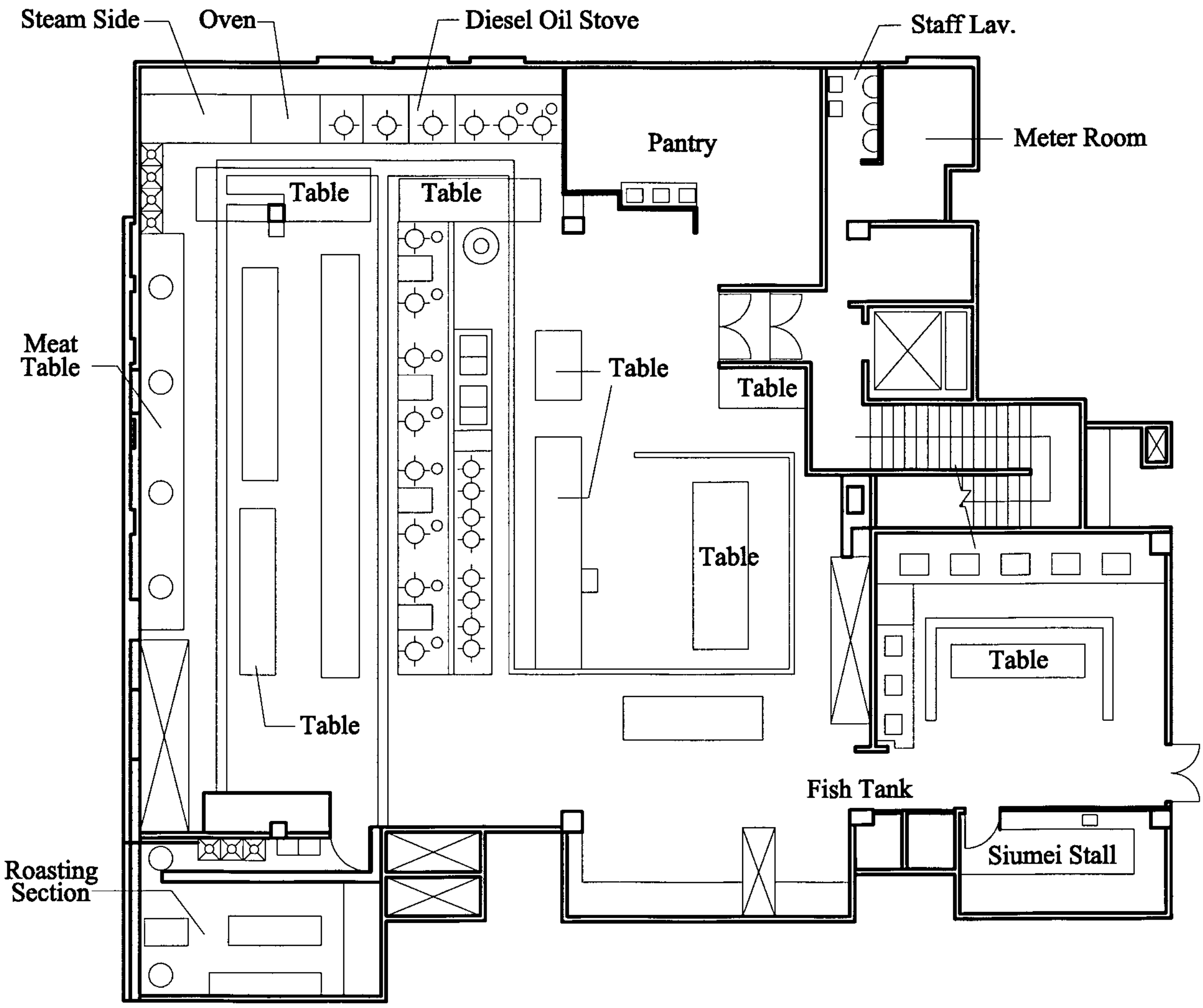


Figure 5.2: A typical kitchen

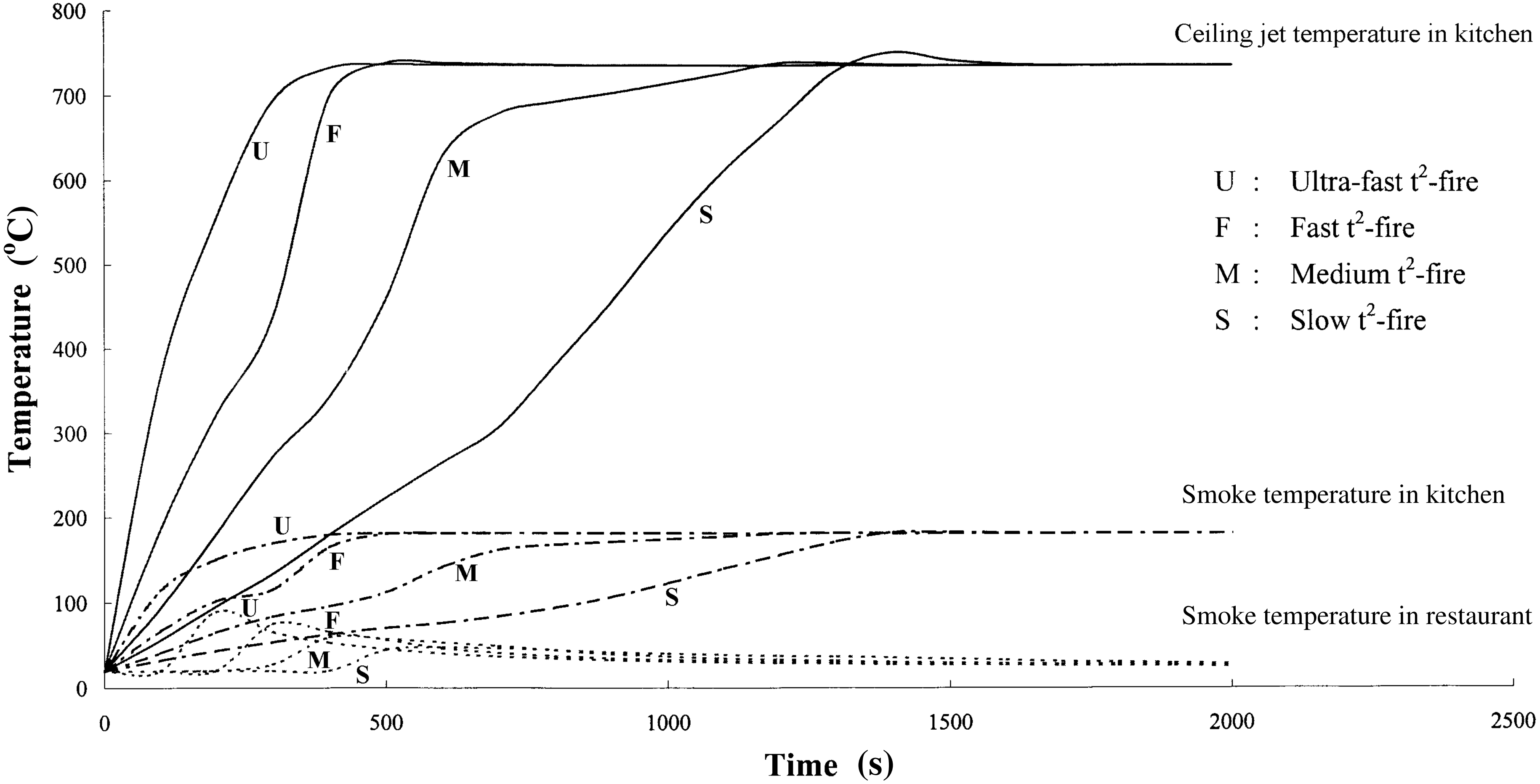


Figure 5.3: Predicted temperature

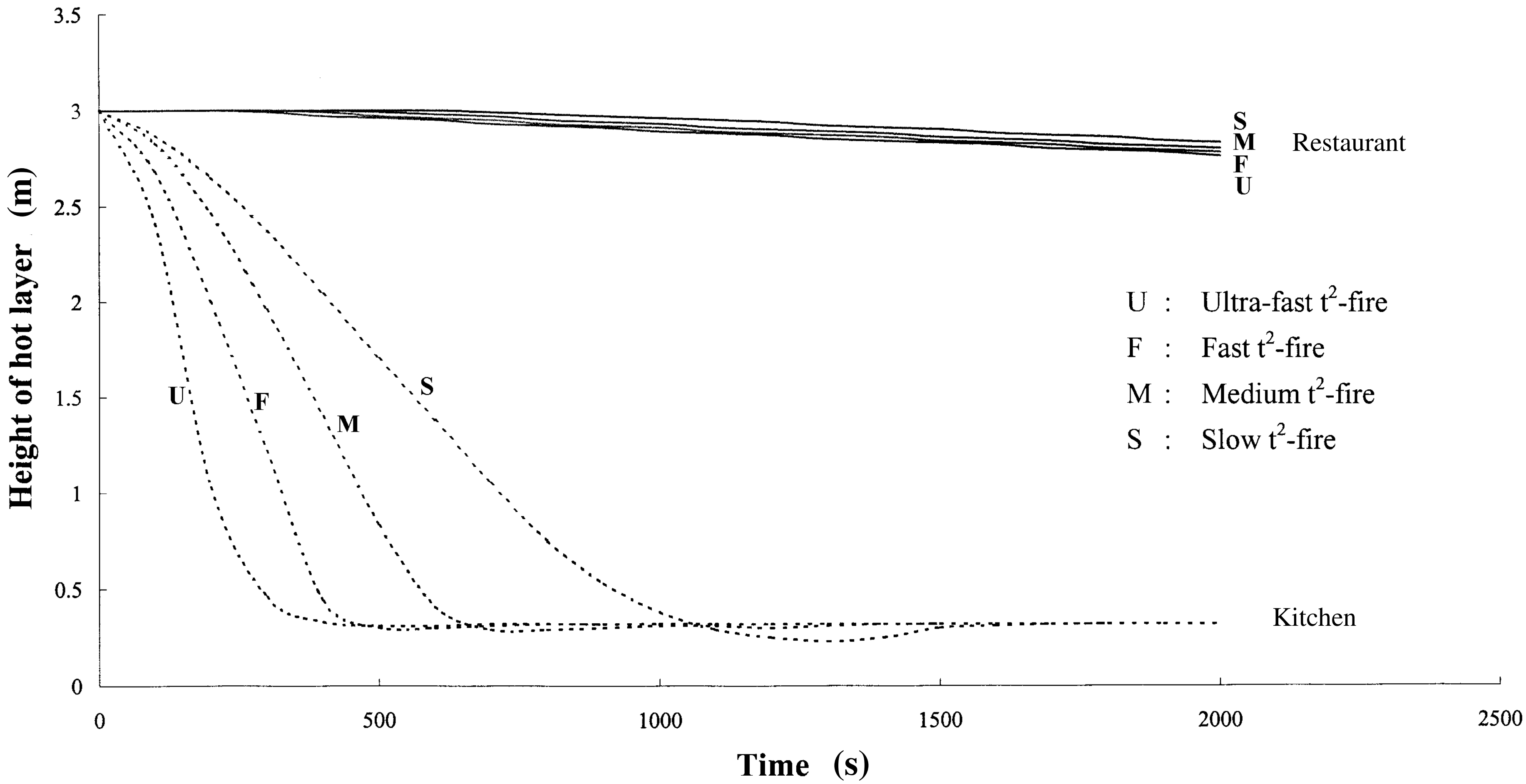


Figure 5.4: Predicted smoke layer interface height

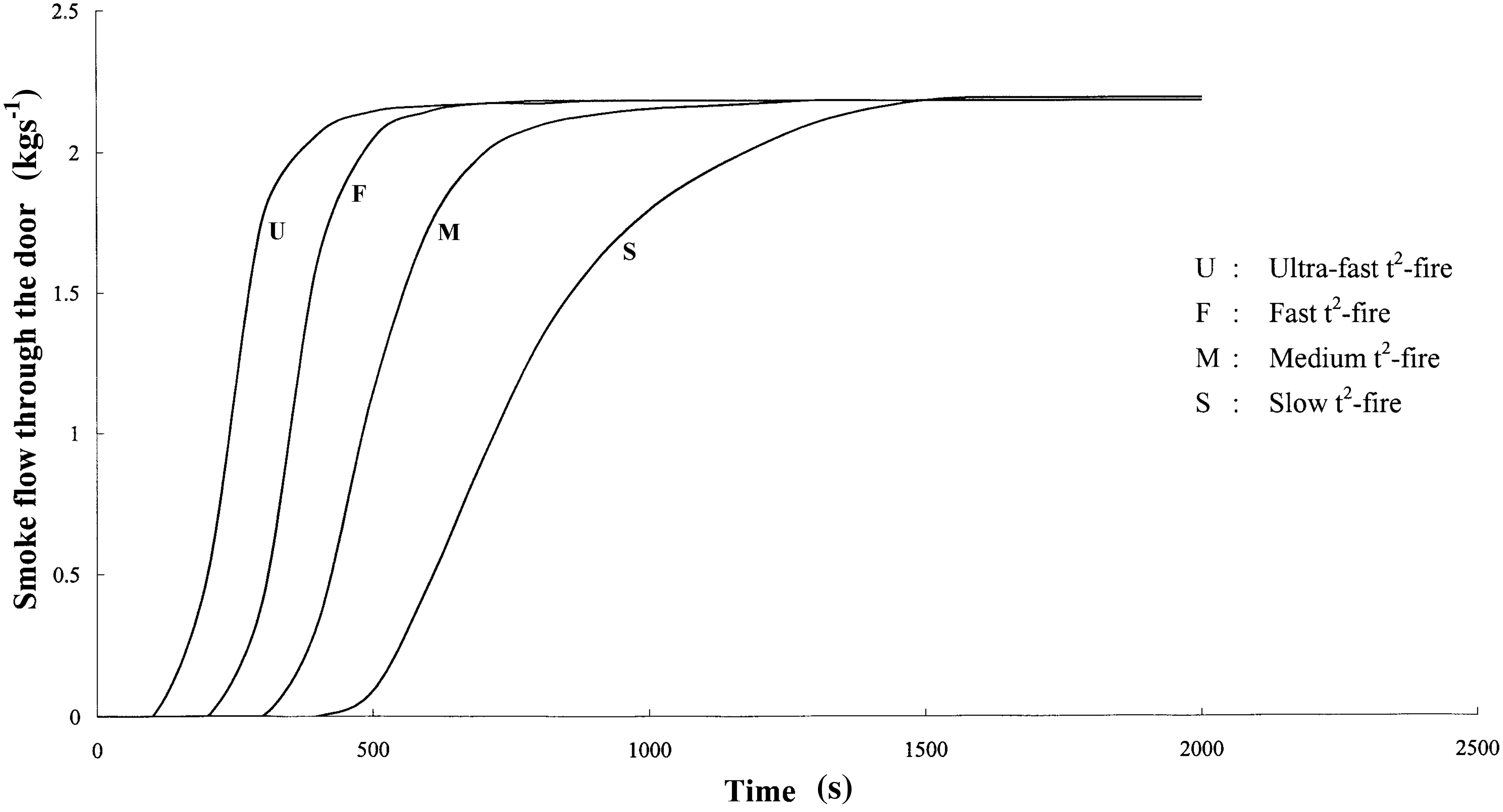


Figure 5.5: Mass flow rate of smoke out of the kitchen door

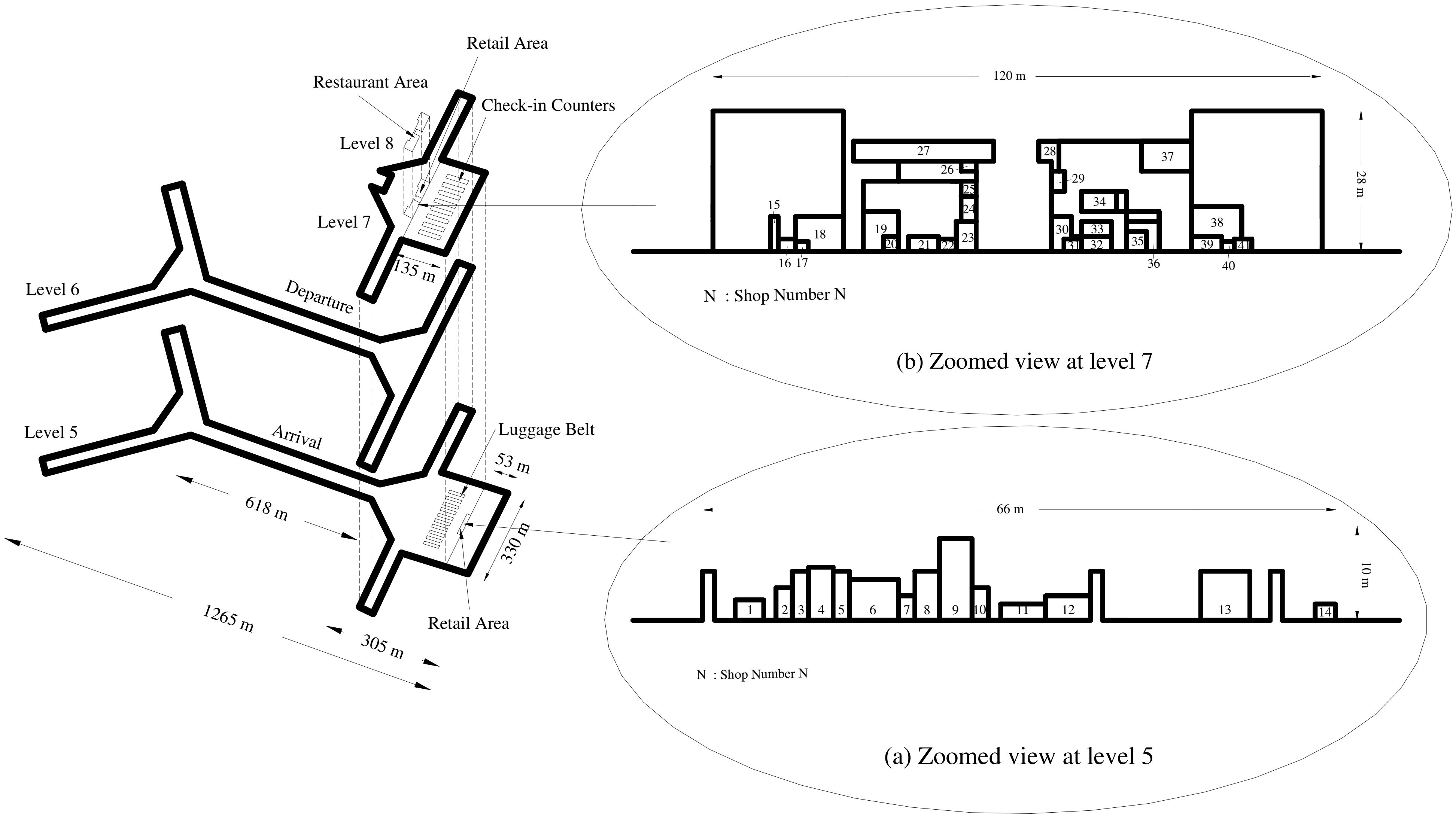


Figure 6.1: Layout of the retail areas in the non-restricted areas of airport terminal

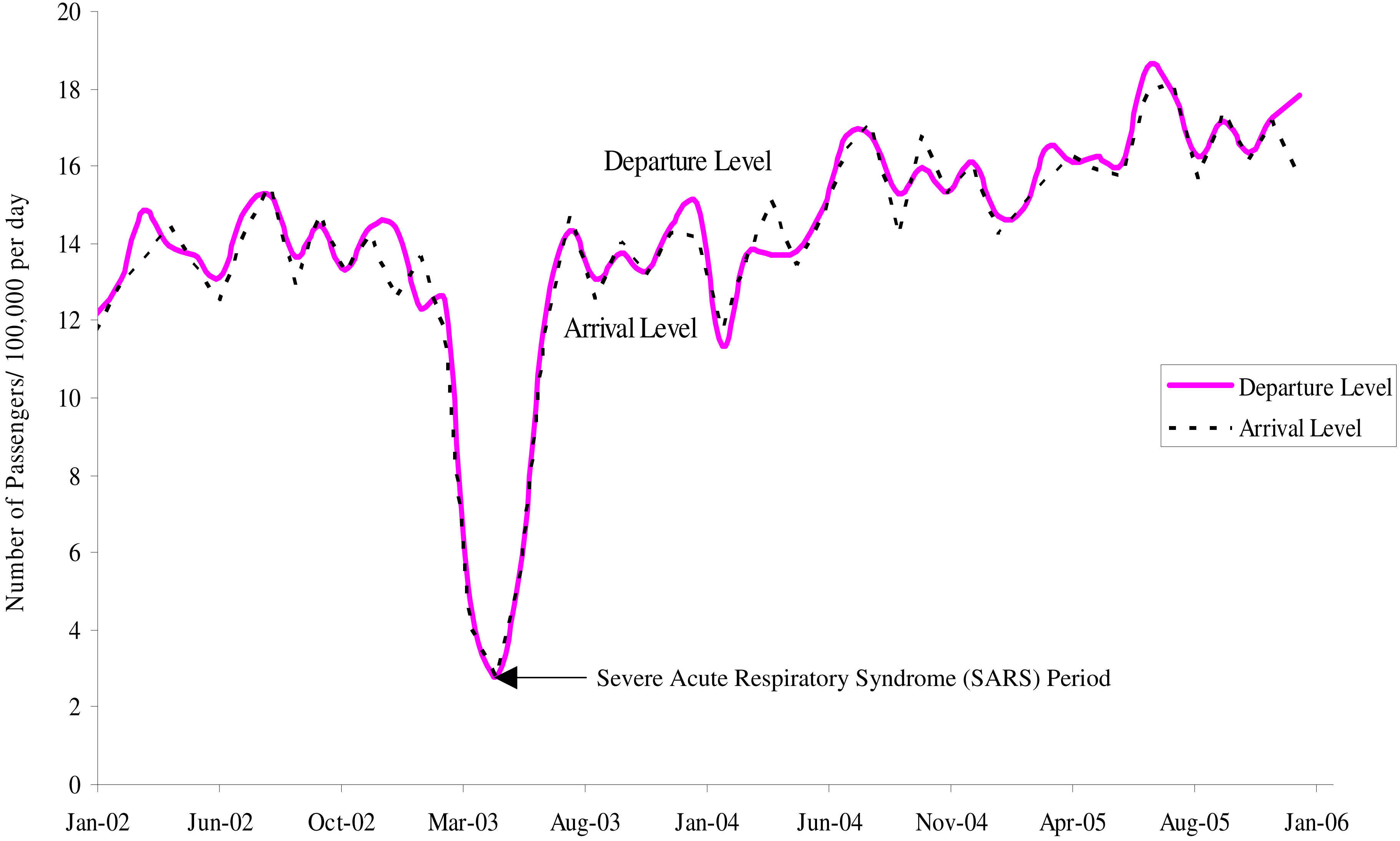
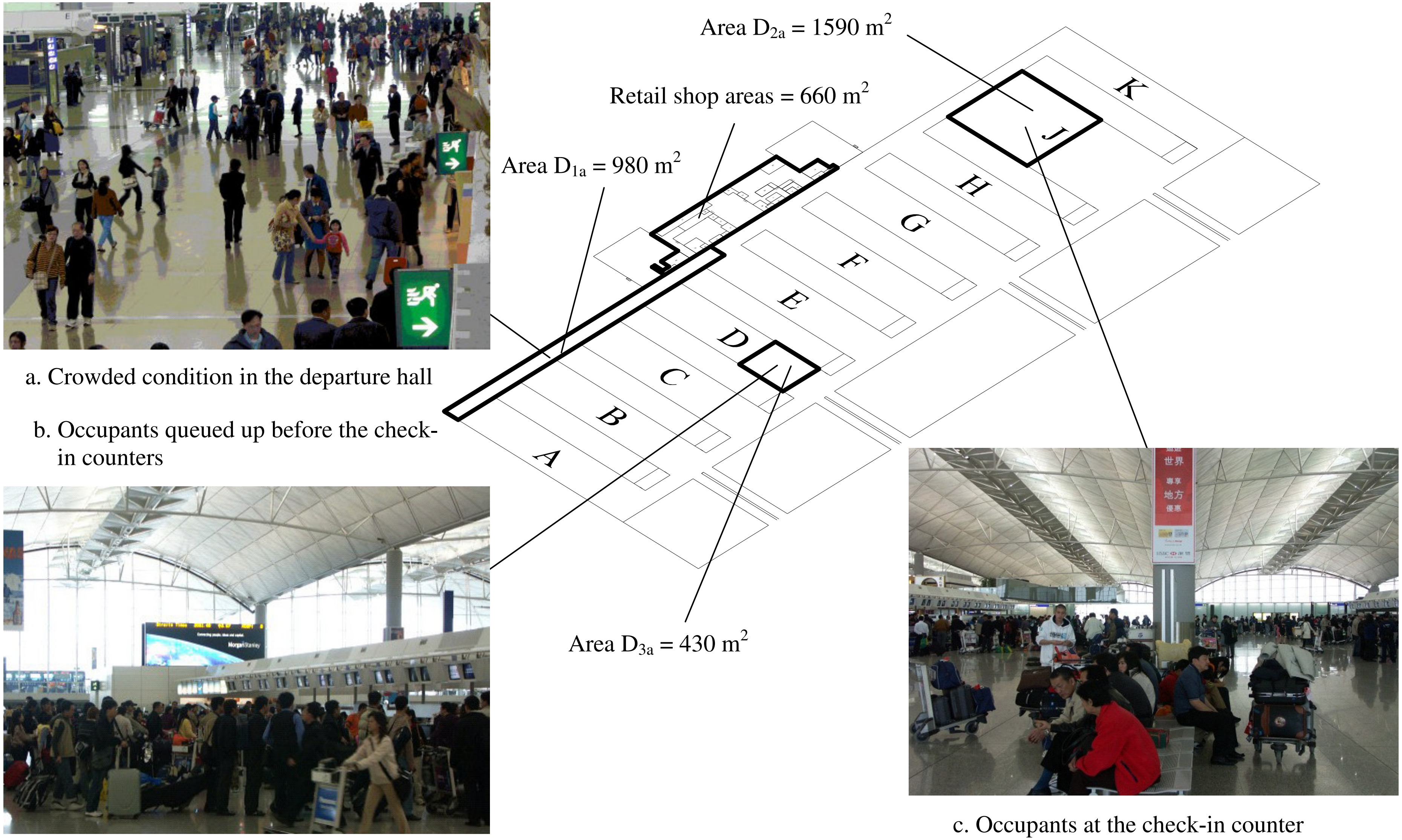


Figure 6.2: Statistical data of the total number of passengers in the departure level and arrival level



a. Crowded condition in the departure hall

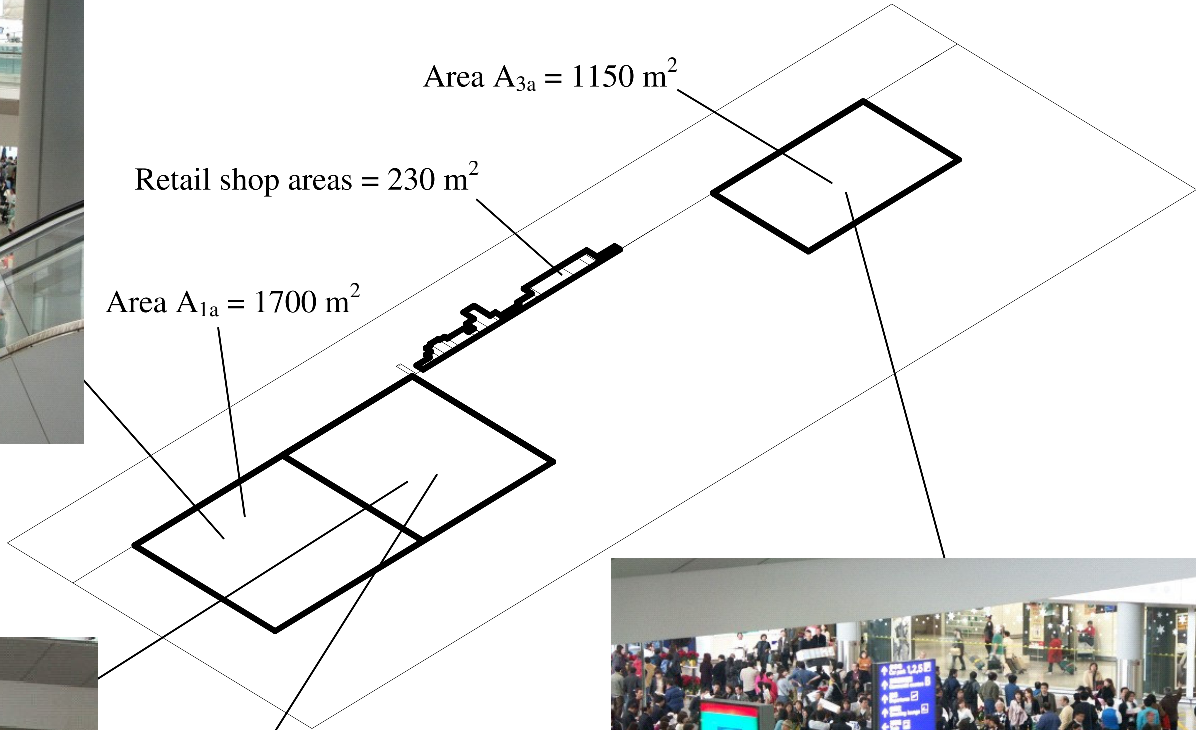
b. Occupants queued up before the check-in counters

c. Occupants at the check-in counter

Figure 6.3: Selected area of the departure level at 4:00 pm on 24 December 2004

a. Crowded condition in the waiting area B of arrival hall

b. Occupants waiting in the waiting area B of arrival hall



c. Occupants in the waiting area A of arrival hall

Figure 6.4: Selected area of the arrival level at 3:00 pm on 30 December 2004

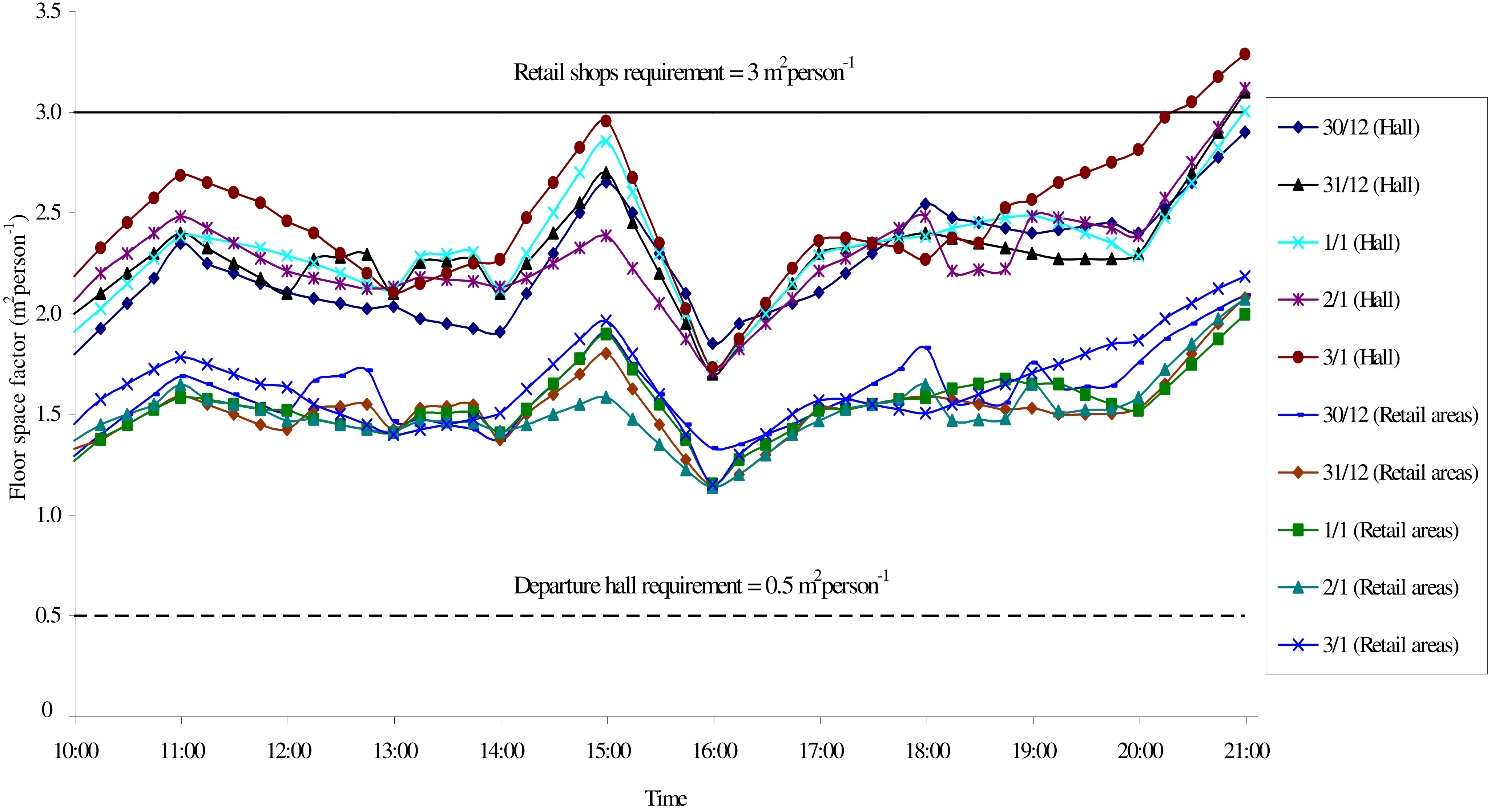


Figure 6.5: Surveyed results at the departure level from 30 December 2004 to 3 January 2005

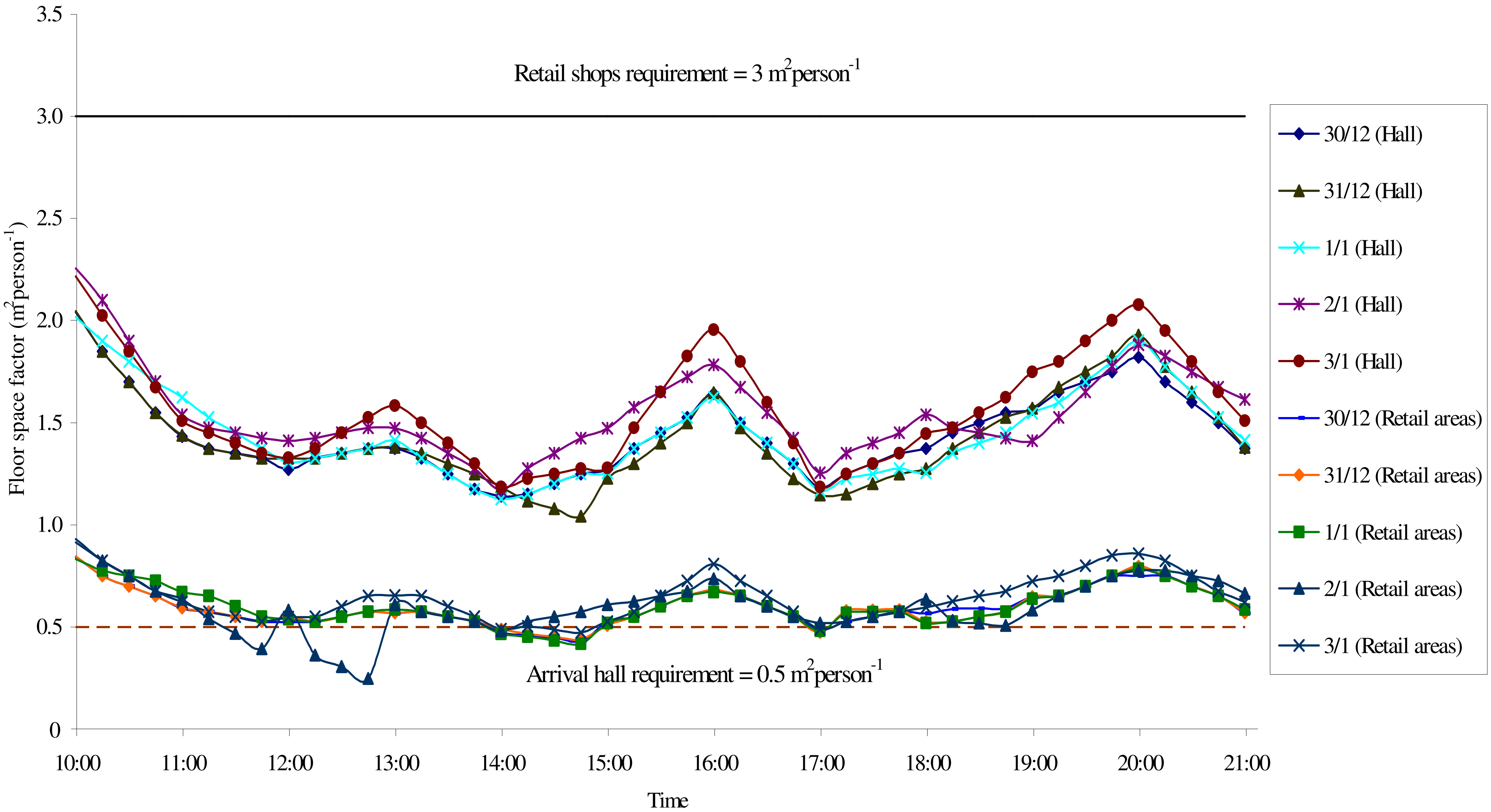


Figure 6.6: Surveyed results at the arrival level from 30 December 2004 to 3 January 2005

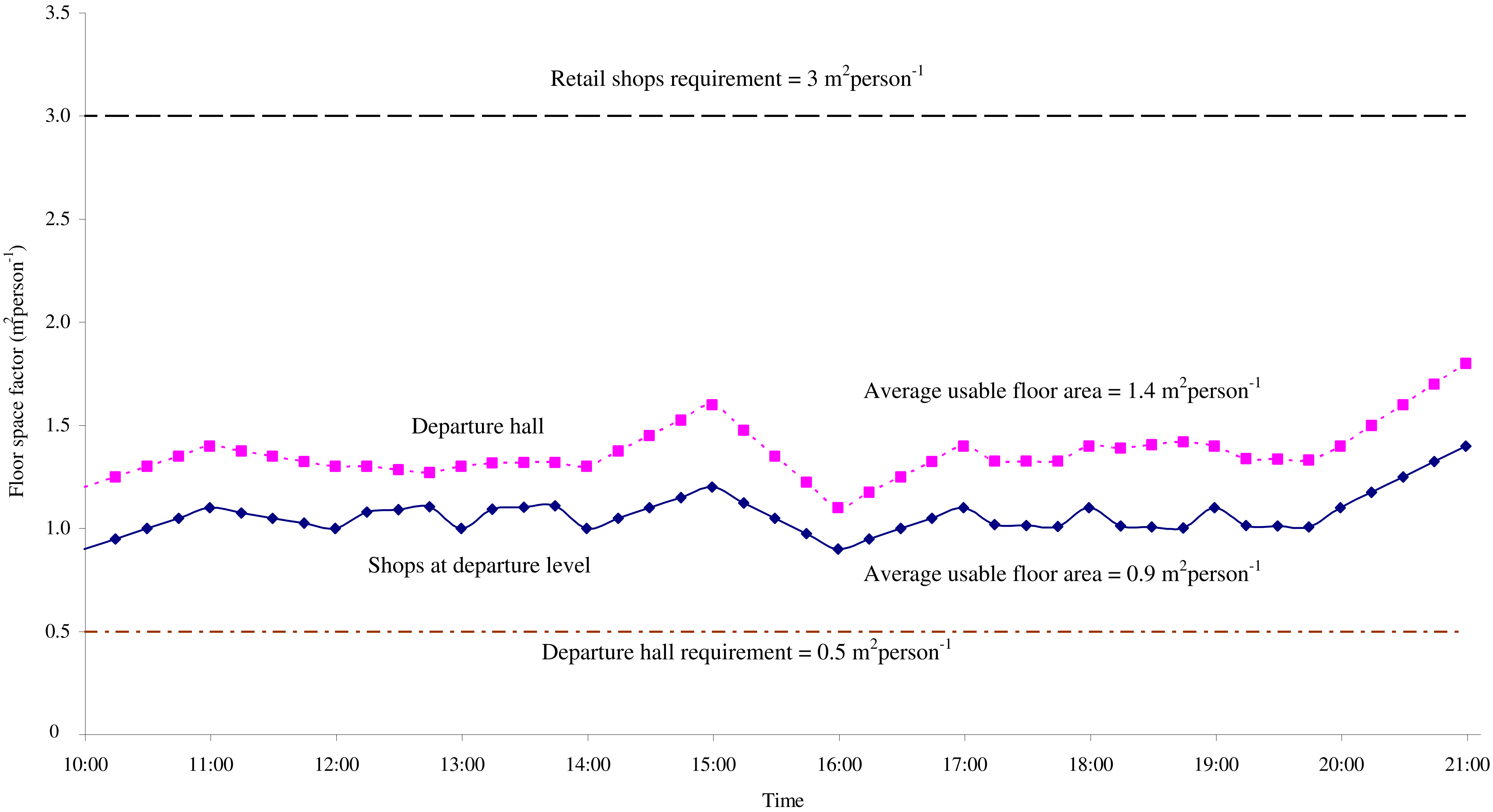


Figure 6.7: Surveyed results of the departure level at 24 December 2004

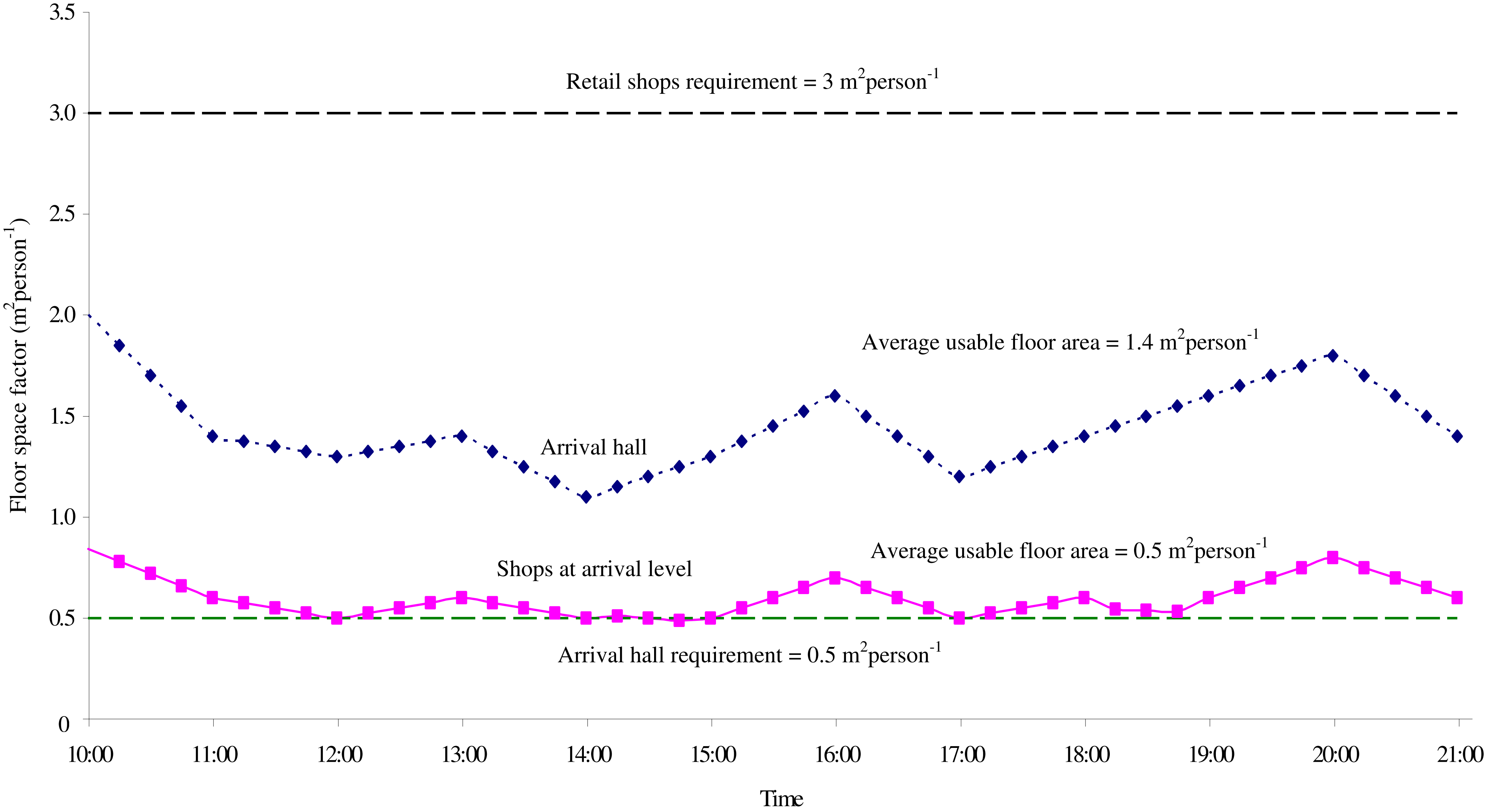


Figure 6.8: Surveyed results of the arrival level at 30 December 2004

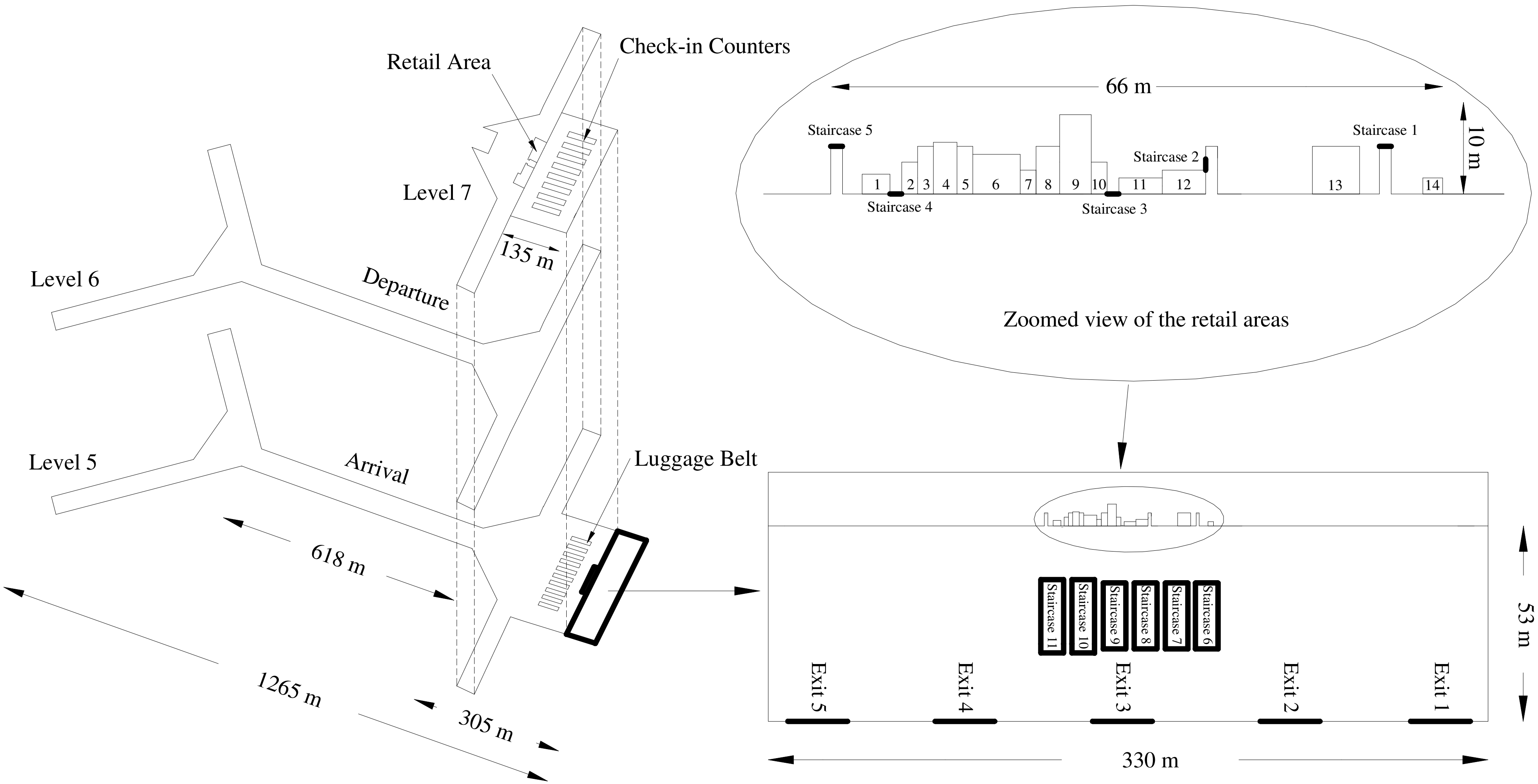


Figure 7.1: Layout of the arrival level

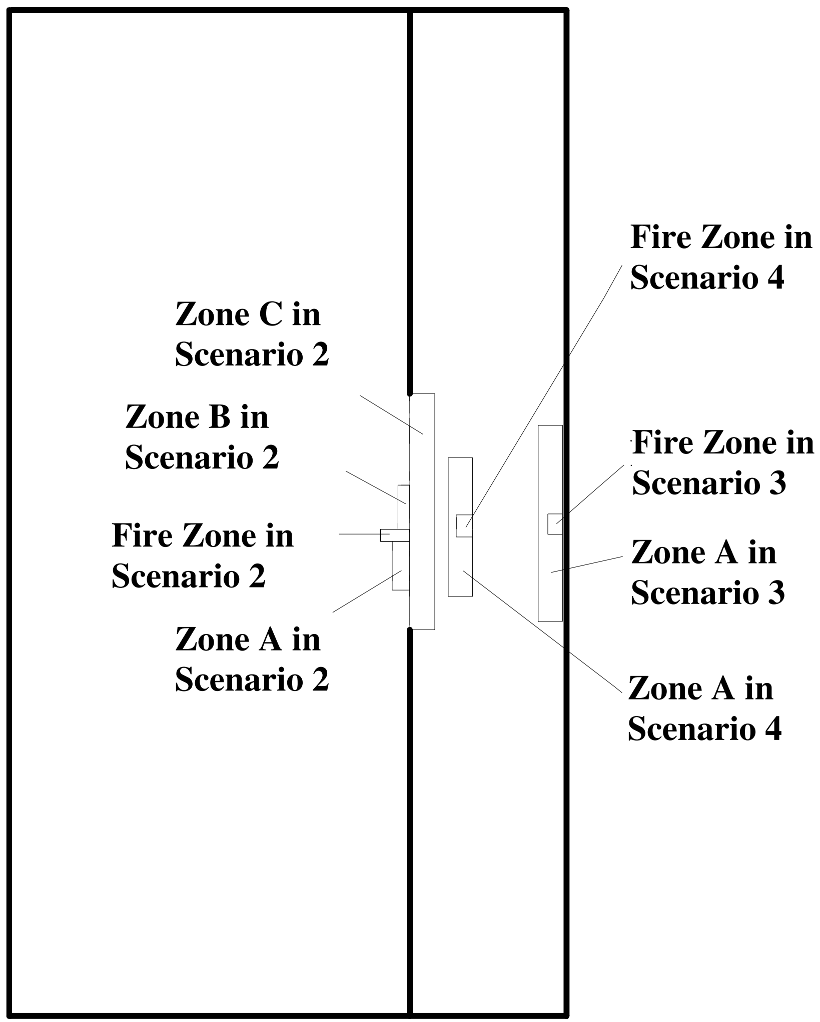


Figure 7.2: Zoning of each scenario in the arrival level

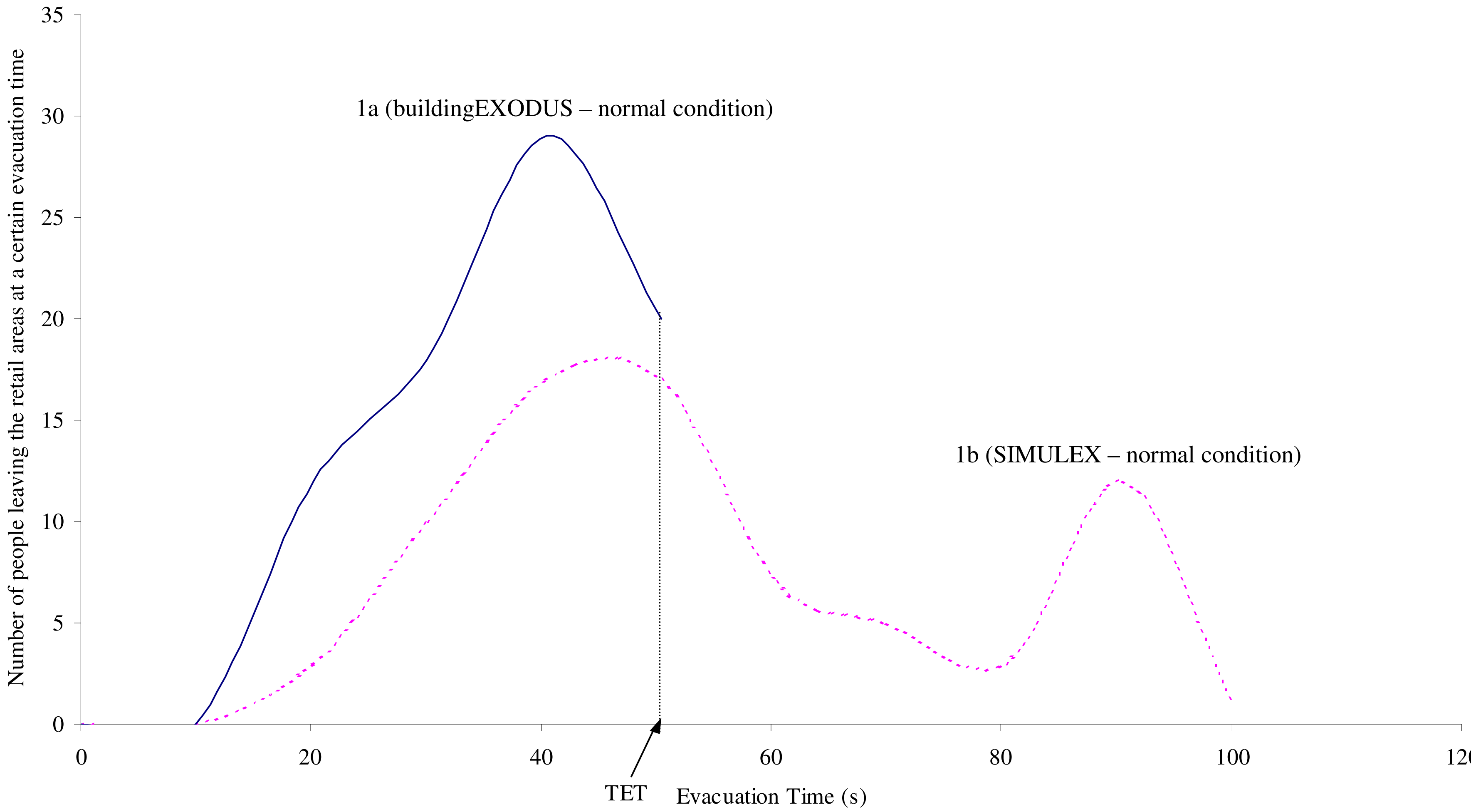


Figure 7.3: Evacuation time of sub-scenarios 1a and 1b

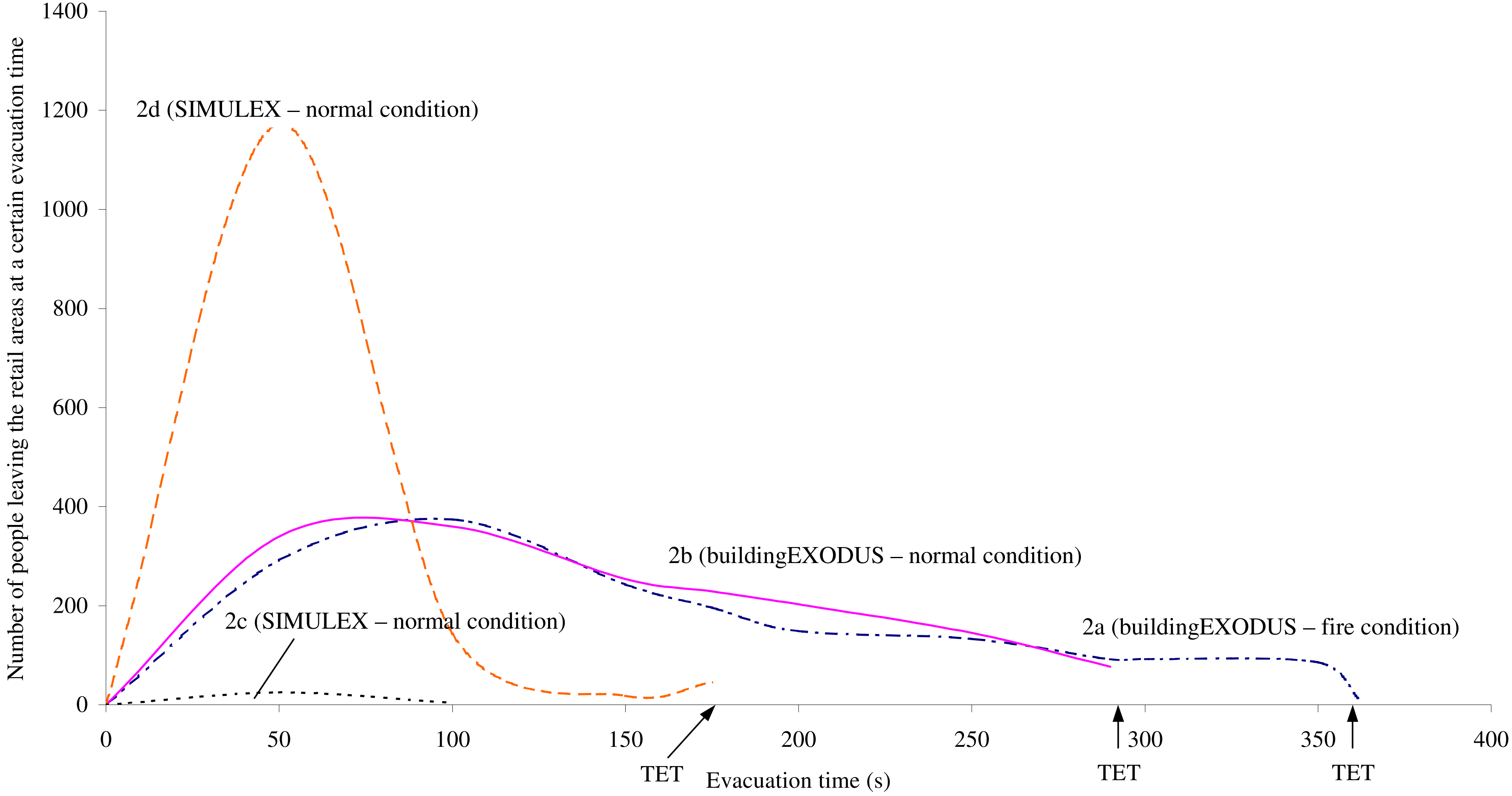


Figure 7.4: Evacuation time of sub-scenarios 2a to 2d

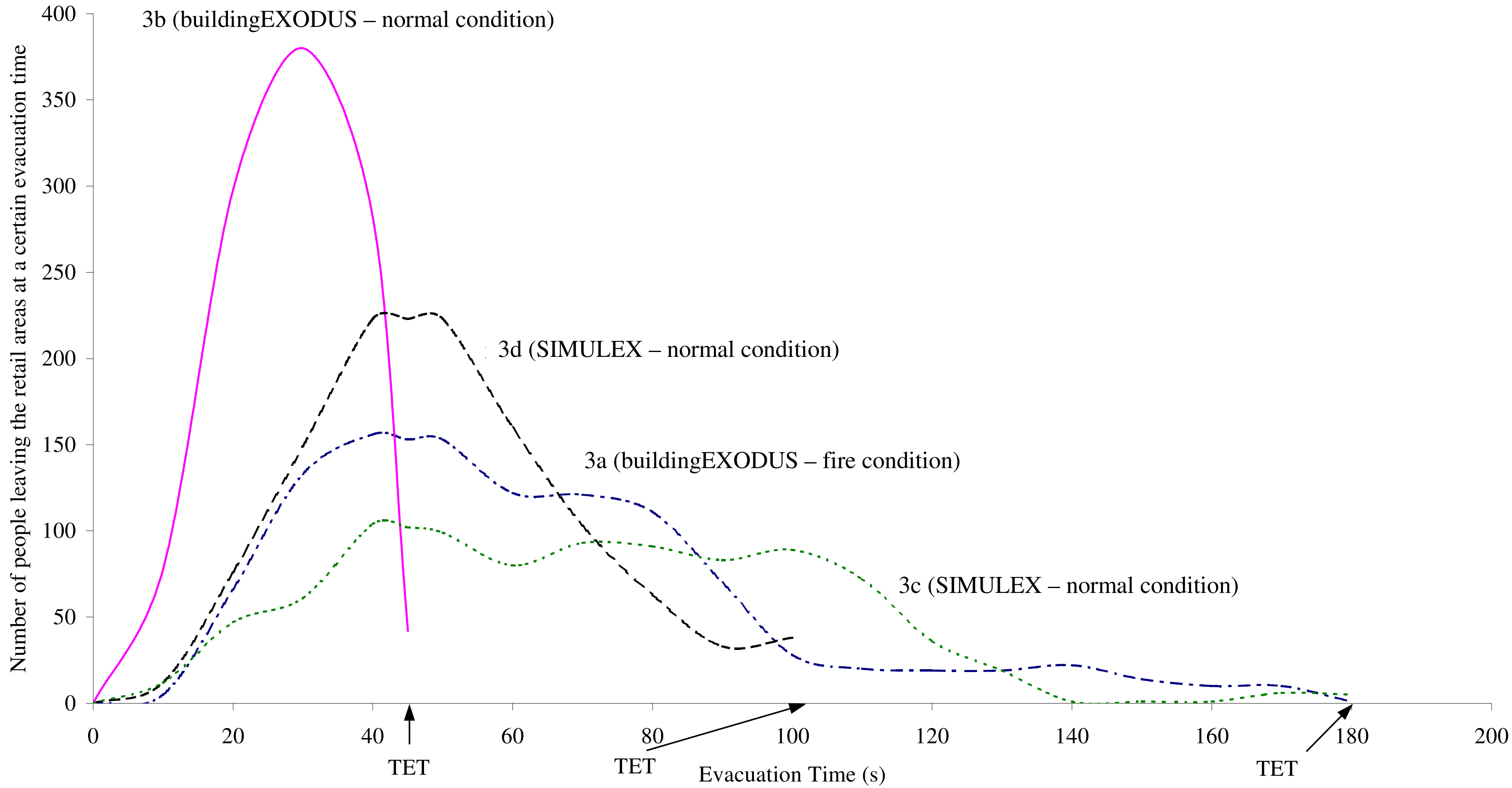


Figure 7.5: Evacuation time of sub-scenarios 3a to 3d

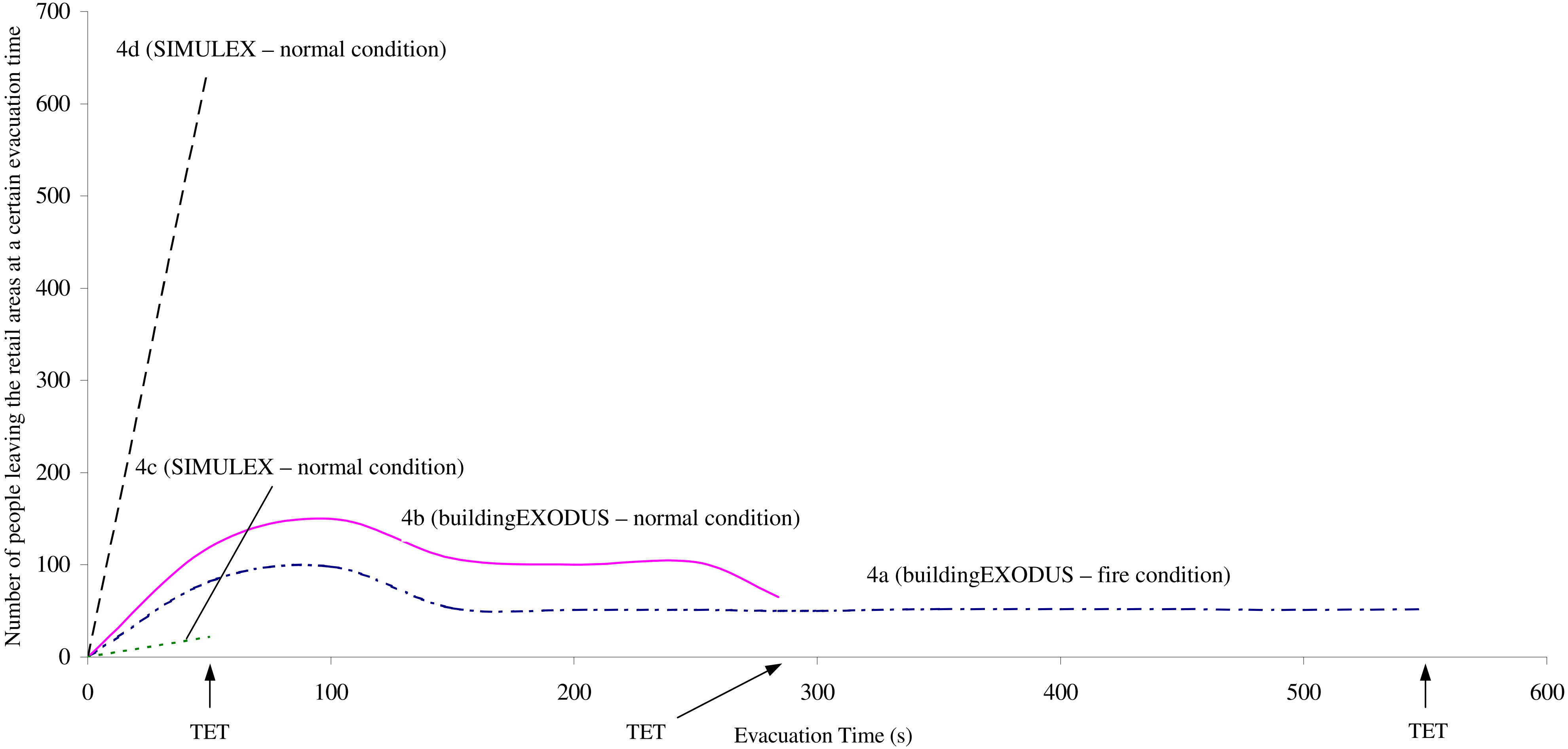
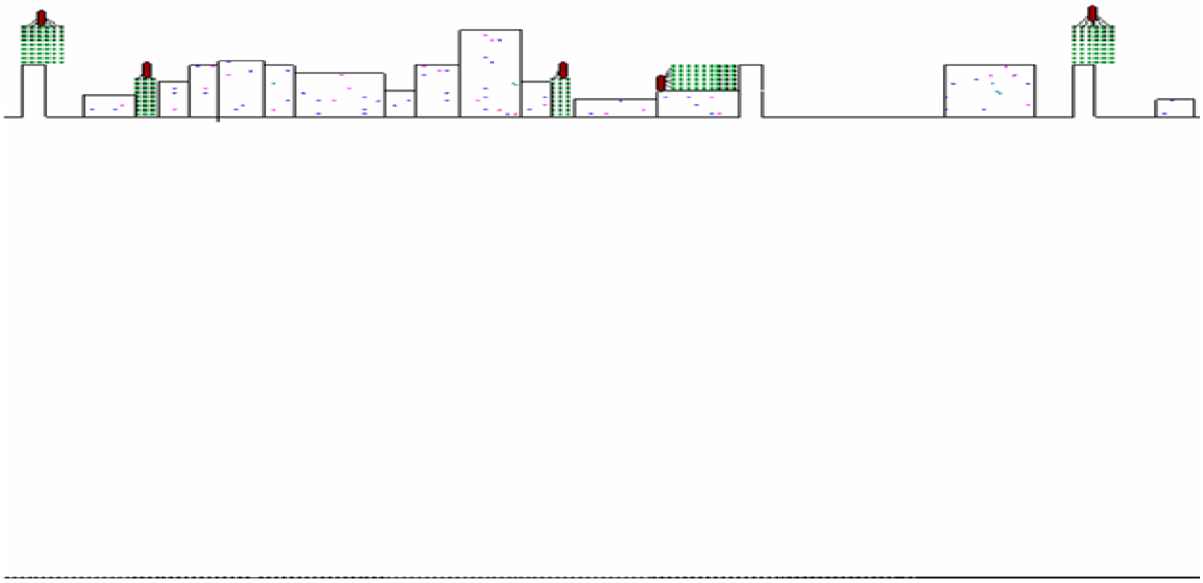
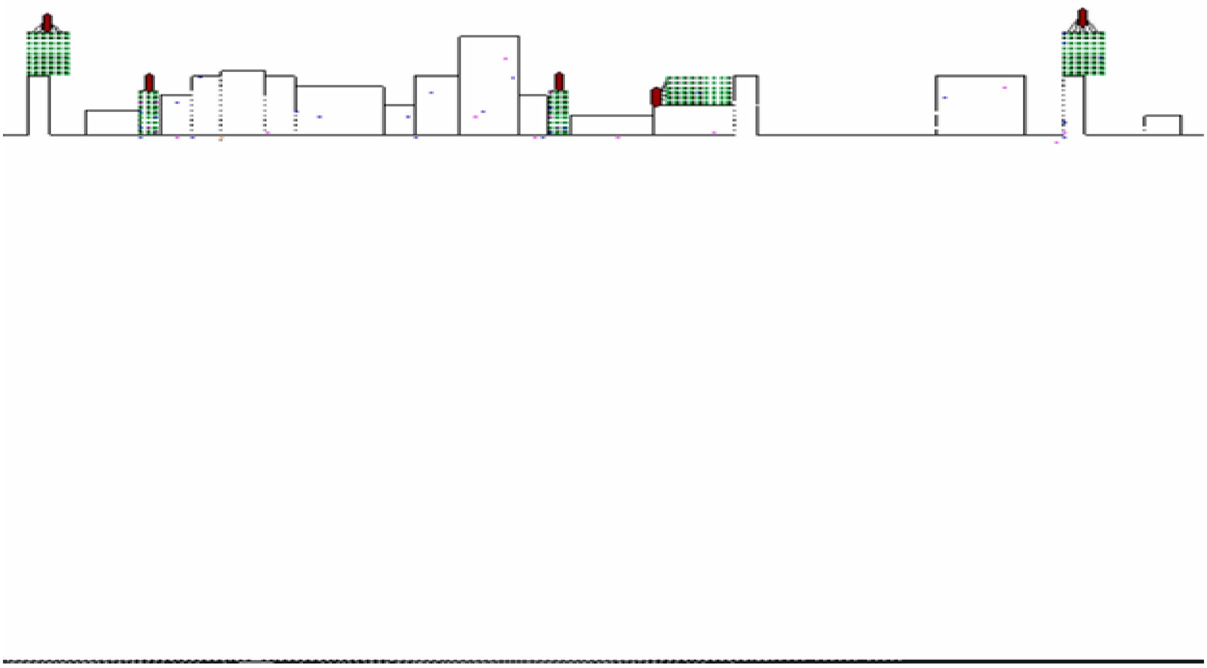


Figure 7.6: Evacuation time of sub-scenarios 4a to 4d

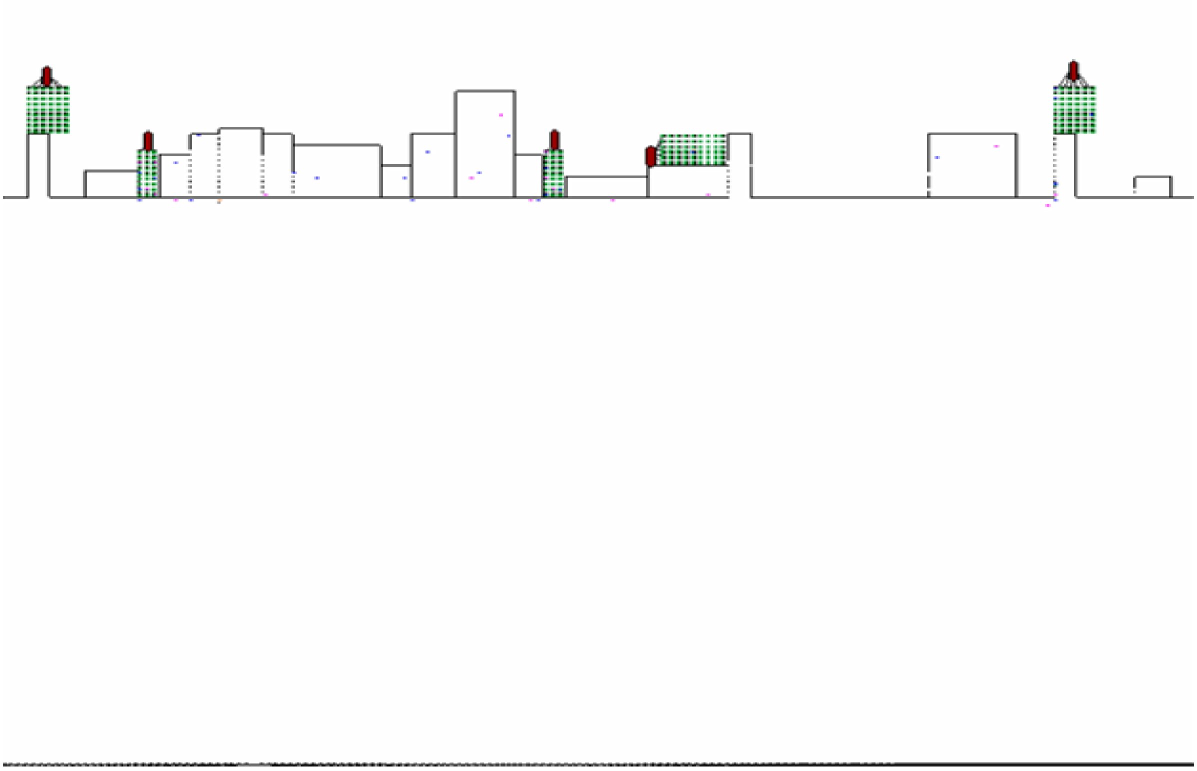
Sub-scenario 1a



The occupants at 0 s

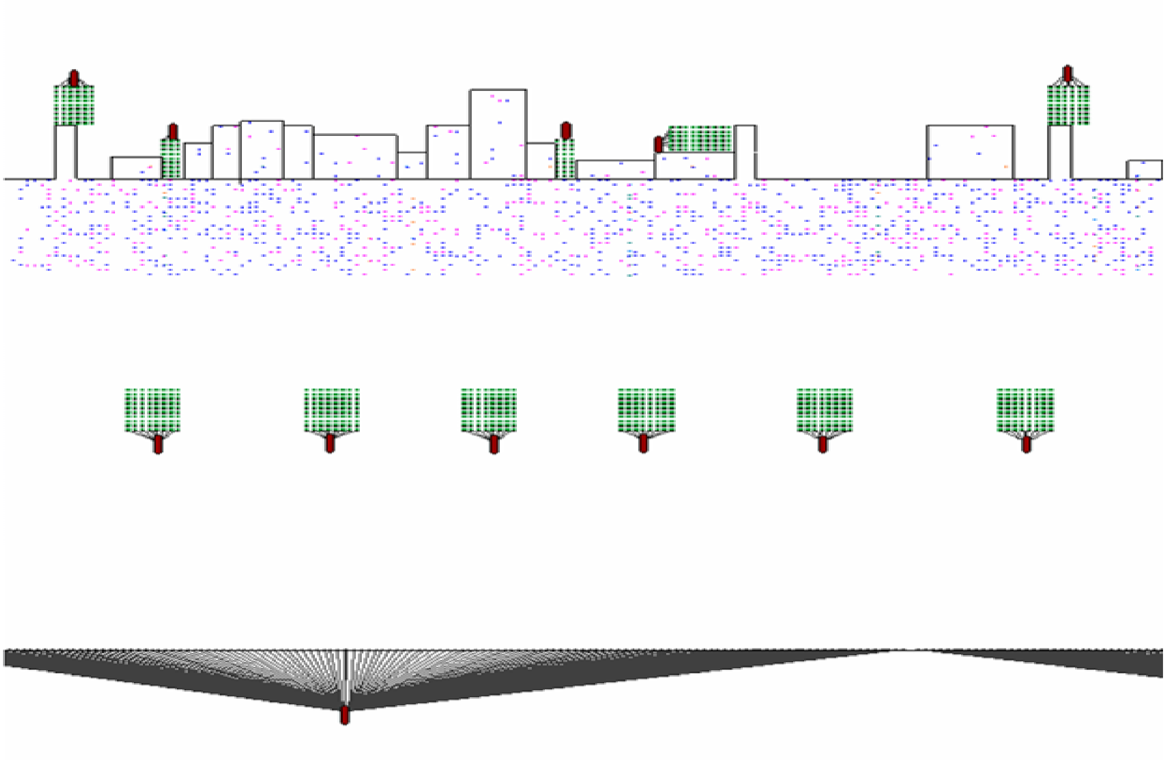


The occupants at 25 s

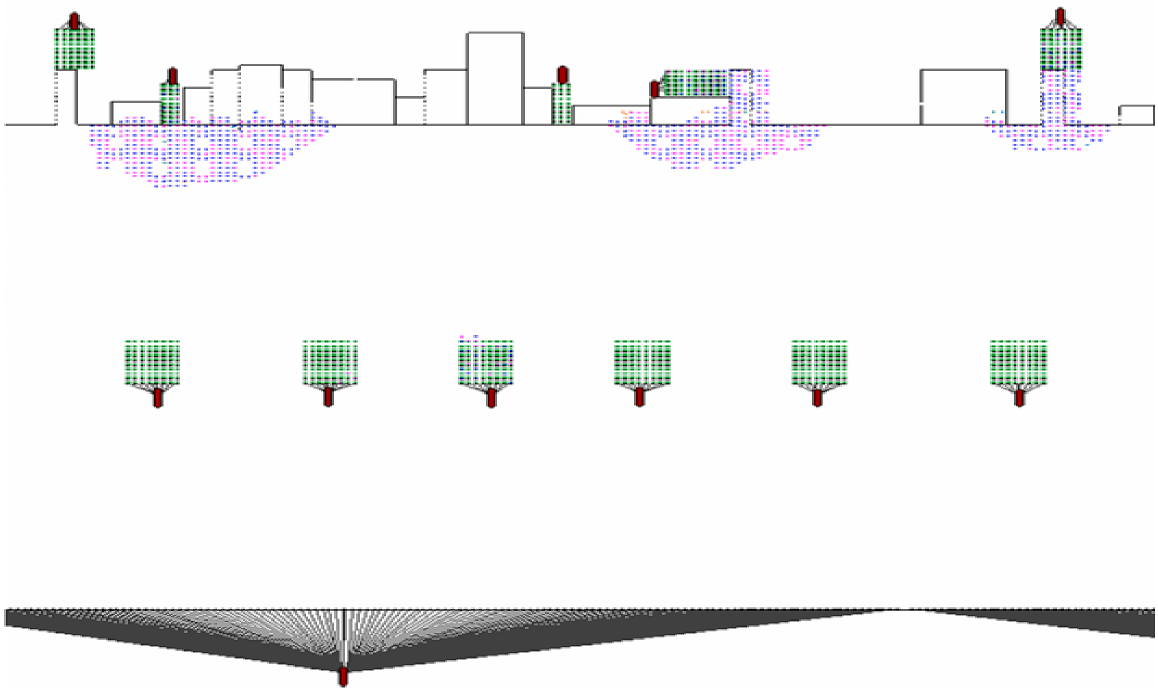


All the occupants evacuated at 50 s

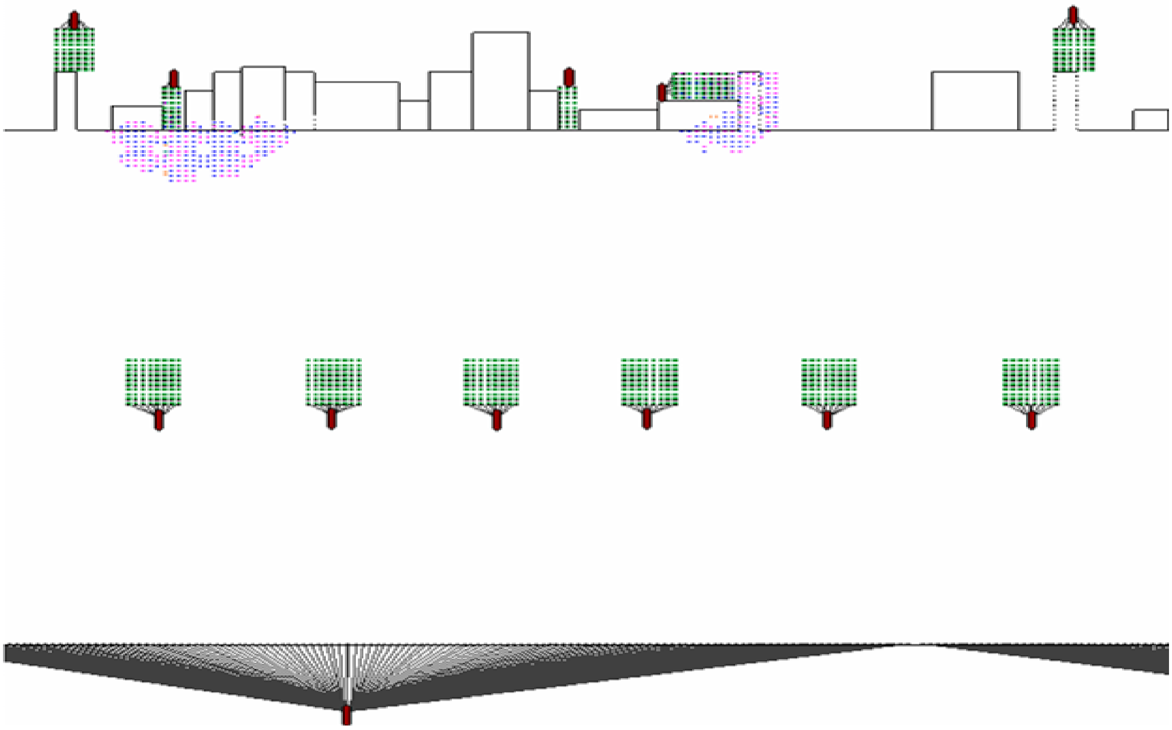
Sub-scenario 2a



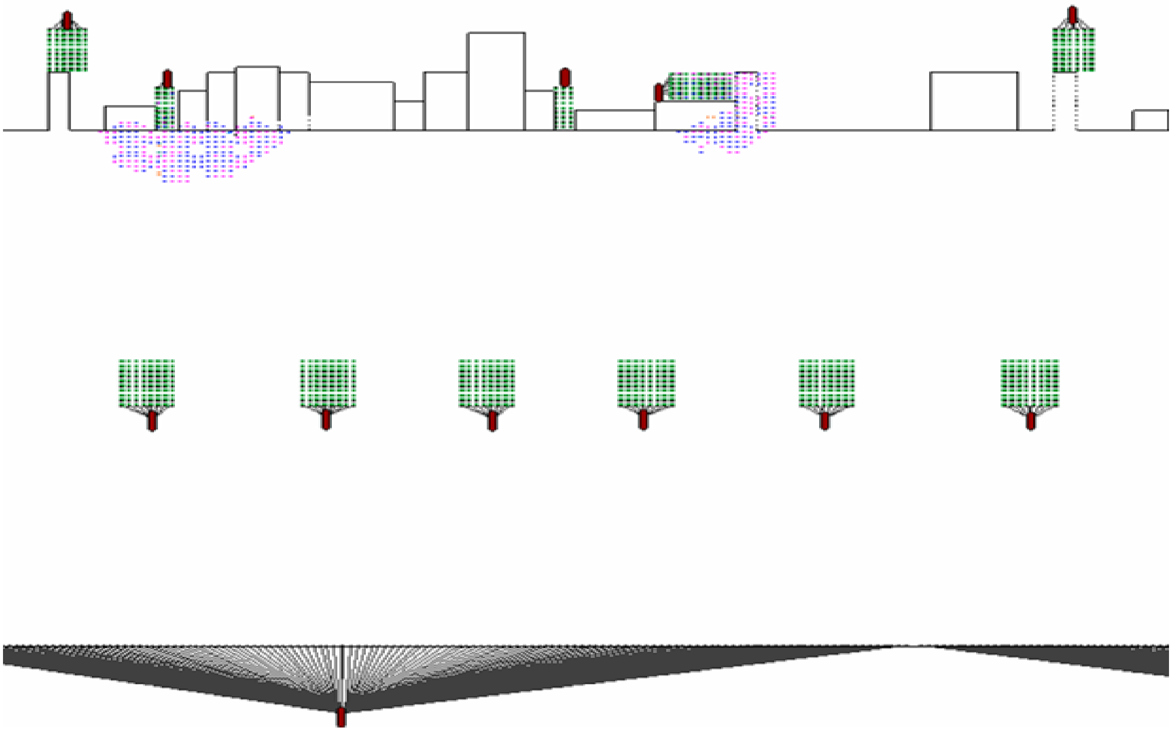
The occupants at 0 s



The occupants at 50 s

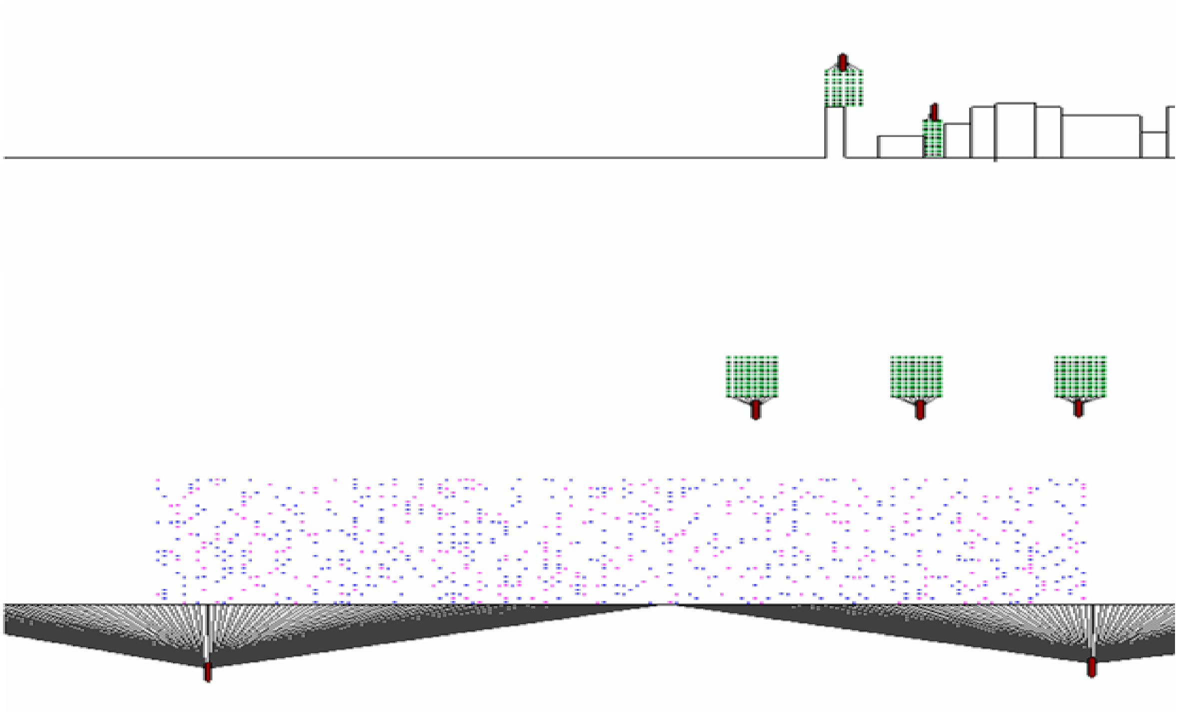


The occupants at 200 s

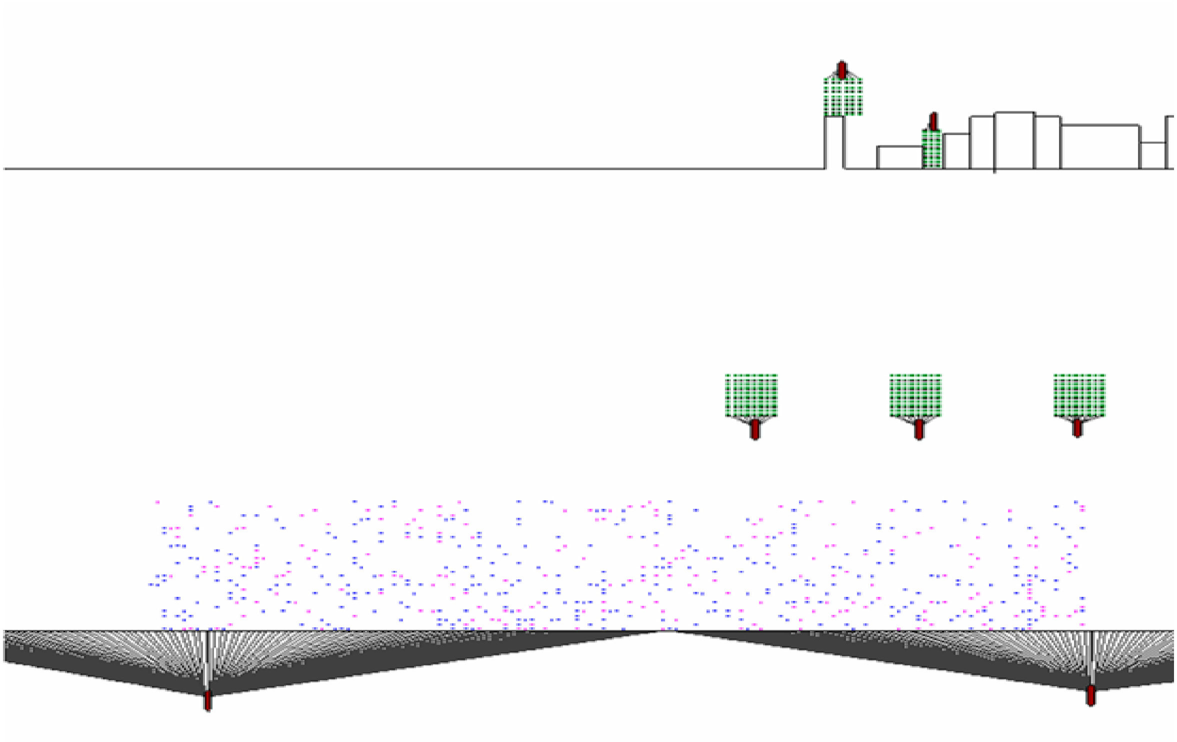


All the occupants evacuated at 363 s

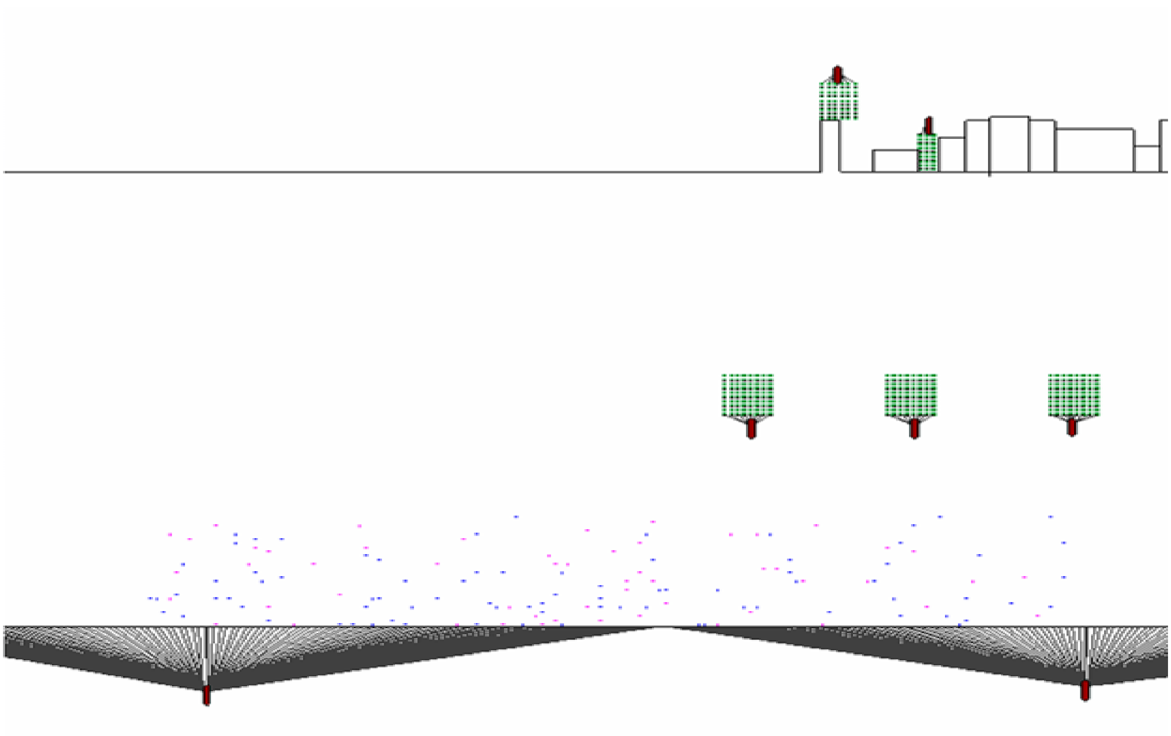
Sub-scenario 3b



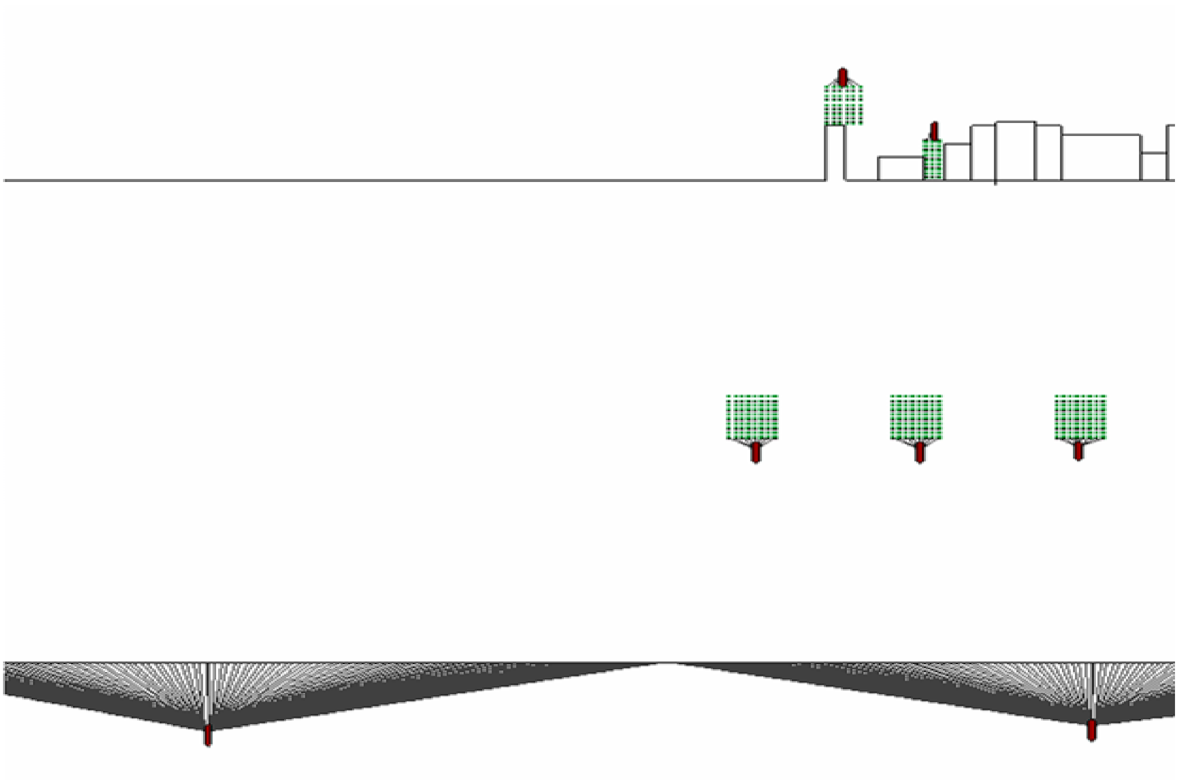
The occupants at 0 s



The occupants at 15 s

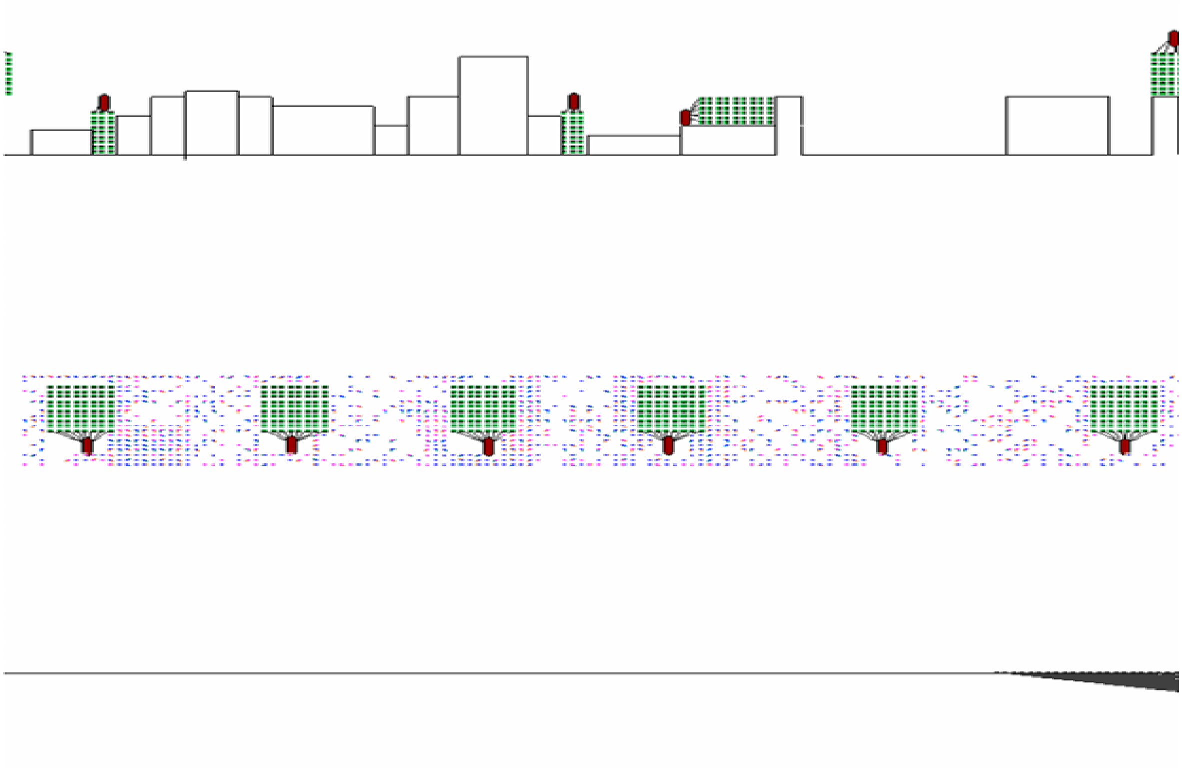


The occupants at 30 s

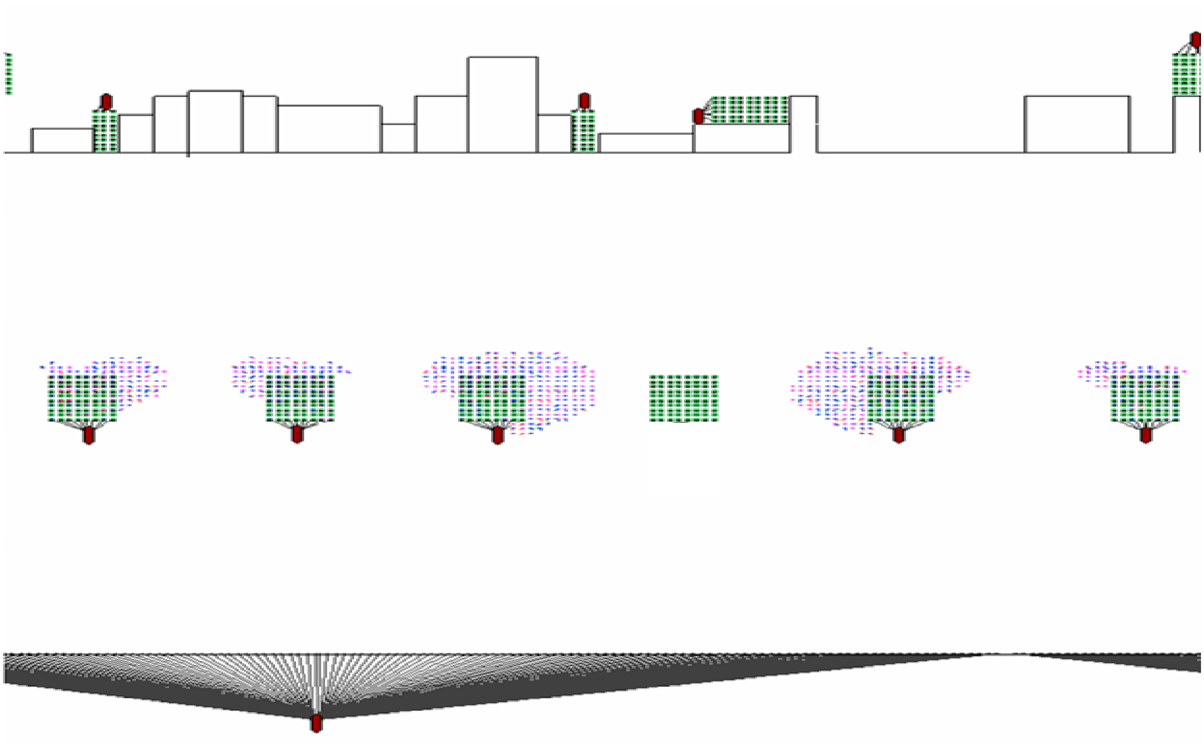


All the occupants evacuated at 45 s

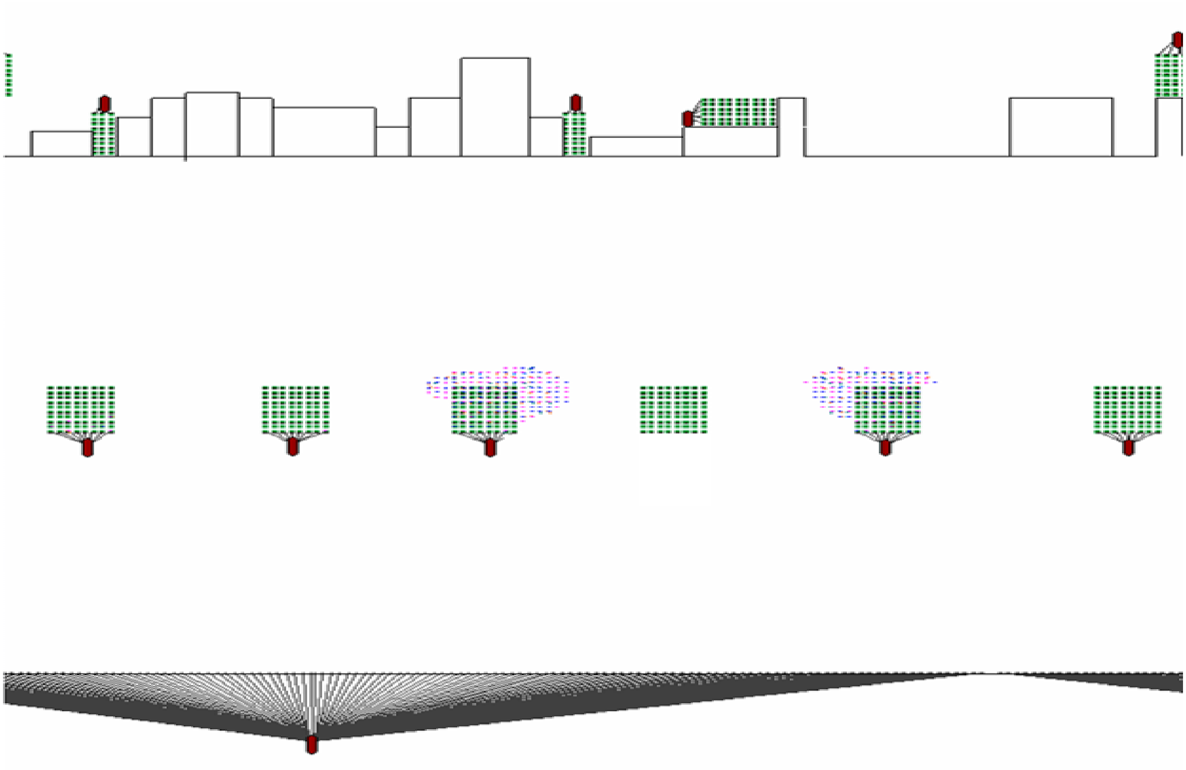
Sub-scenario 4a



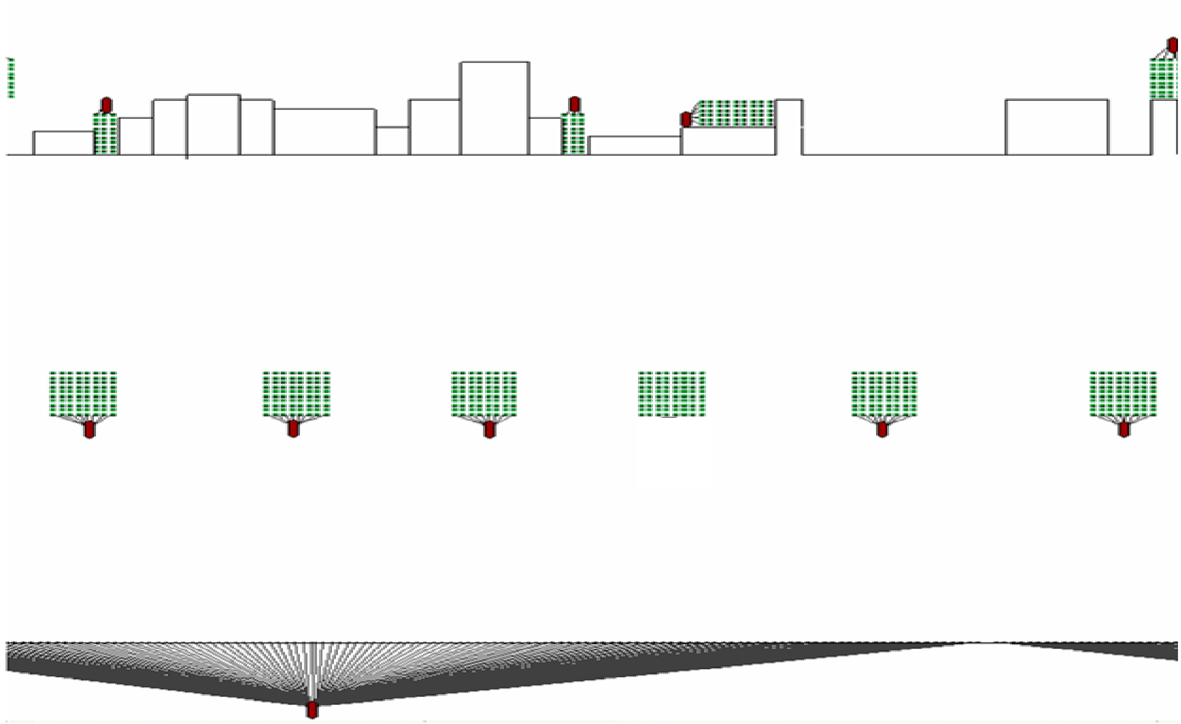
The occupants at 0 s



The occupants at 100 s



The occupants at 200 s



All the occupants evacuated at 548 s

Figure 7.7: The snapshots of the outputs from the simulations of buildingEXODUS

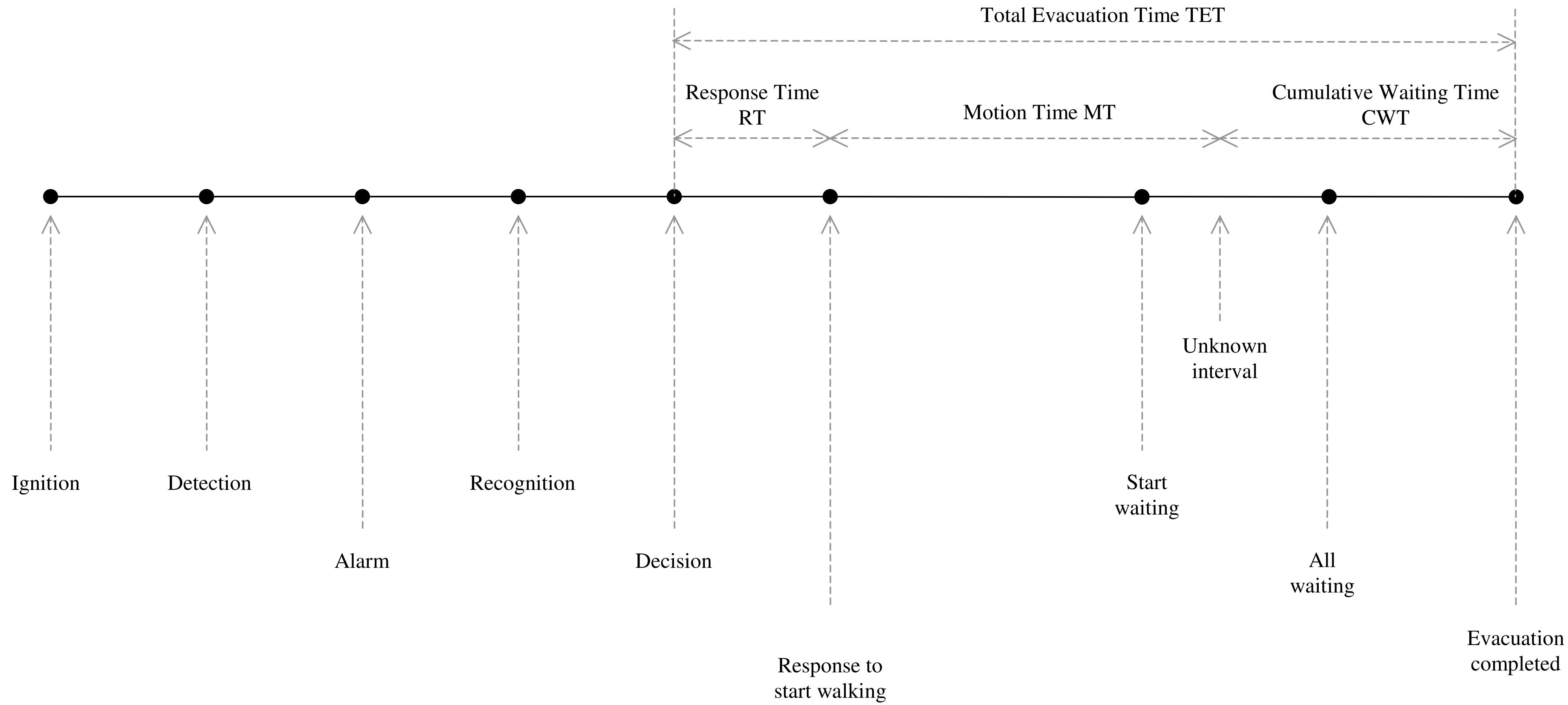


Figure 8.1: Time line

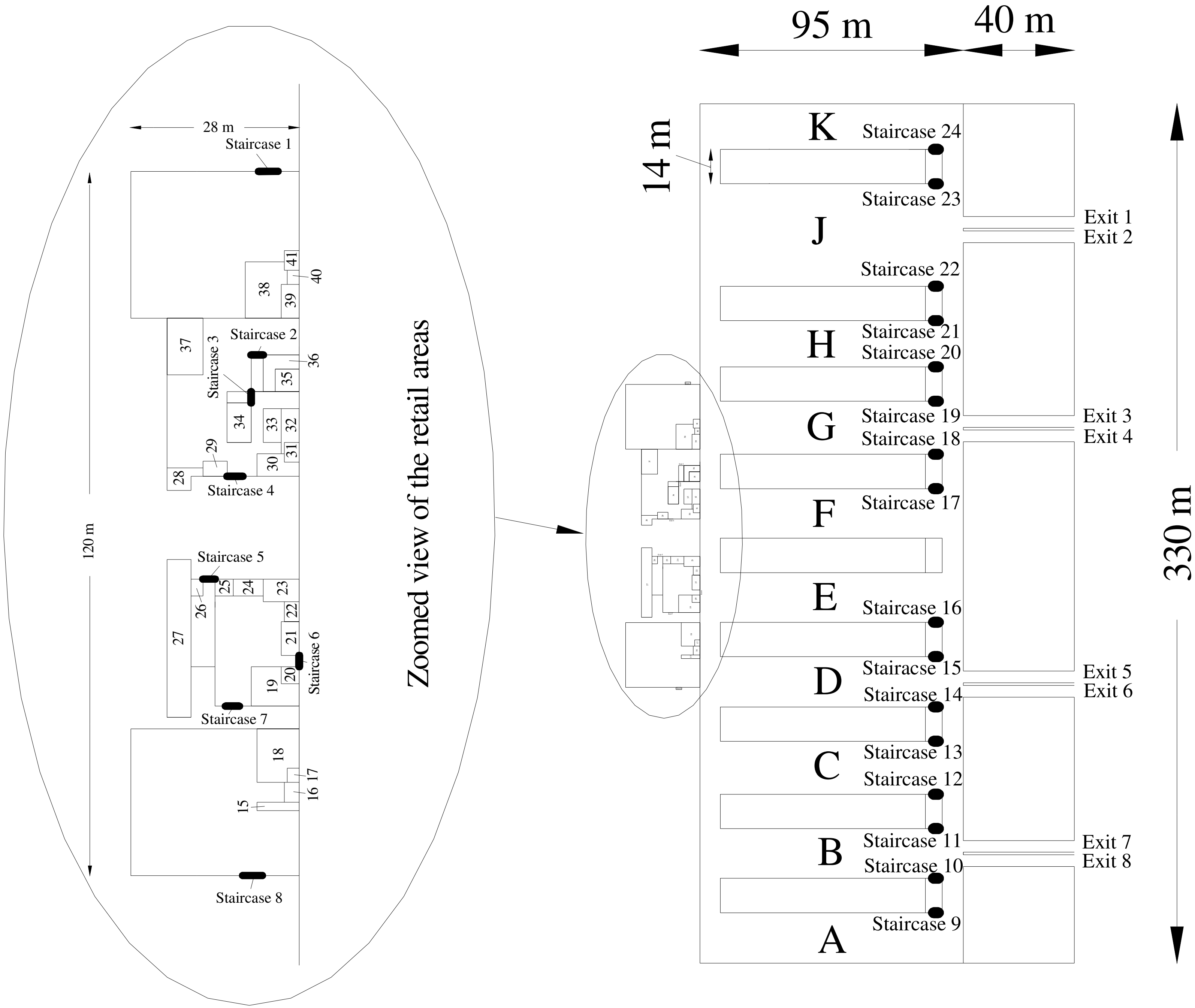


Figure 8.2: Layout of the departure level

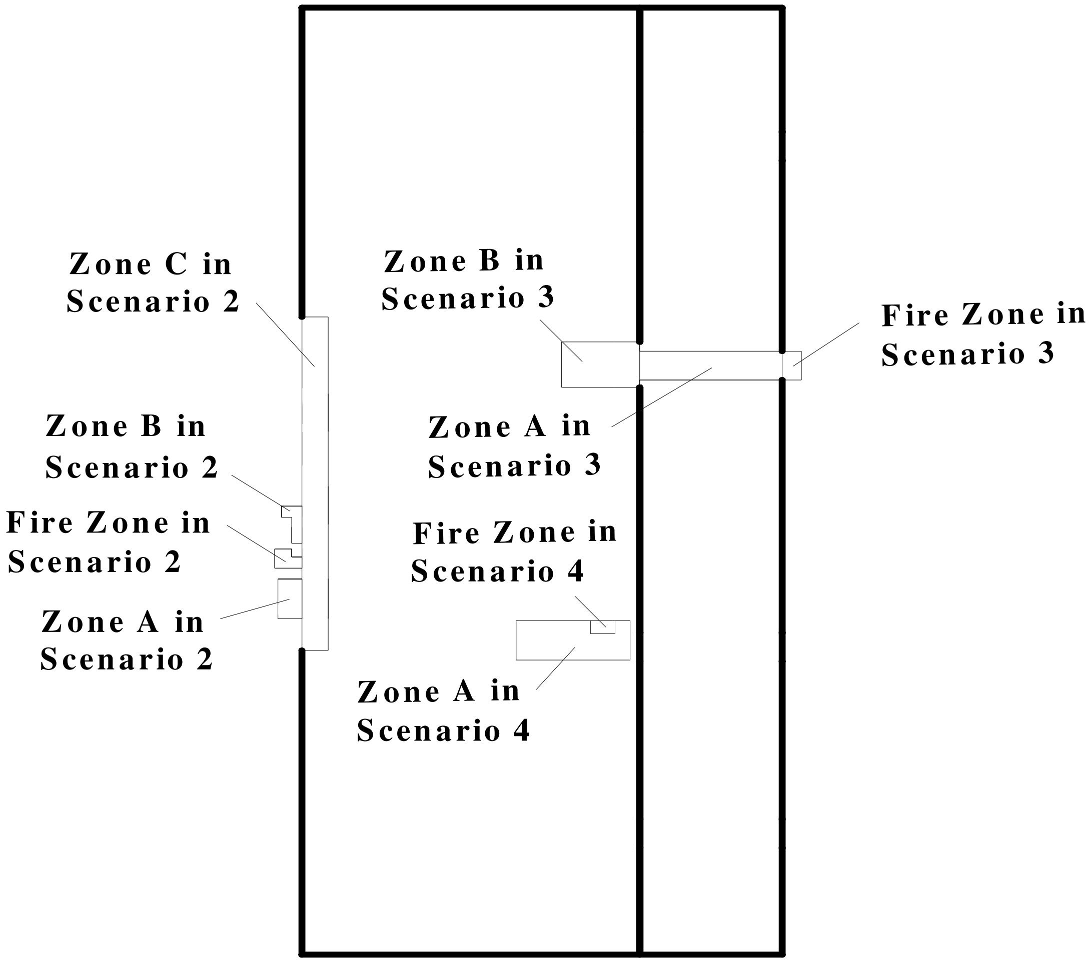
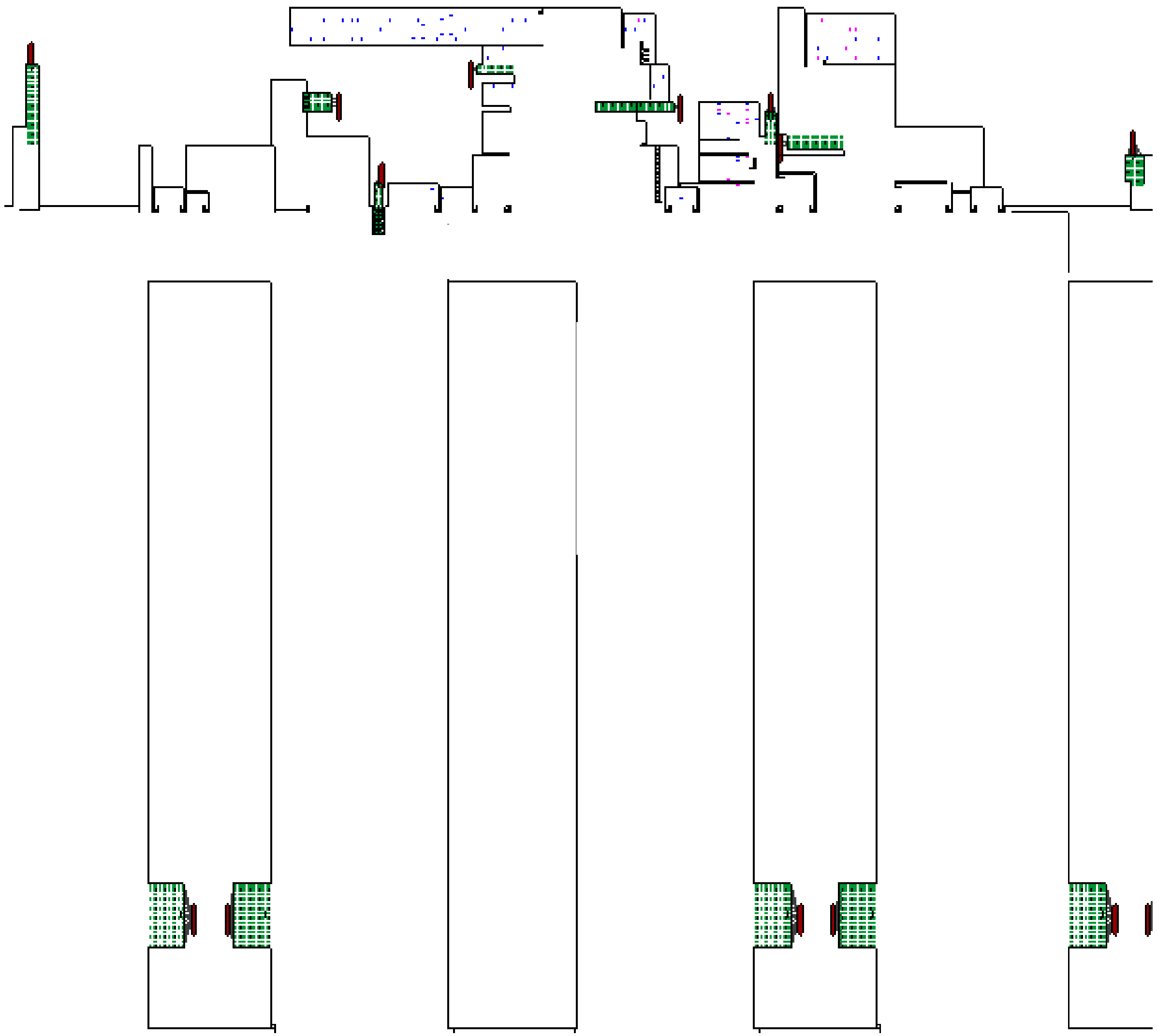
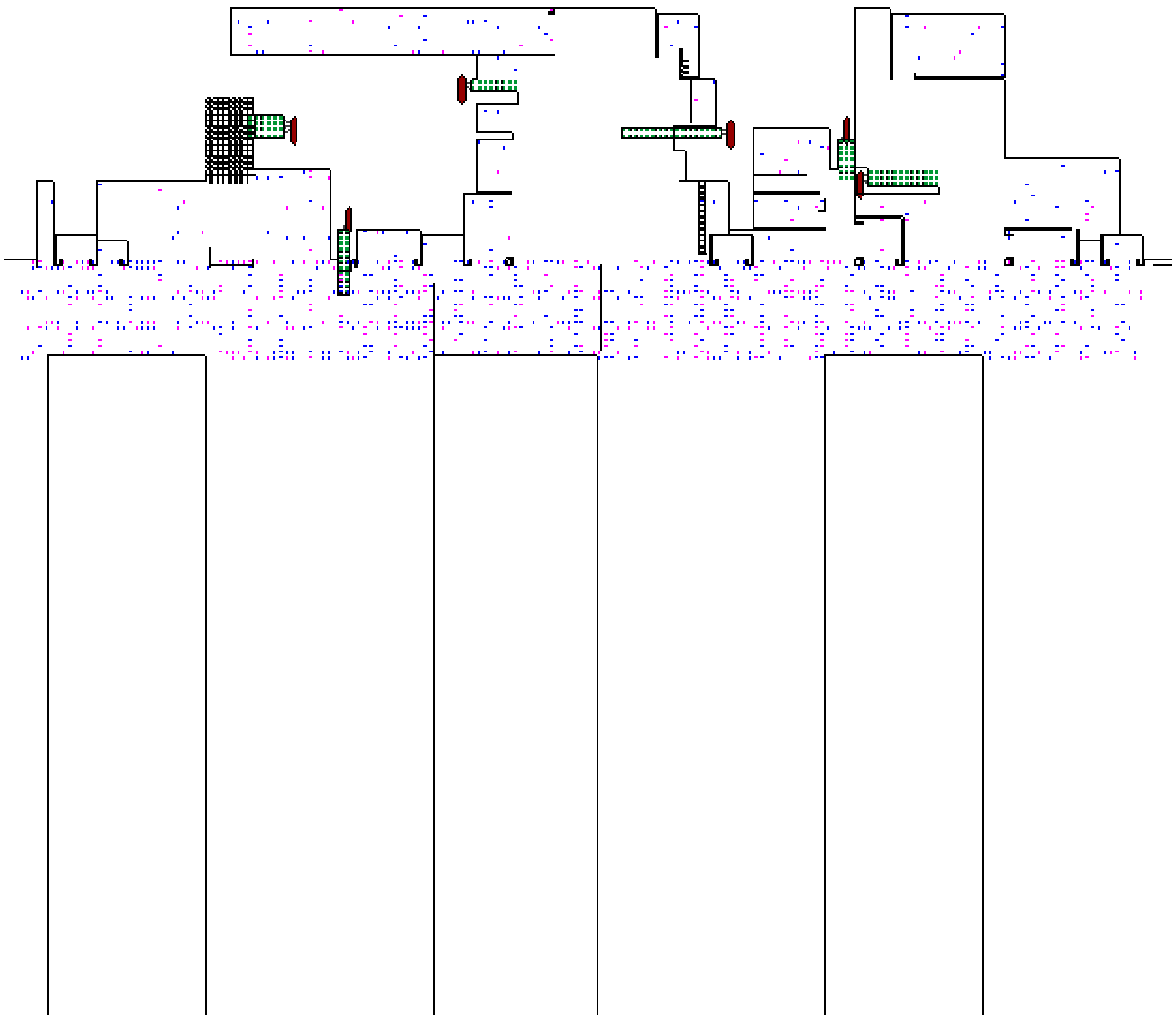


Figure 8.3: Zoning of each scenario in the departure level

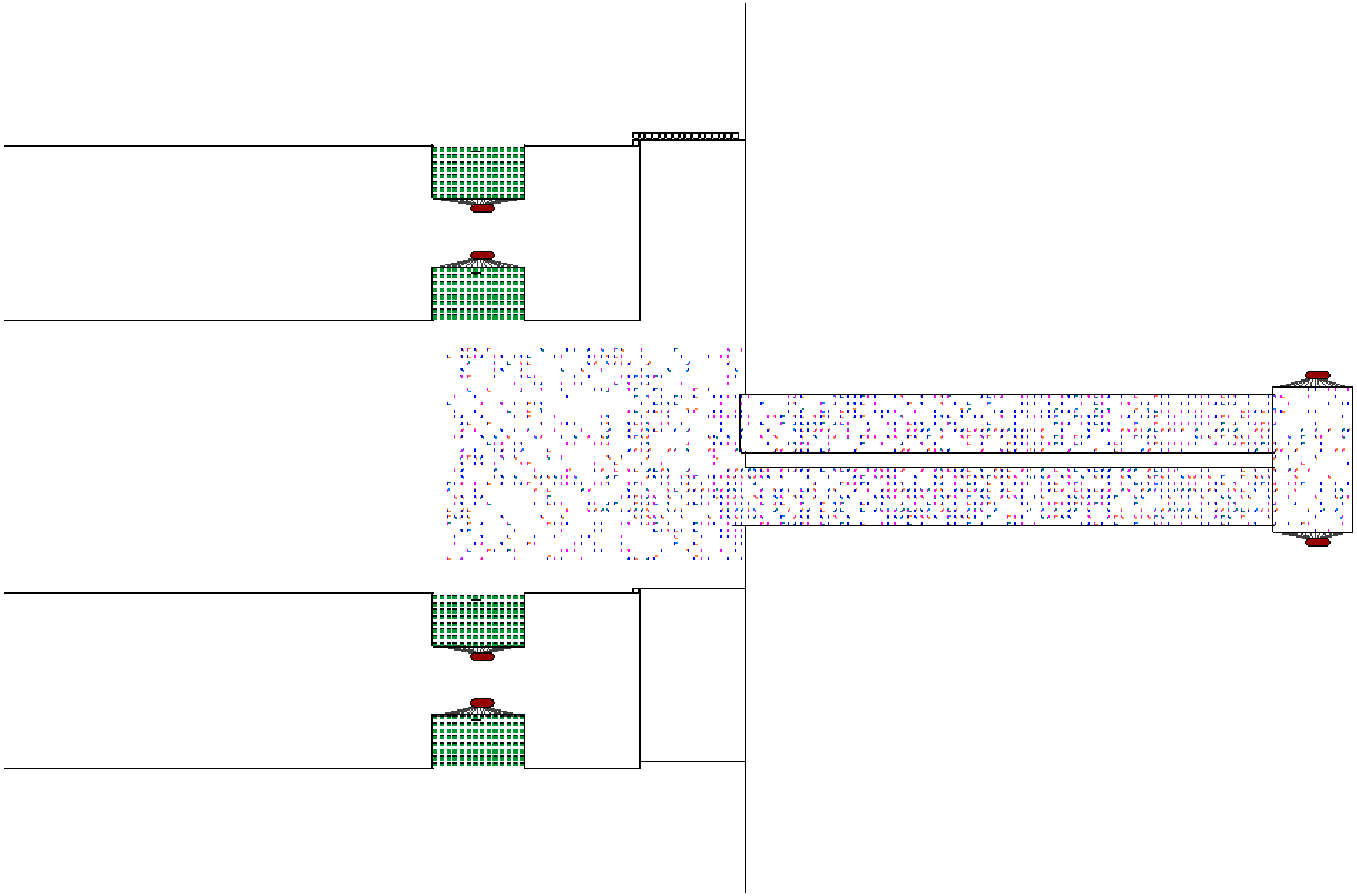
Sub-scenario 1a



Sub-scenario 2a



Sub-scenario 3b



Sub-scenario 4a

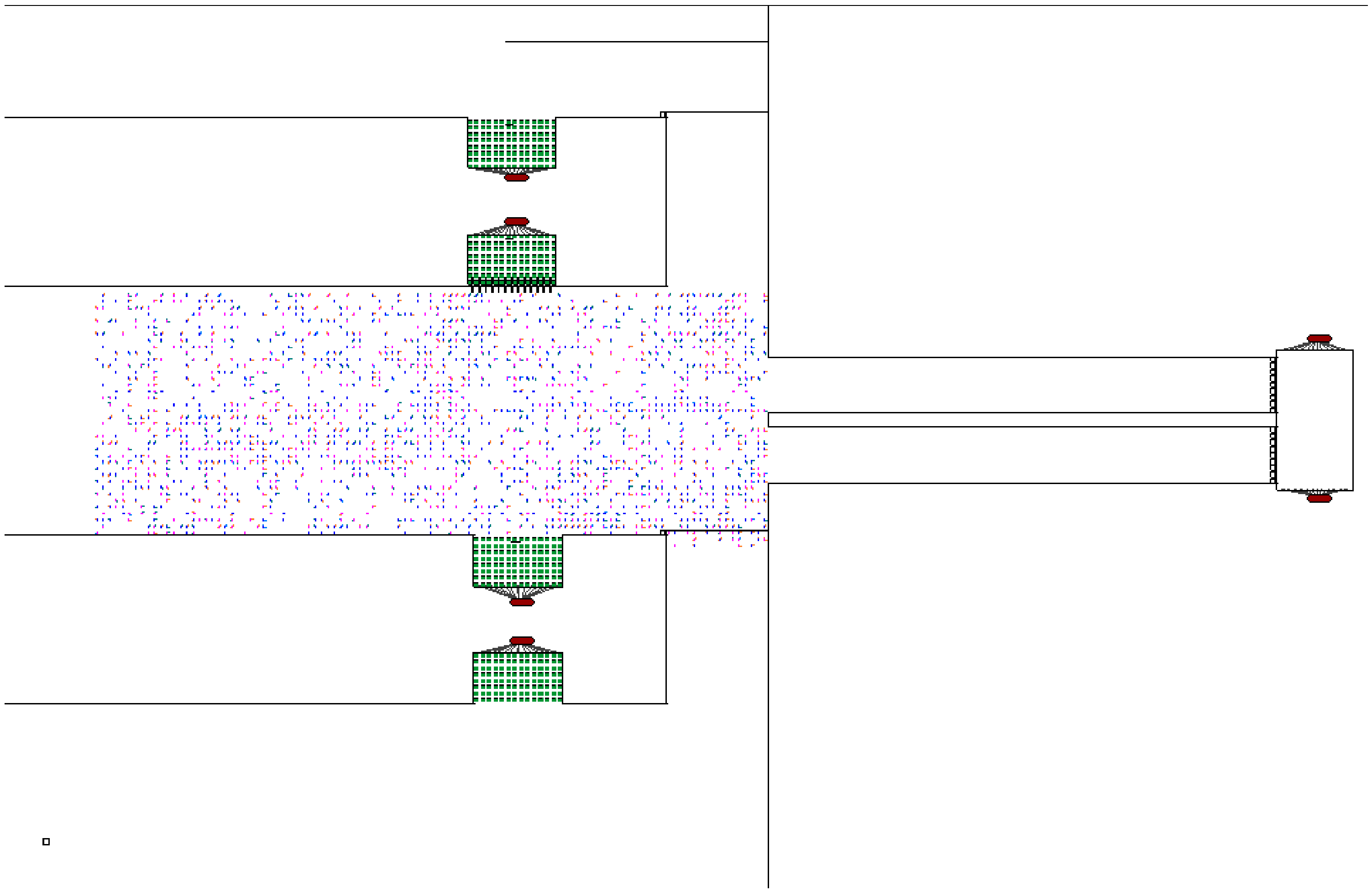


Figure 8.4: The initial locations of occupants in scenarios 1 – 4

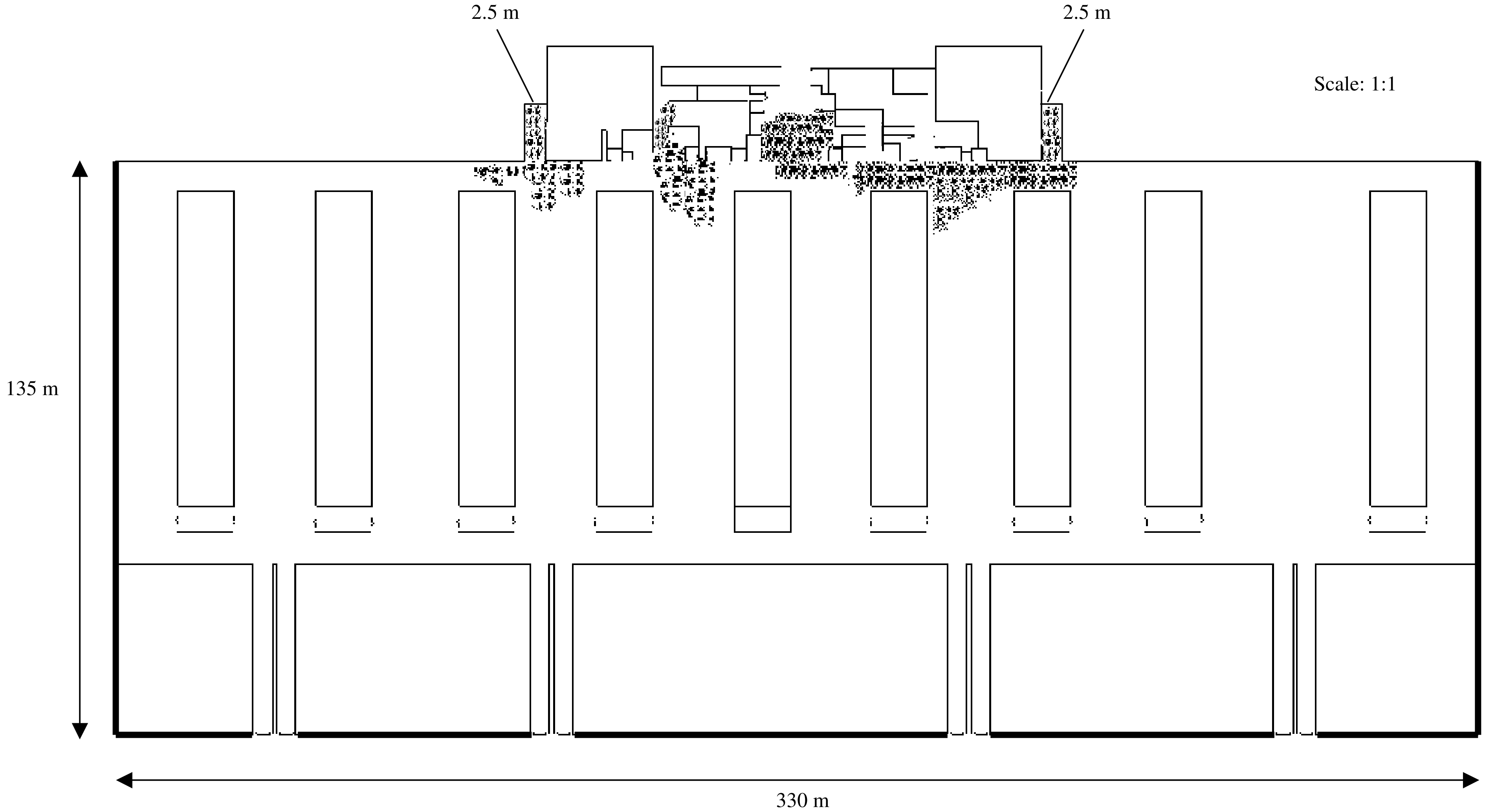


Figure 8.5: Evacuation pattern of sub-scenario 1a at time 40 s

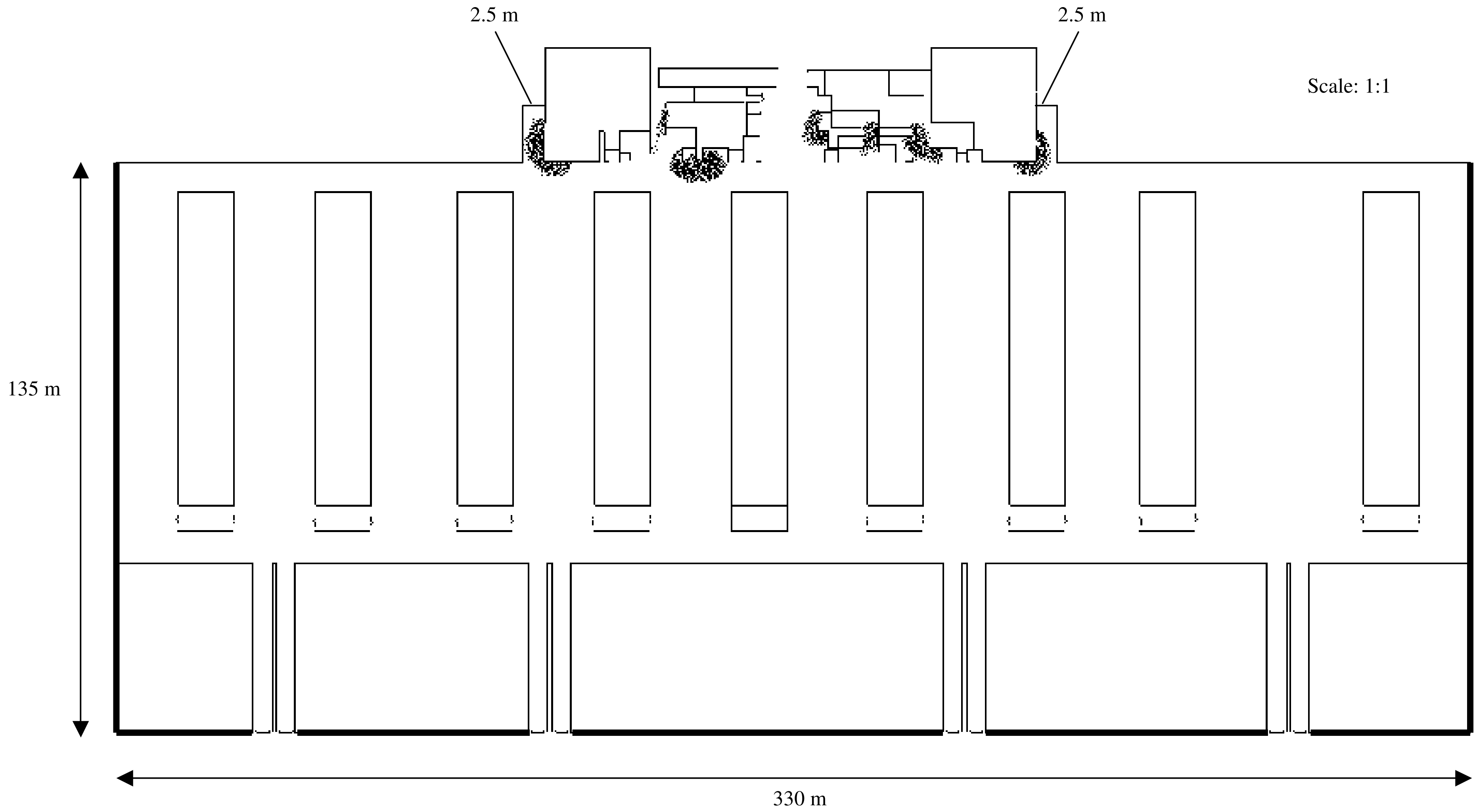


Figure 8.6: Evacuation pattern of sub-scenario 1b at time 40 s

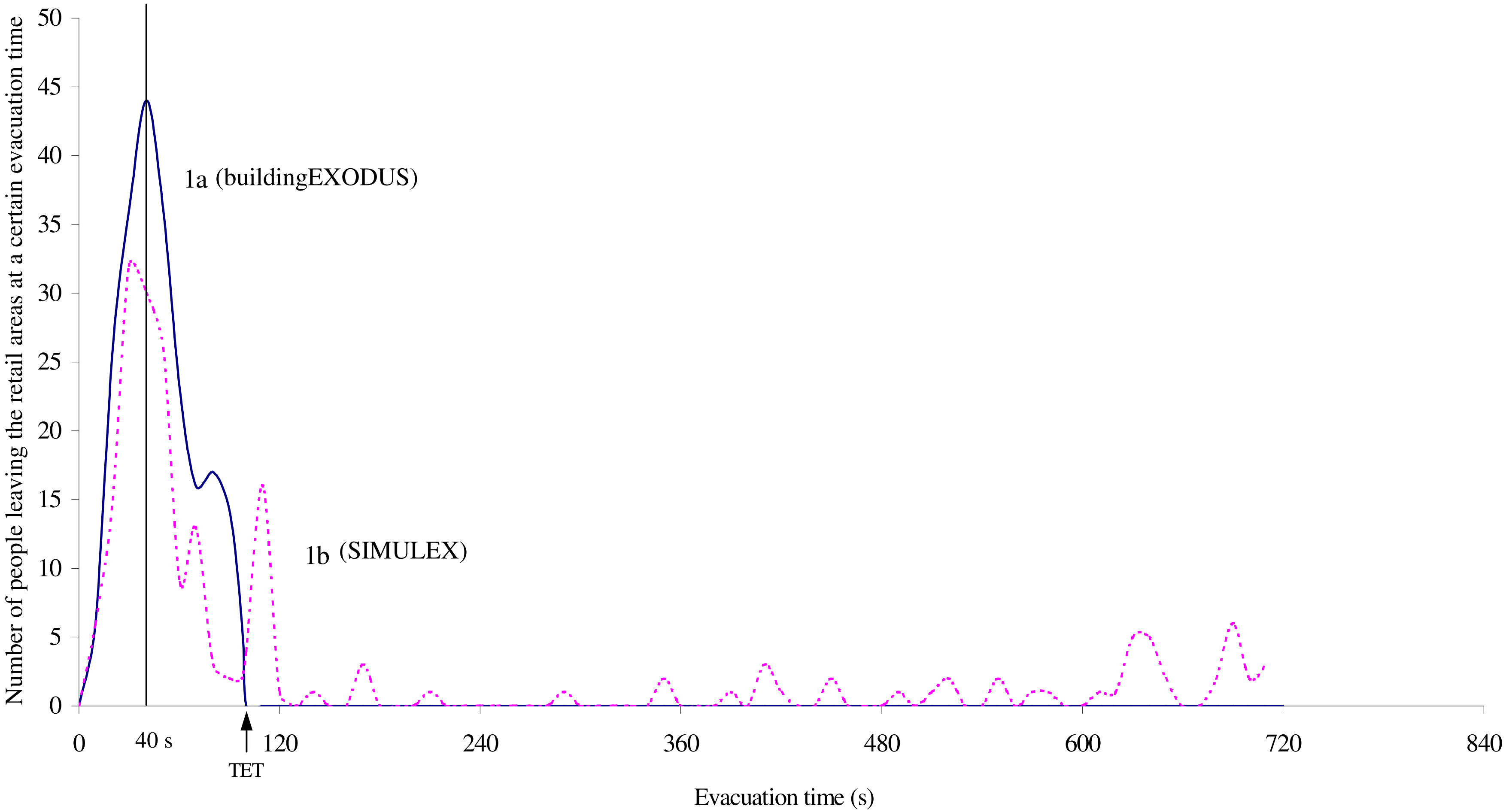


Figure 8.7: The comparisons of the evacuation times in scenario 1

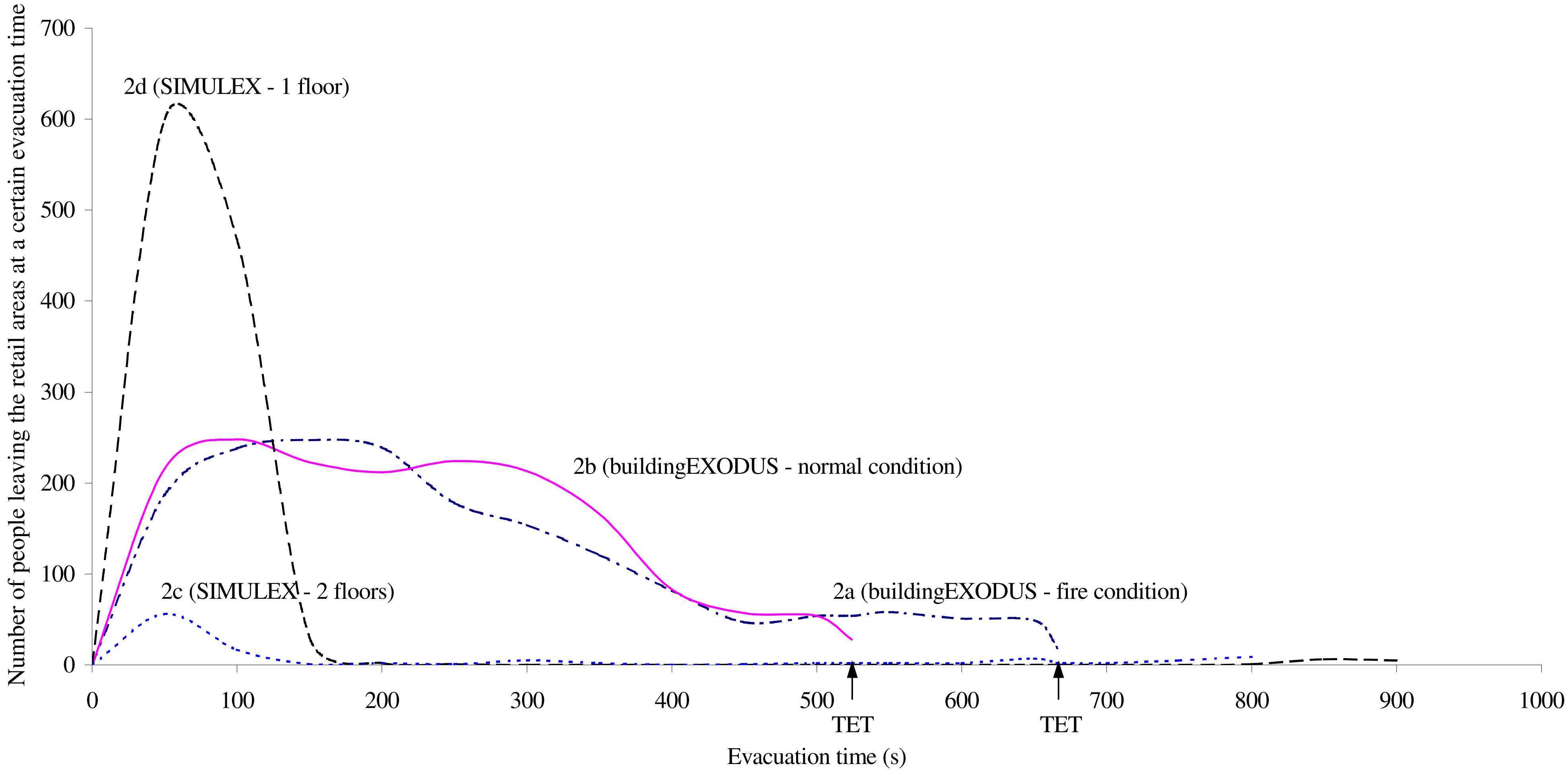


Figure 8.8: The comparisons of the evacuation times in scenarios 2

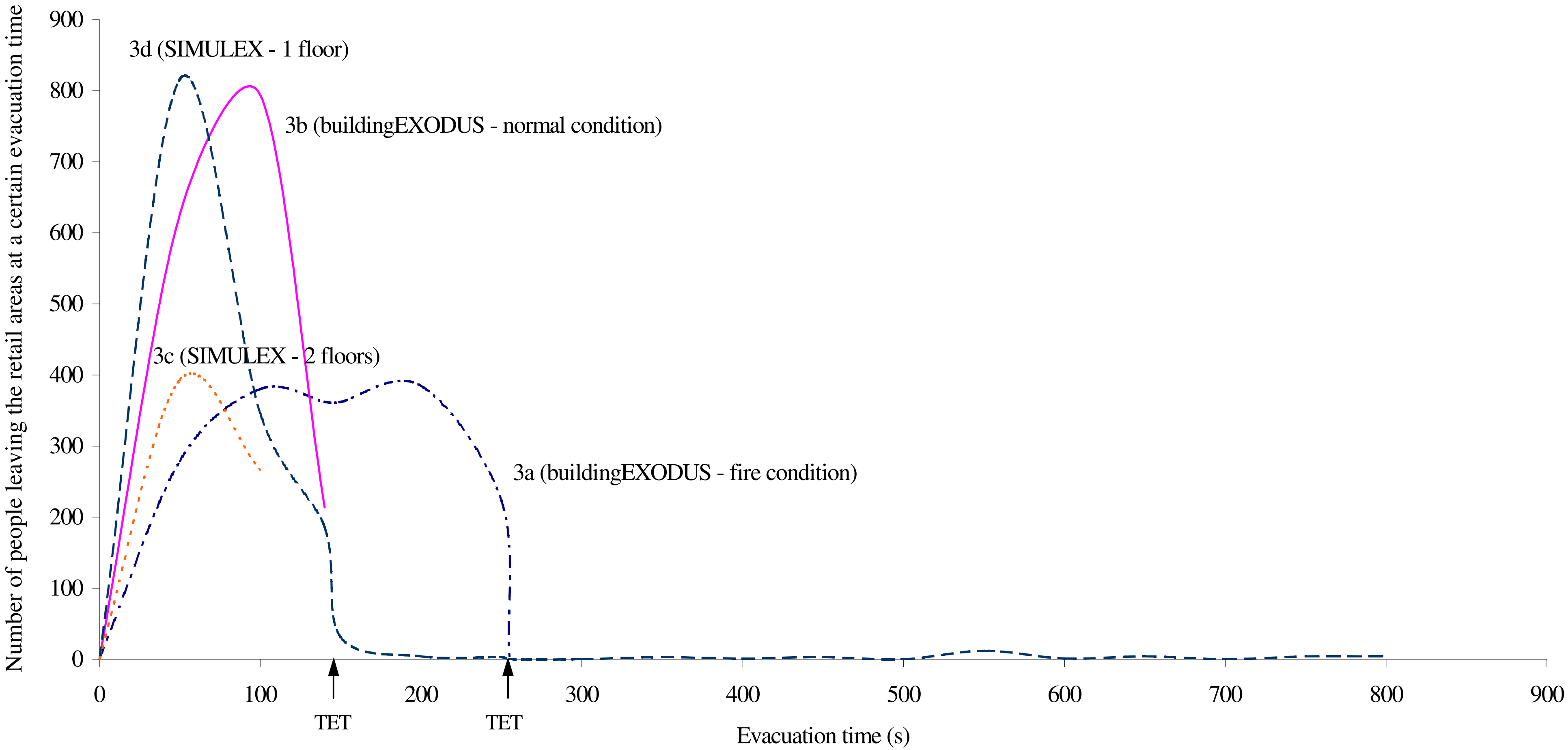


Figure 8.9: The comparisons of the evacuation times in scenarios 3

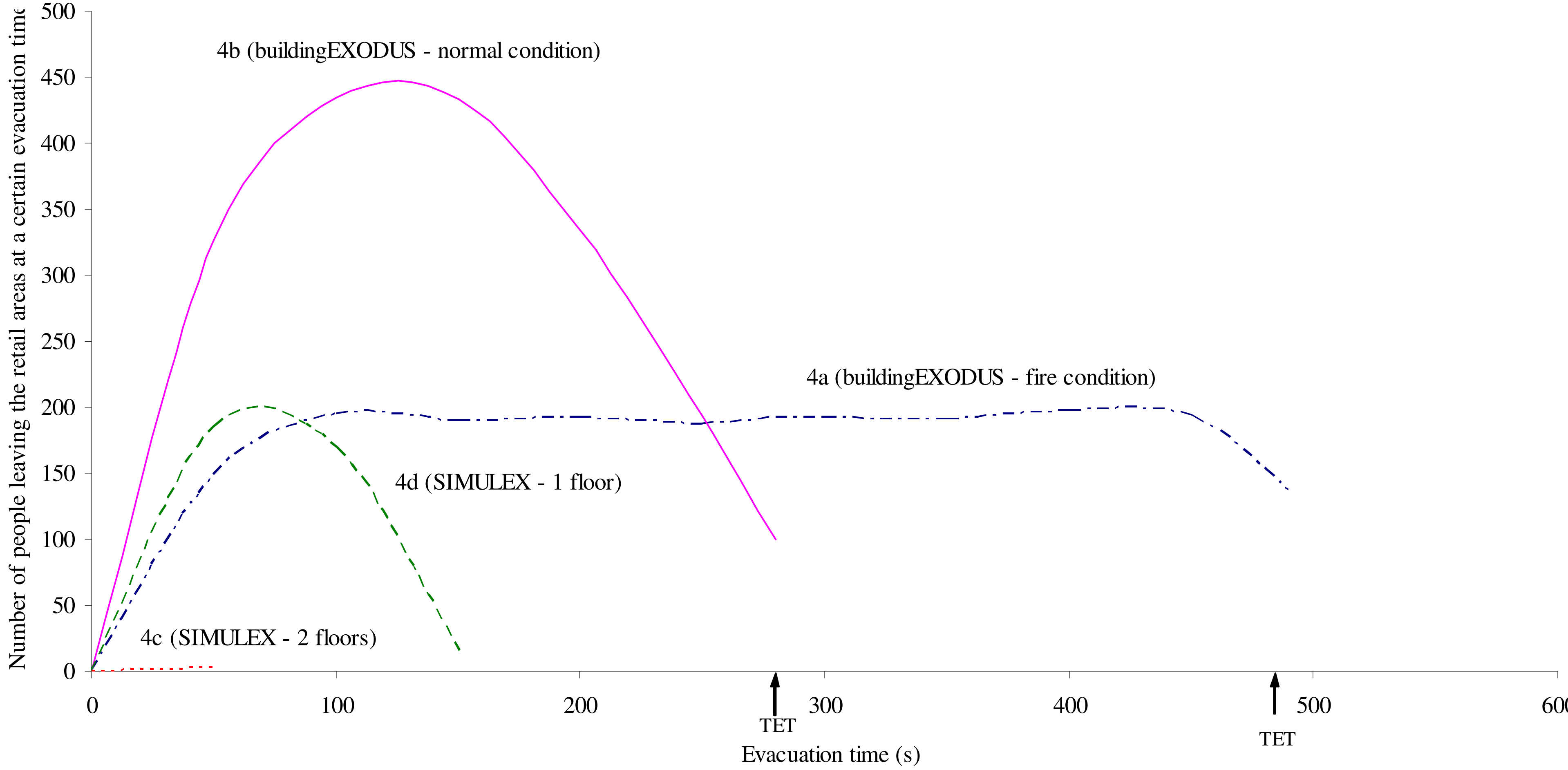


Figure 8.10: The comparisons of the evacuation times in scenarios 4

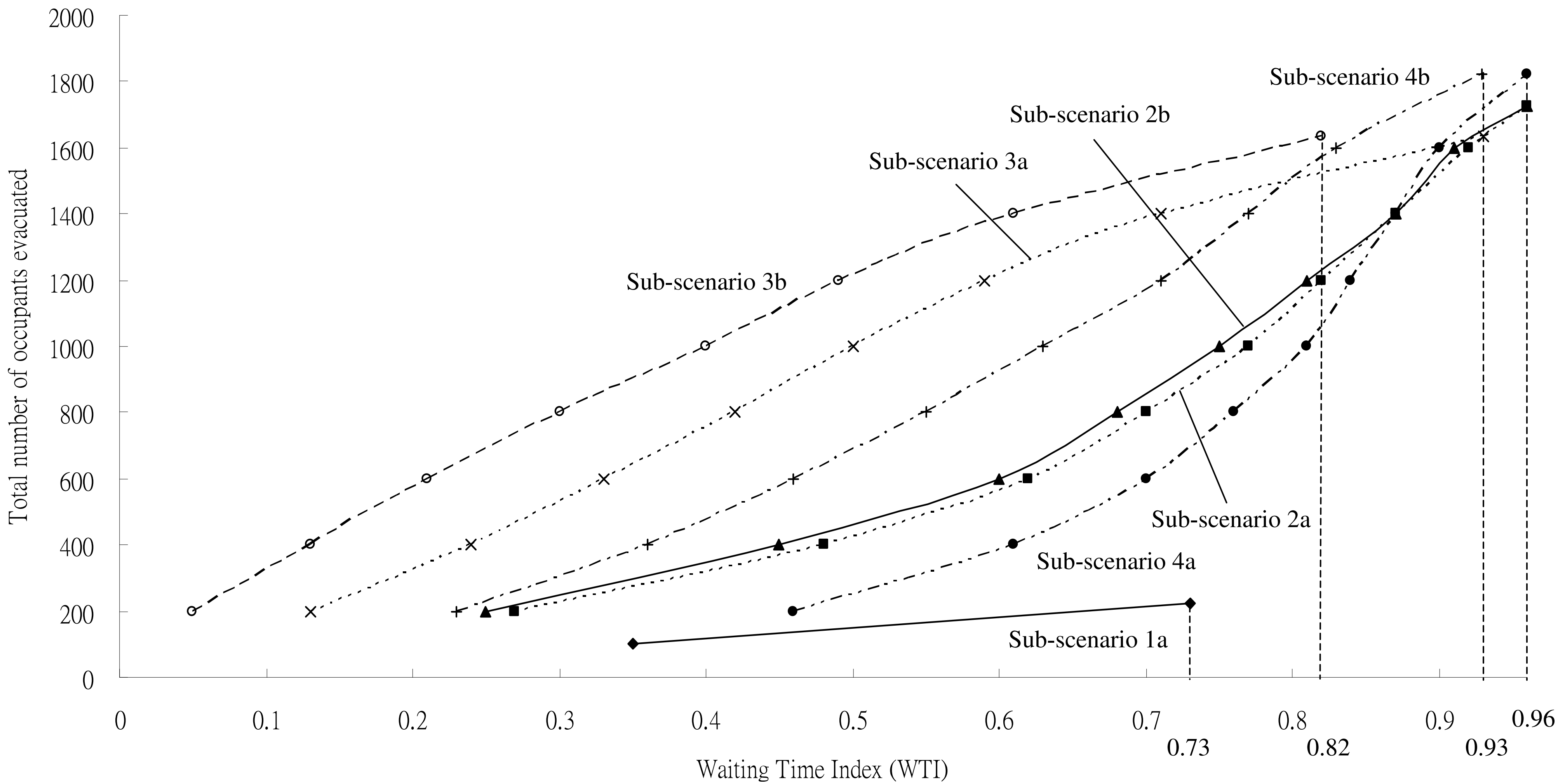
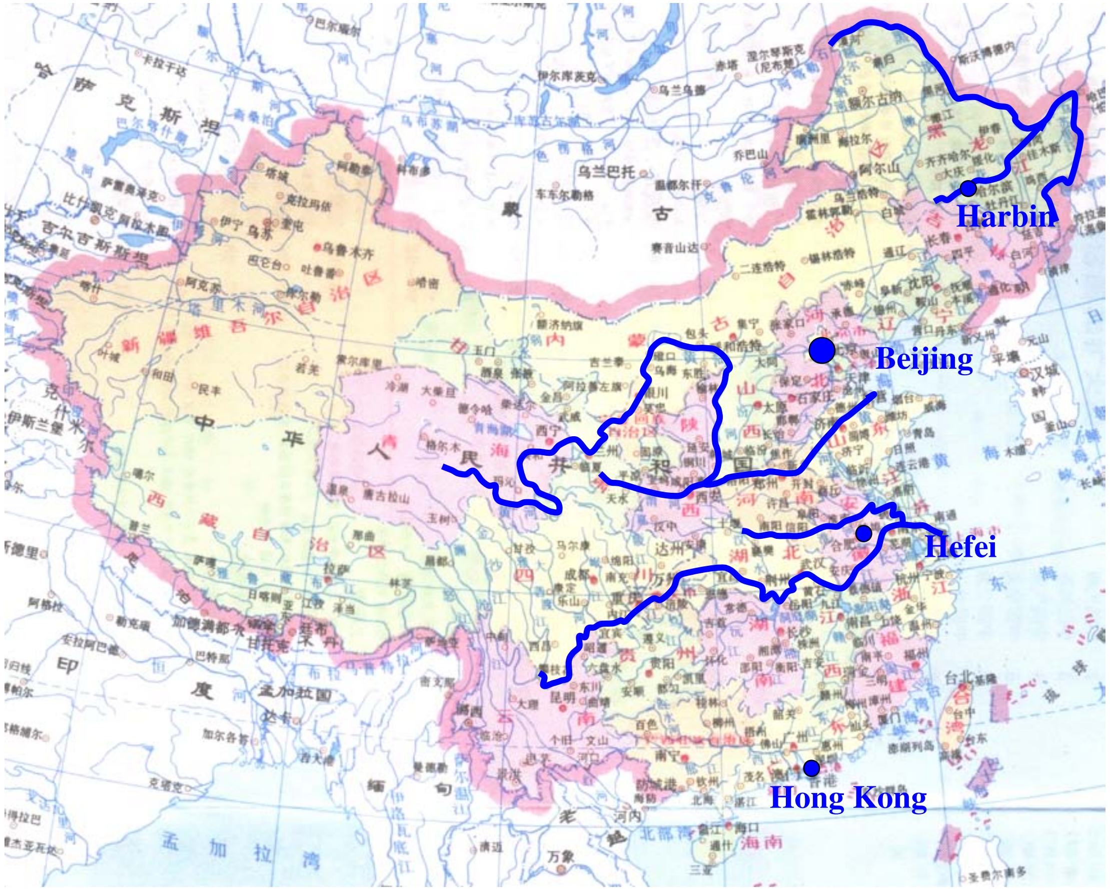
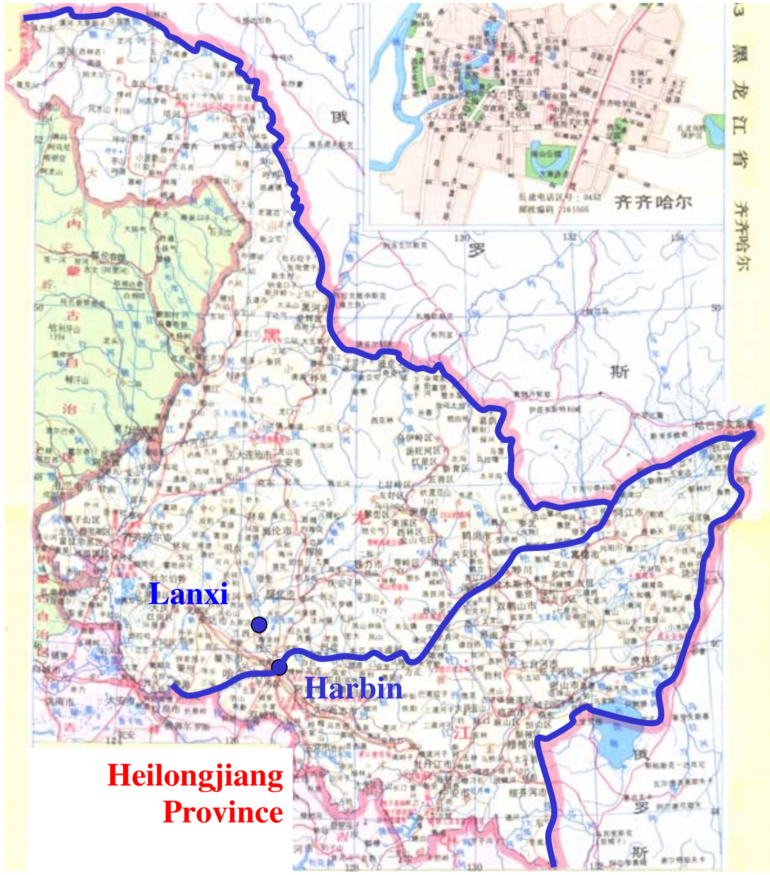


Figure 8.11: Variation of WTI with the number of occupants



(a) Harbin



(b) Lanxi

Figure 9.1: Location of the laboratory

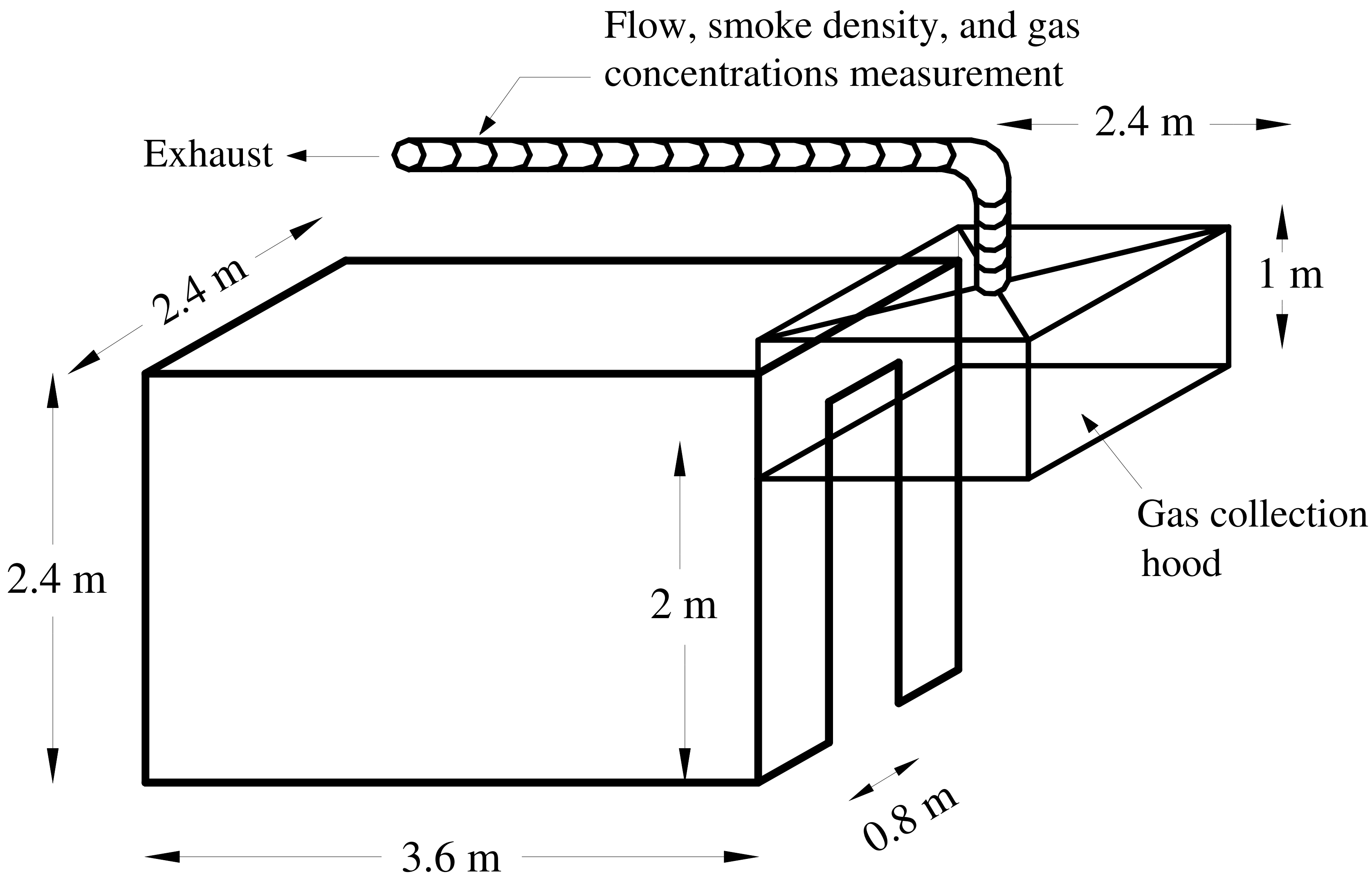


Figure 9.2: The room for full-scale burning tests

Figure 9.3: External view of the experimental hall

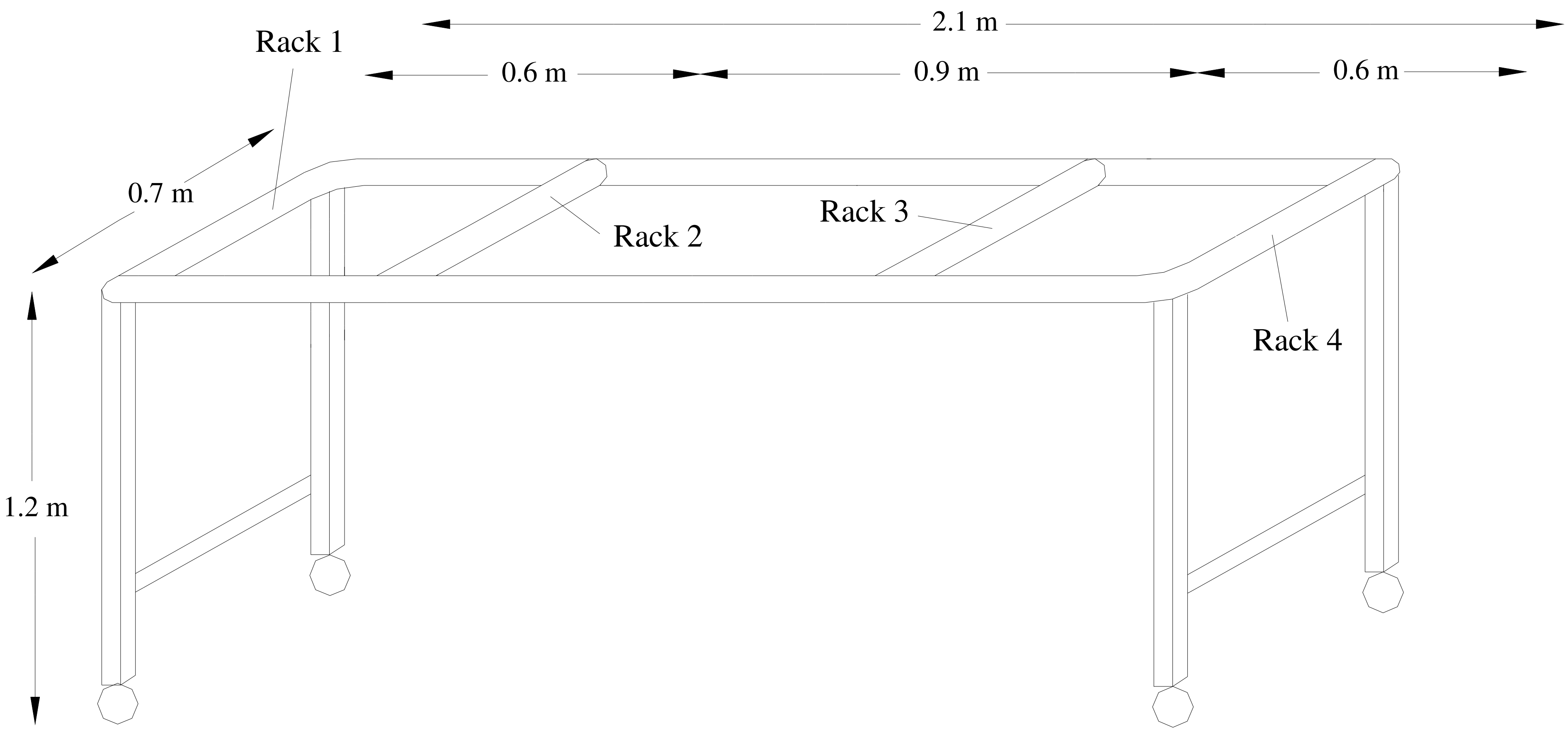
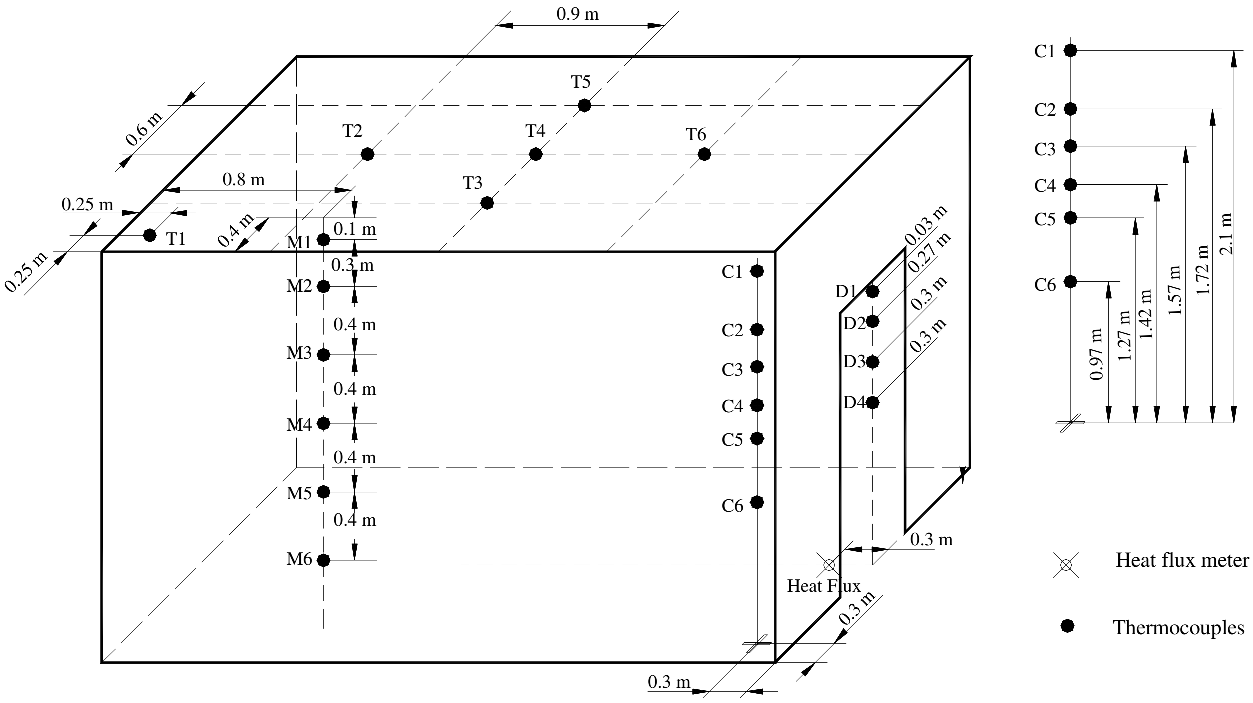
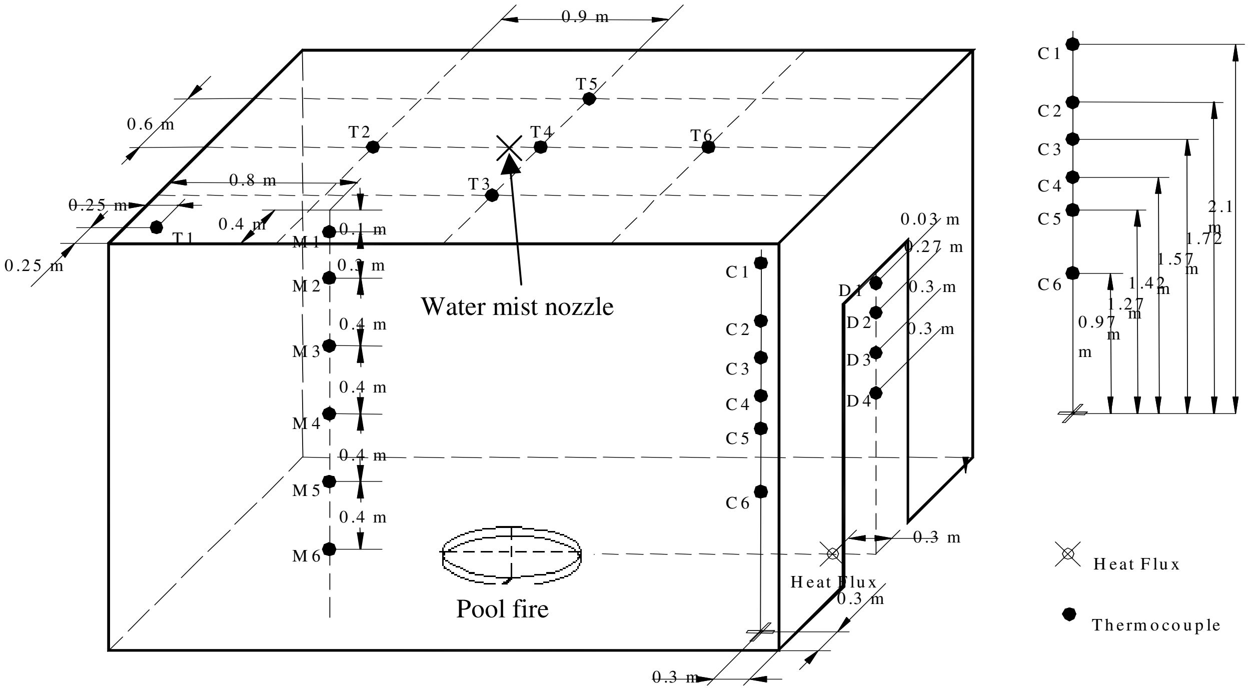


Figure 9.4: Iron clothes hanger

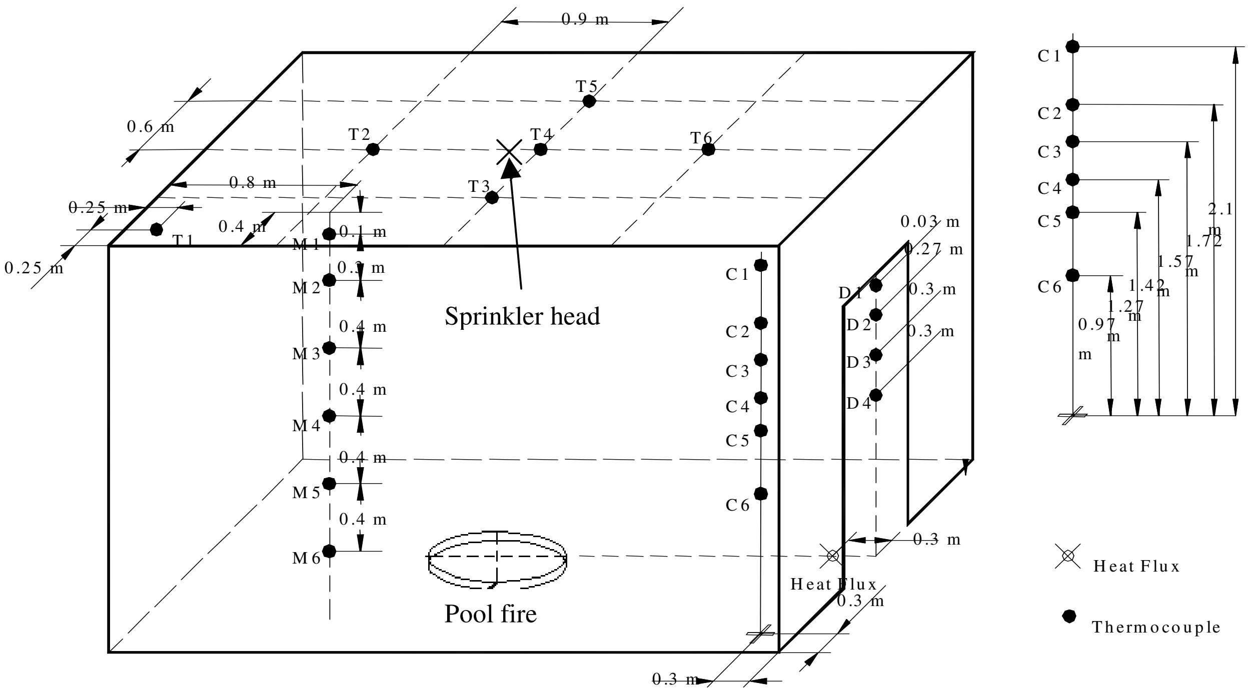
(a) Clothes arrangement



(b) Thermocouple trees



(c) The experiment setup with the WMFSS for Test B3



(d) The experiment setup with the sprinkler system for Test B4

Figure 9.5: Layout of tests B1 to B4

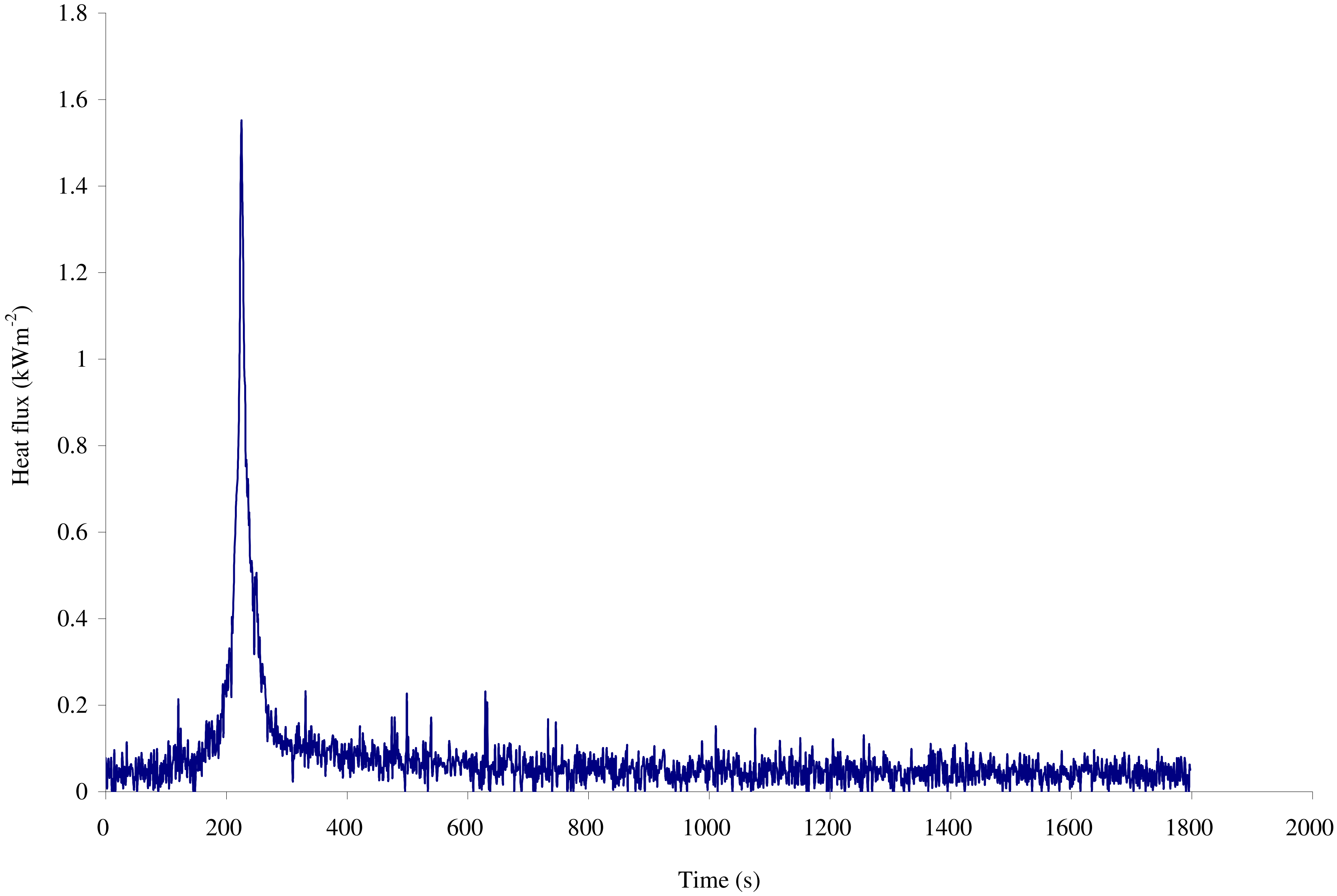


Figure 9.6a: Result of heat flux in test B1

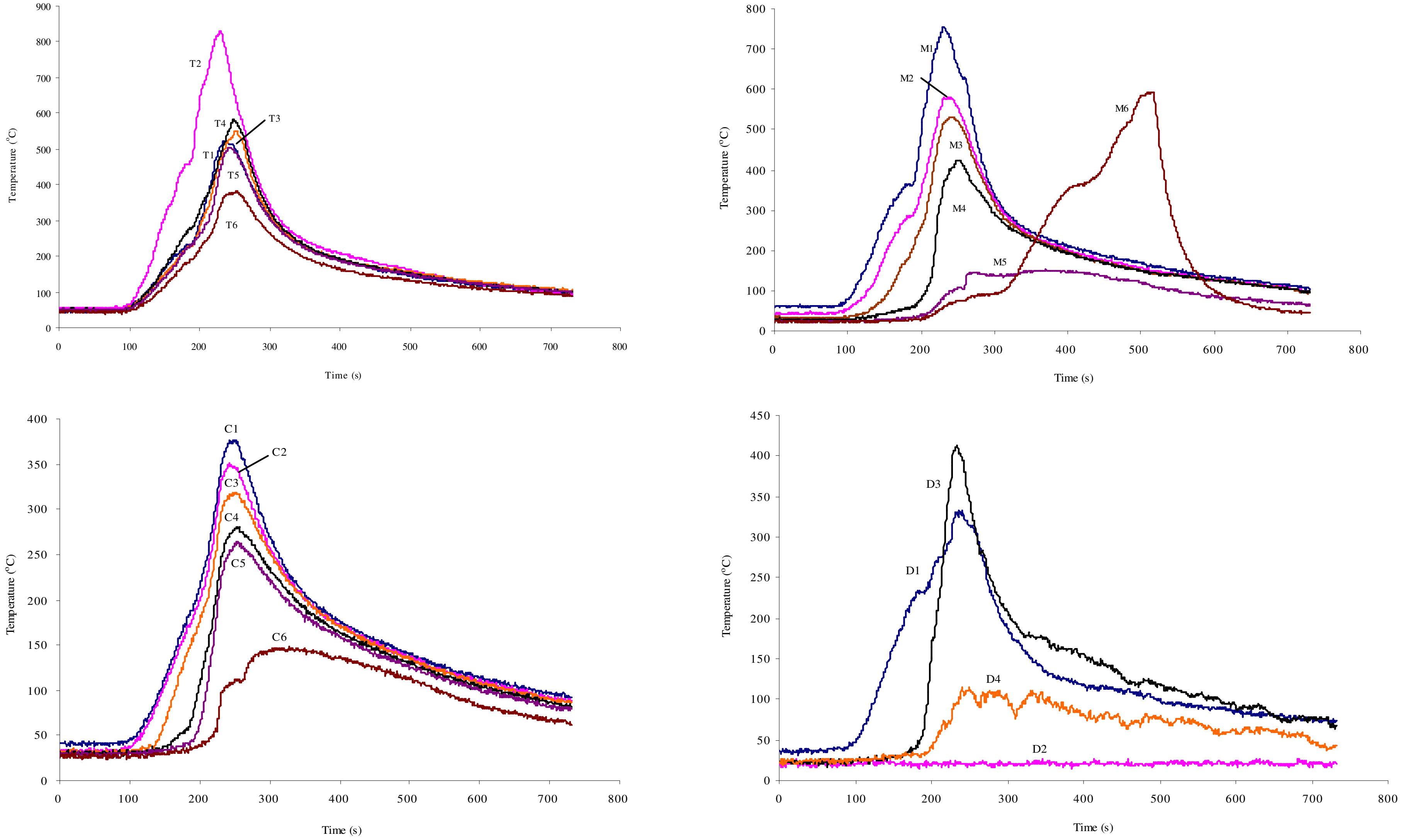


Figure 9.6b: Result of room temperature in test B1

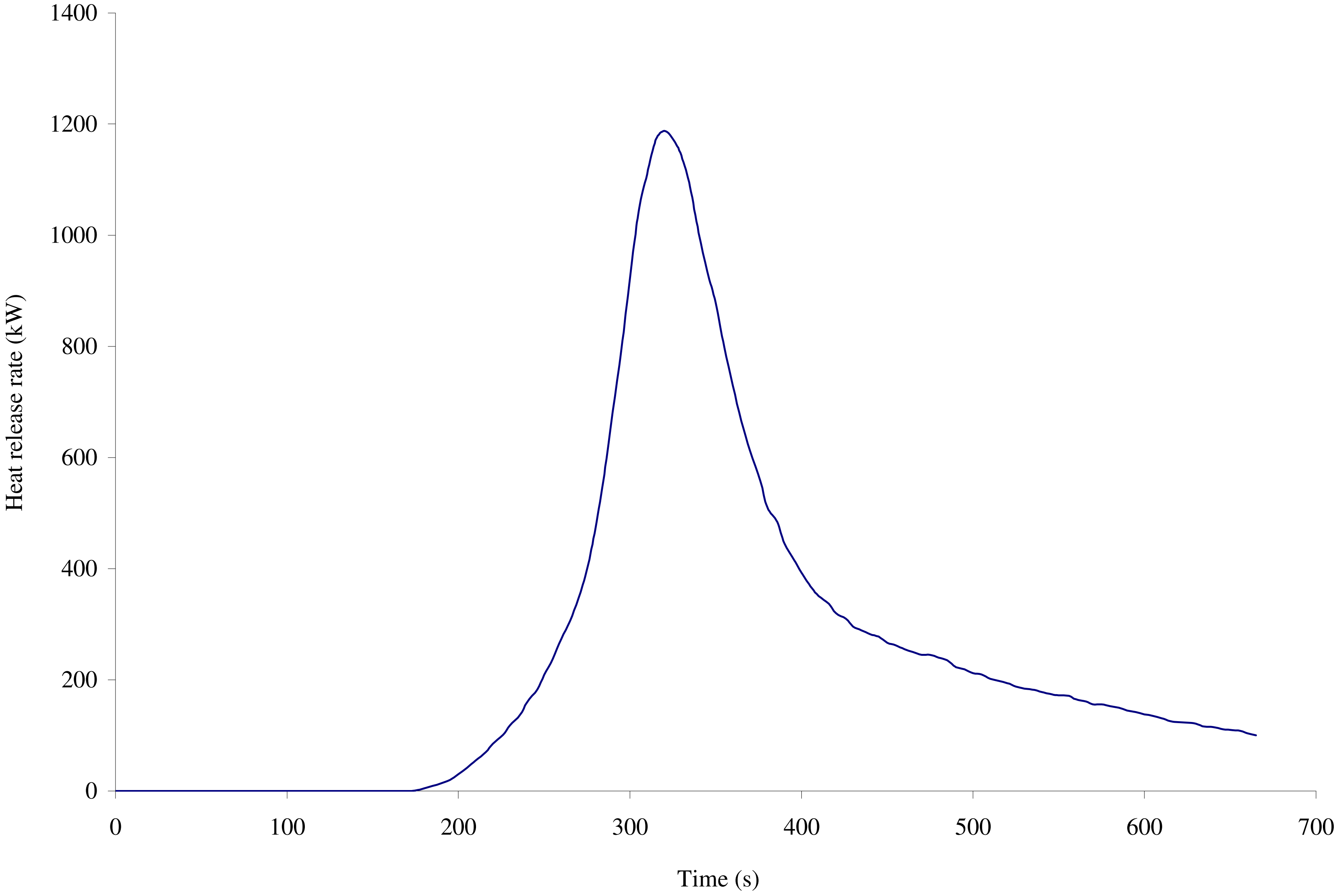


Figure 9.6c: Result of HRR in test B1

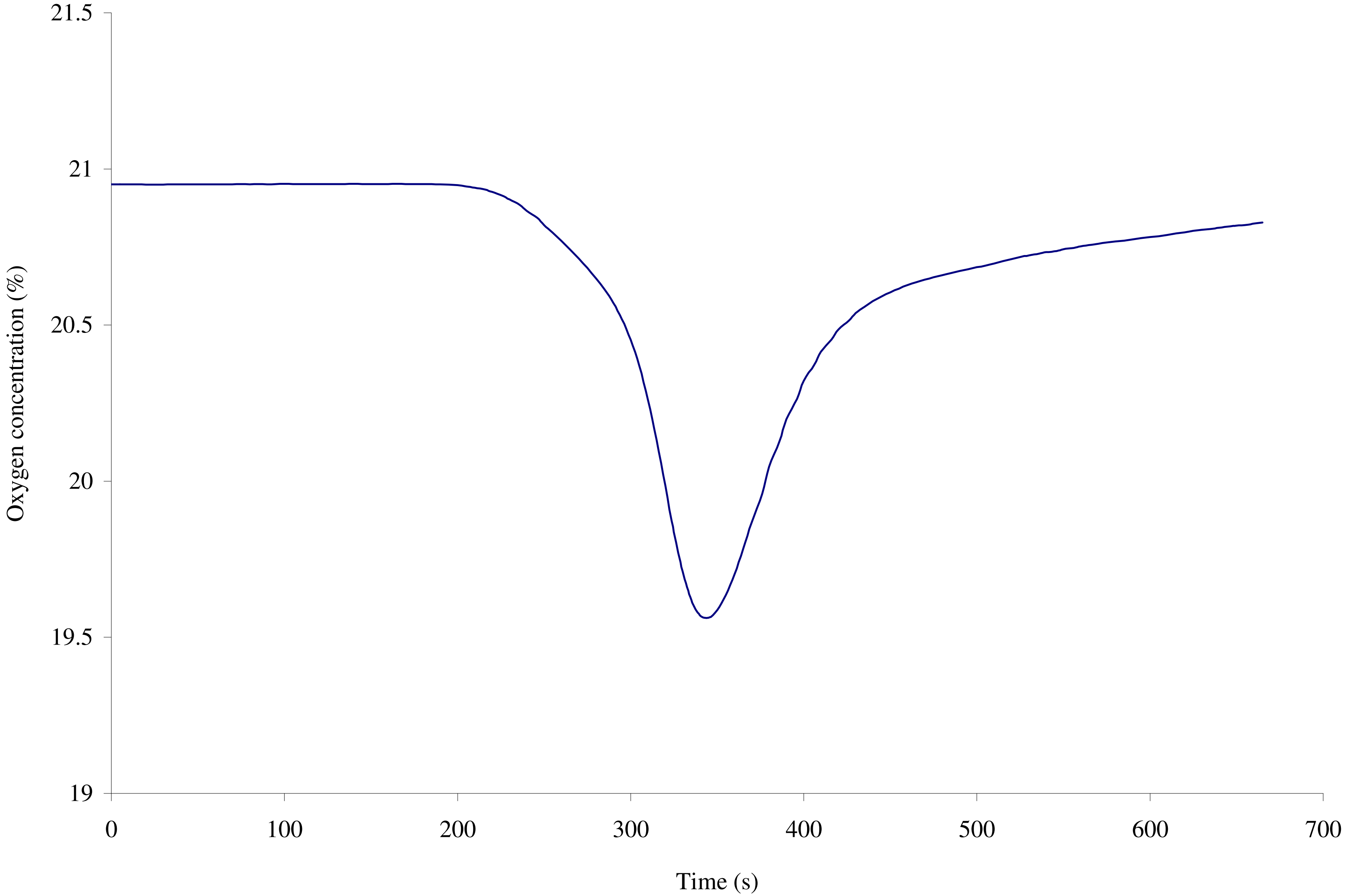


Figure 9.6d: Result of oxygen level in test B1

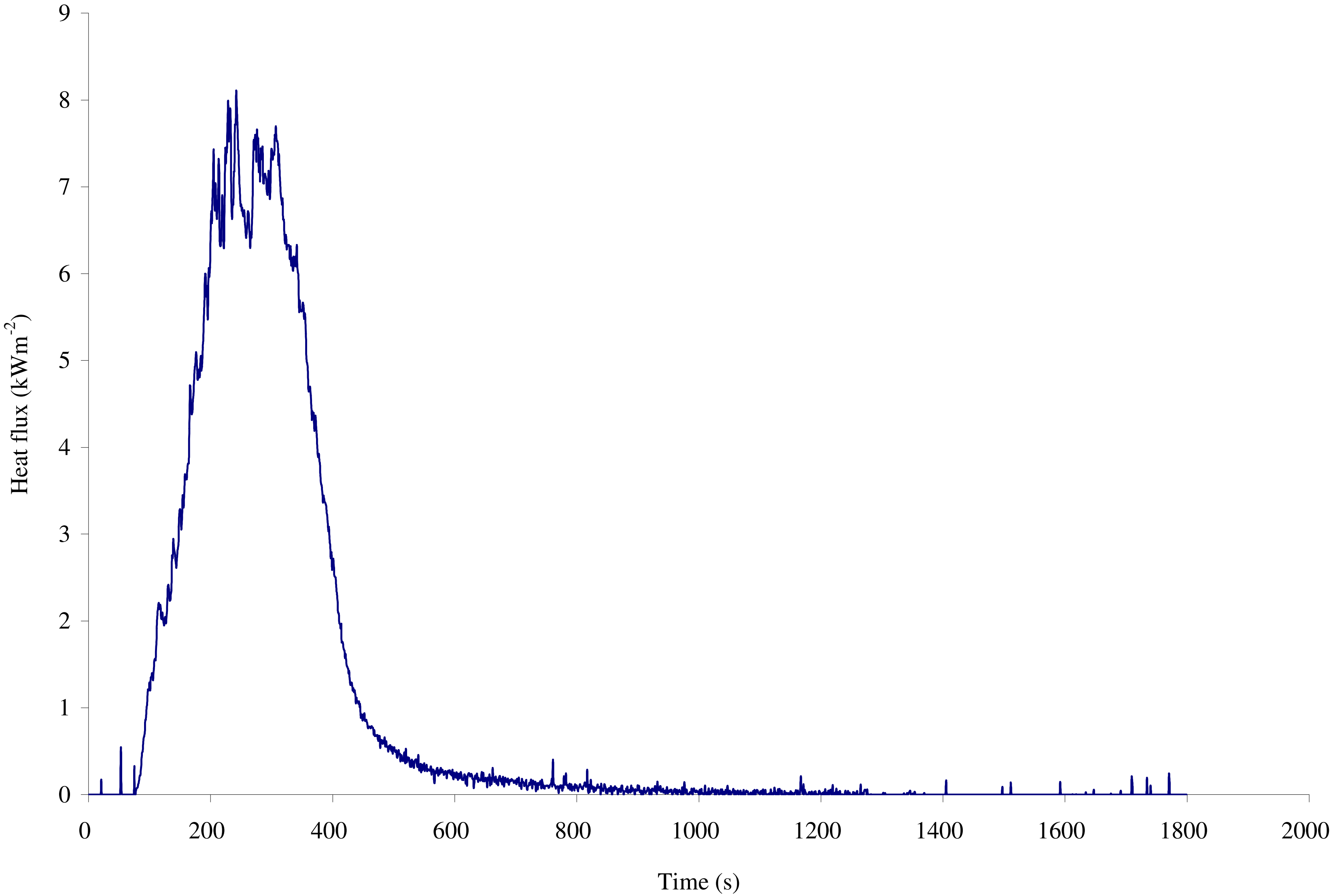


Figure 9.7a: Result of heat flux in test B2

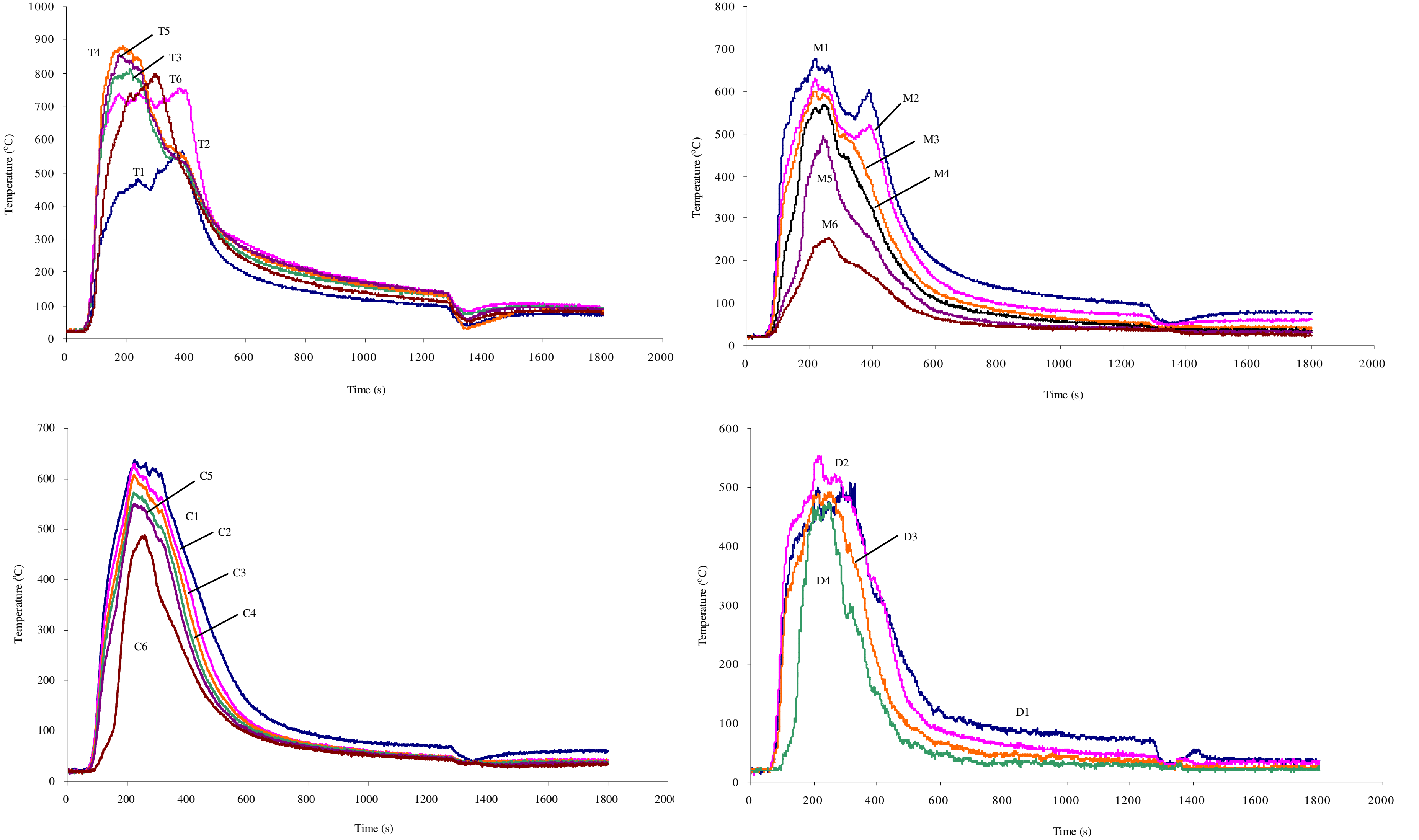


Figure 9.7b: Result of room temperature in test B2

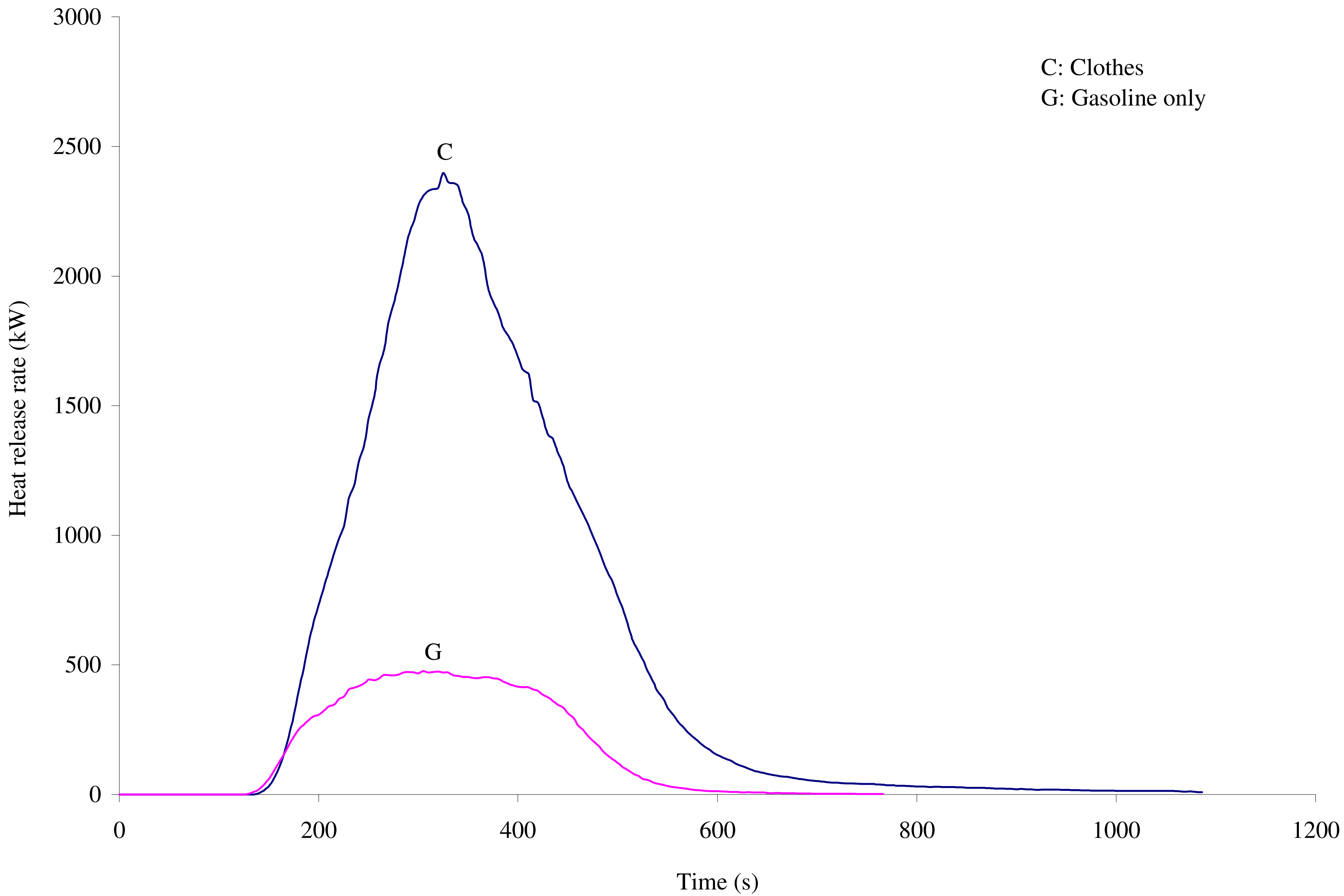


Figure 9.7c: Result of HRR in test B2

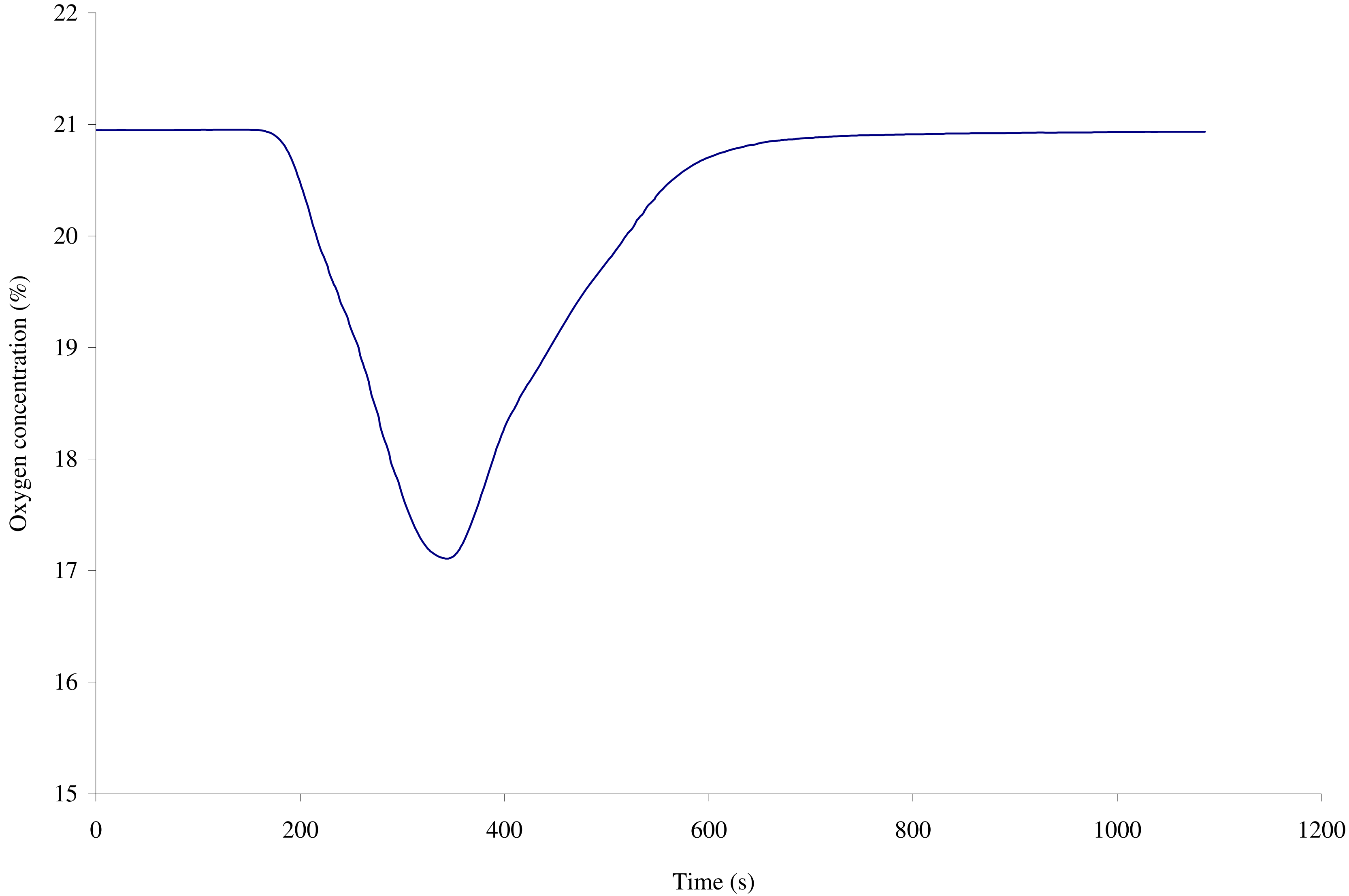


Figure 9.7d: Result of oxygen level in test B2

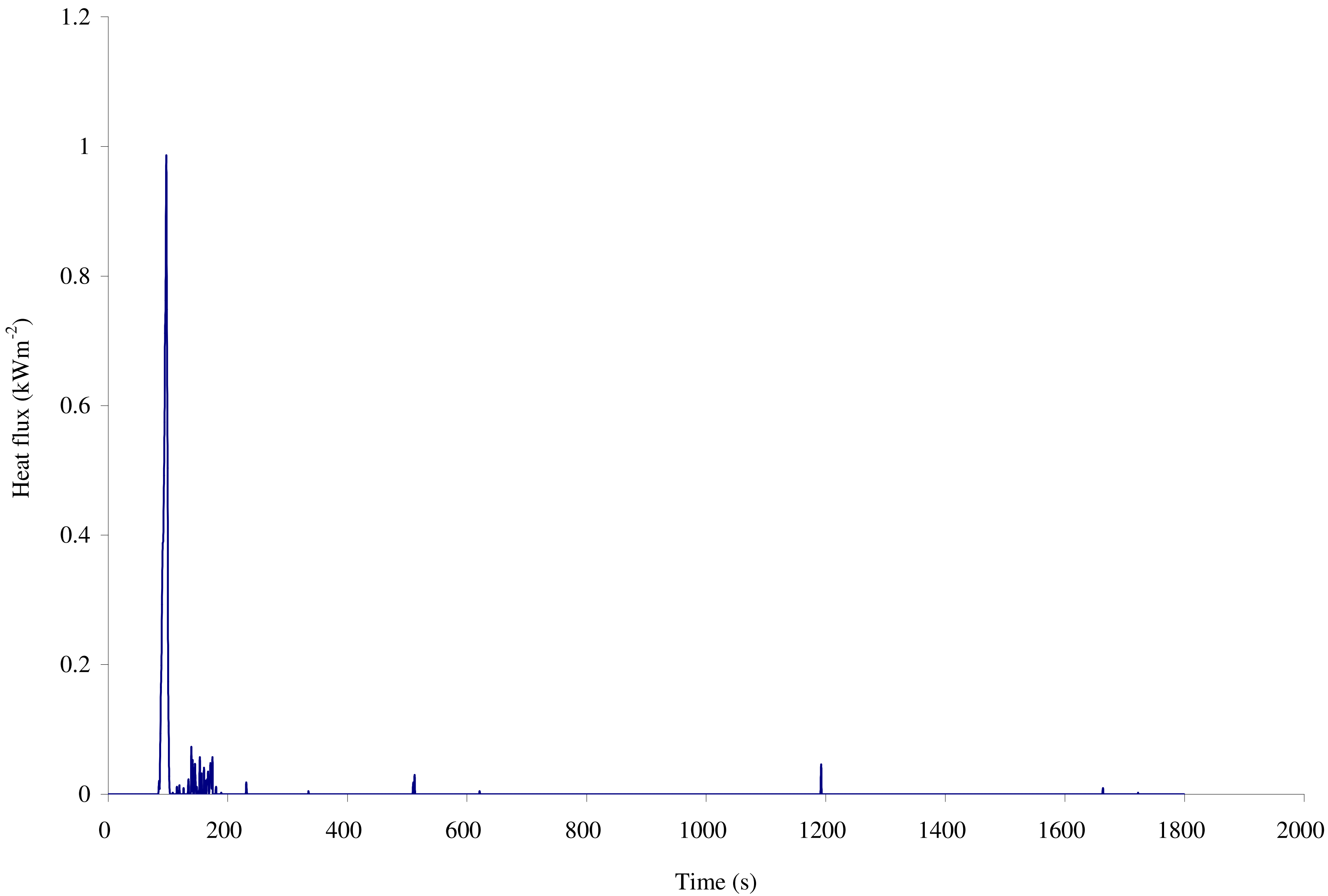


Figure 9.8a: Result of heat flux in test B3

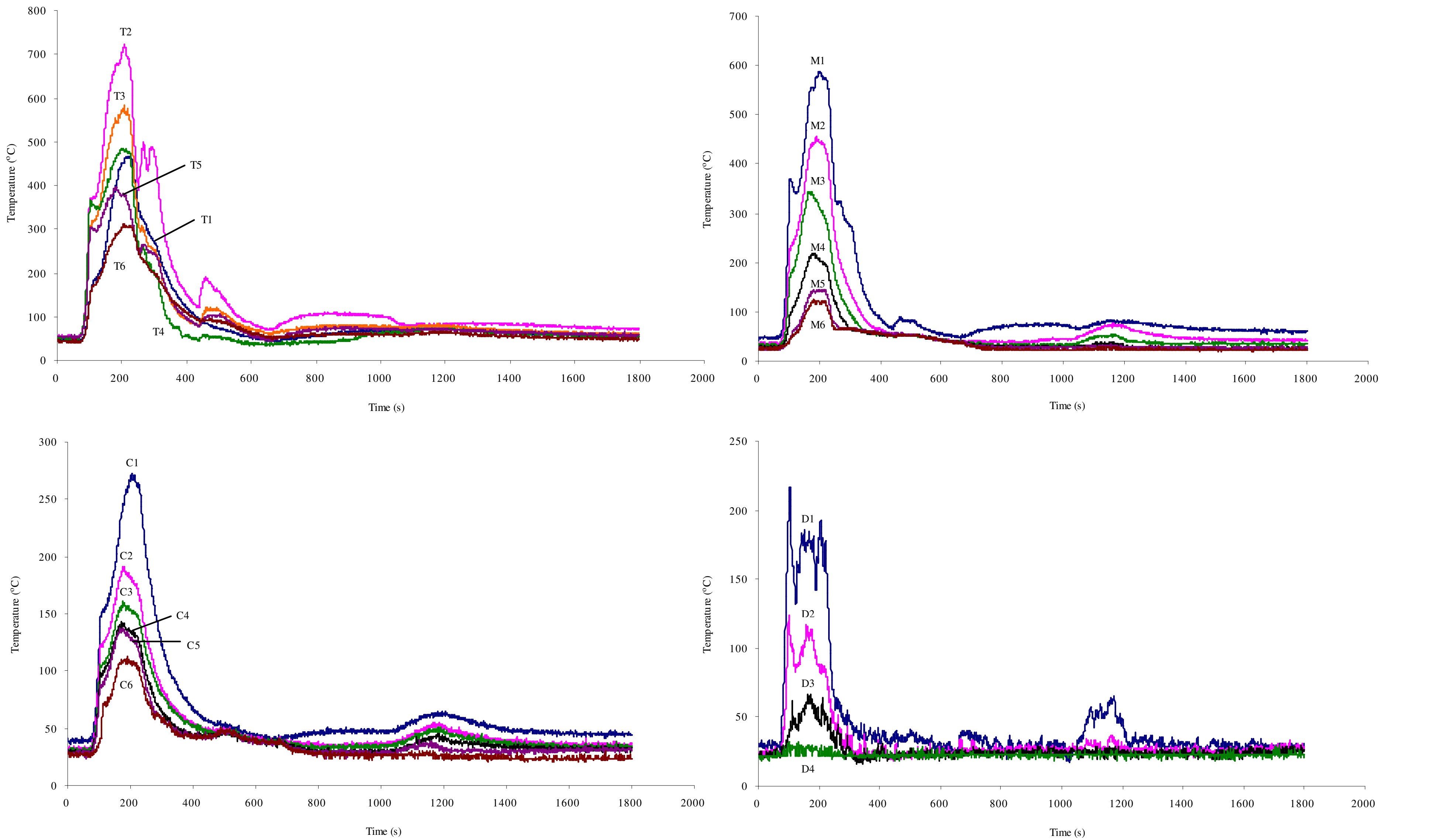


Figure 9.8b: Result of room temperature in test B3

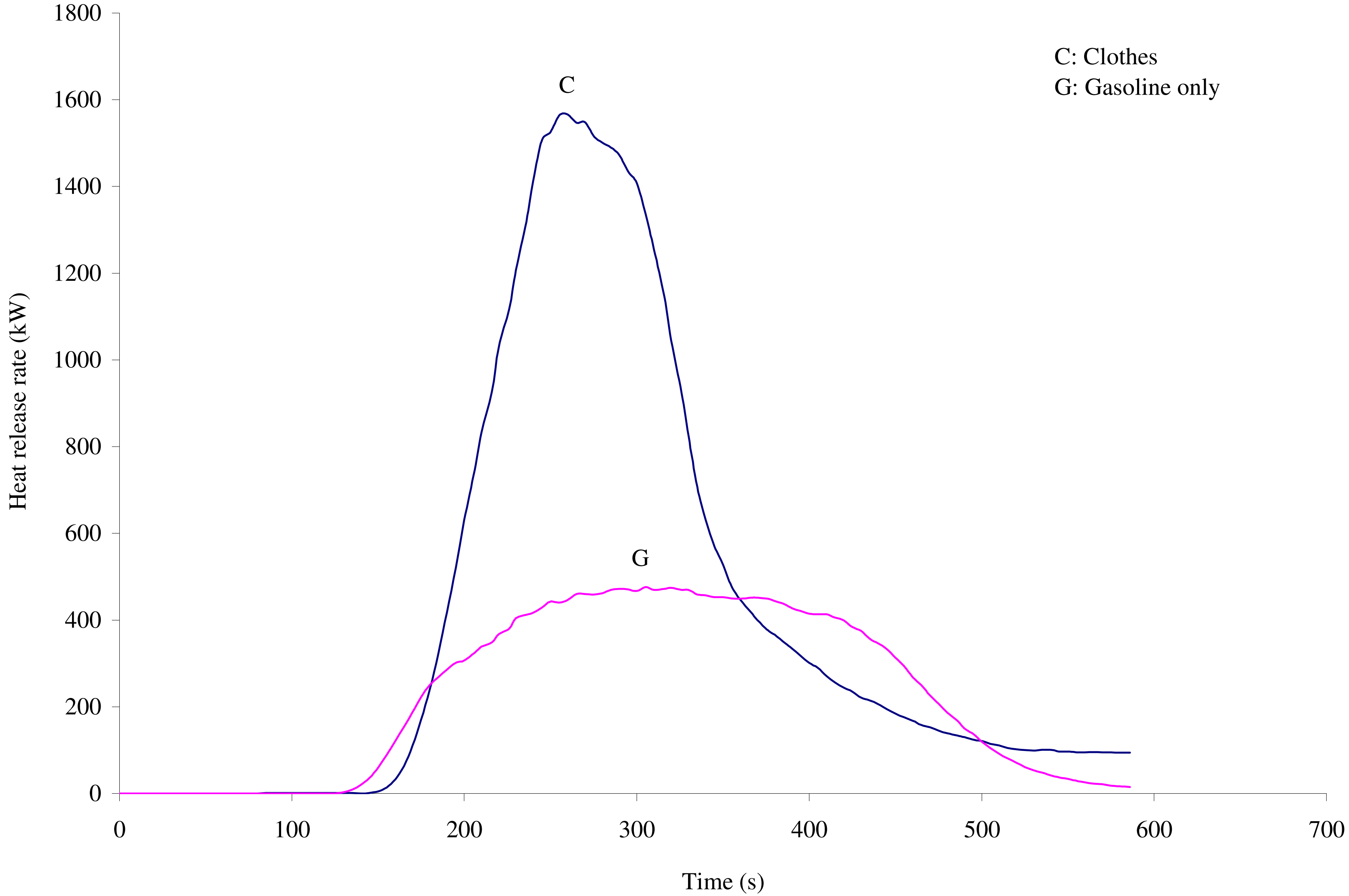


Figure 9.8c: Result of HRR in test B3

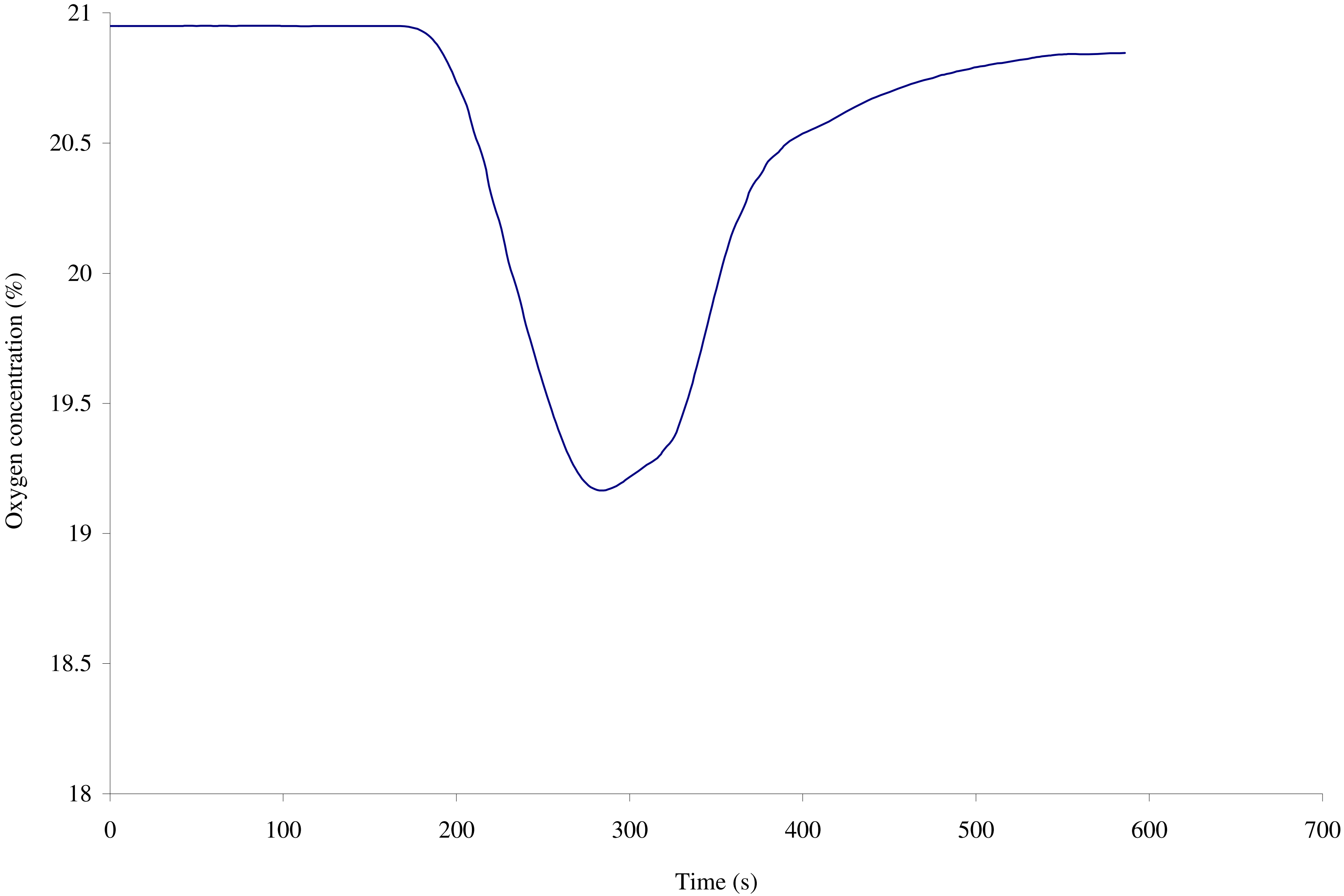


Figure 9.8d: Result of oxygen level in test B3

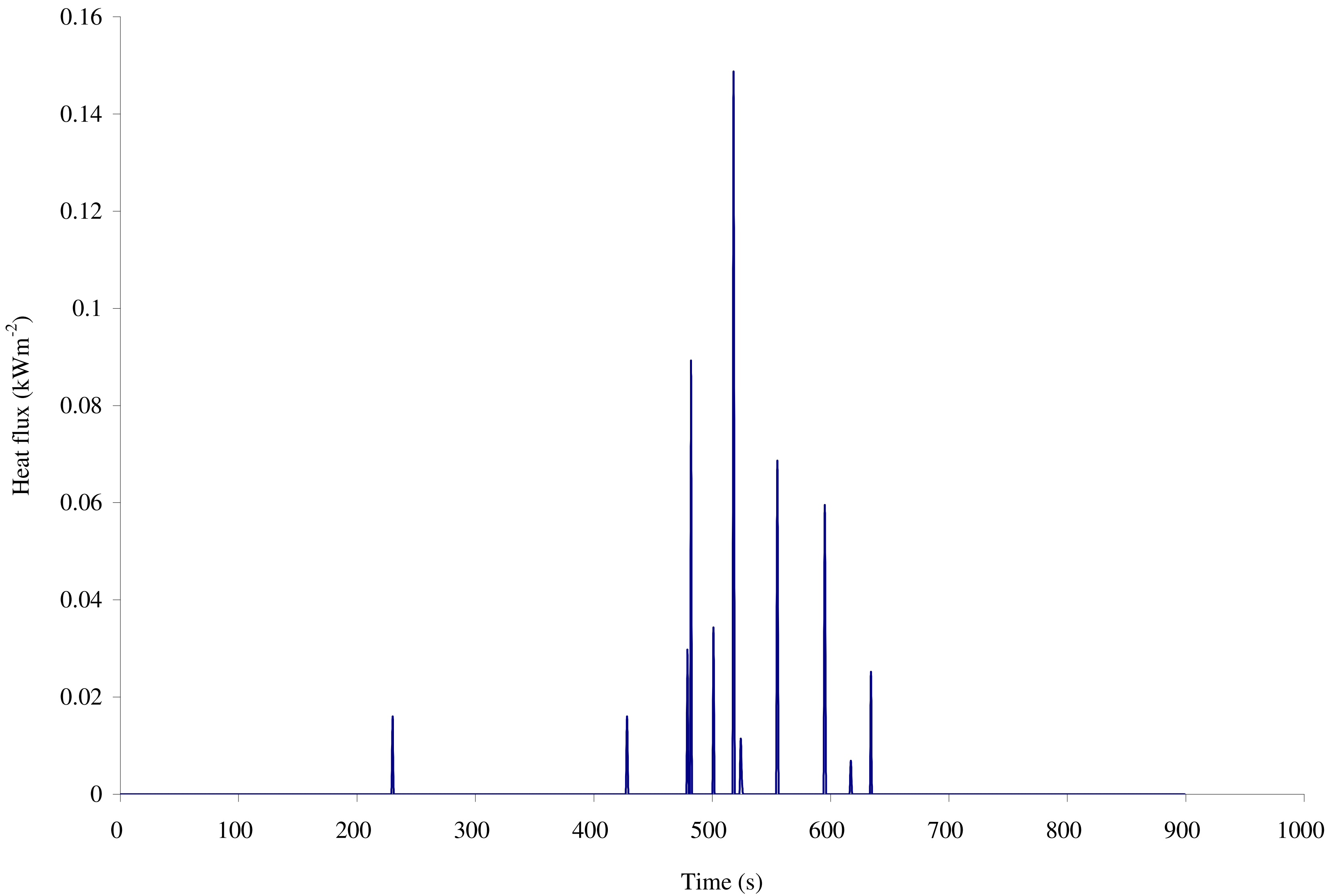


Figure 9.9a: Result of heat flux in test B4

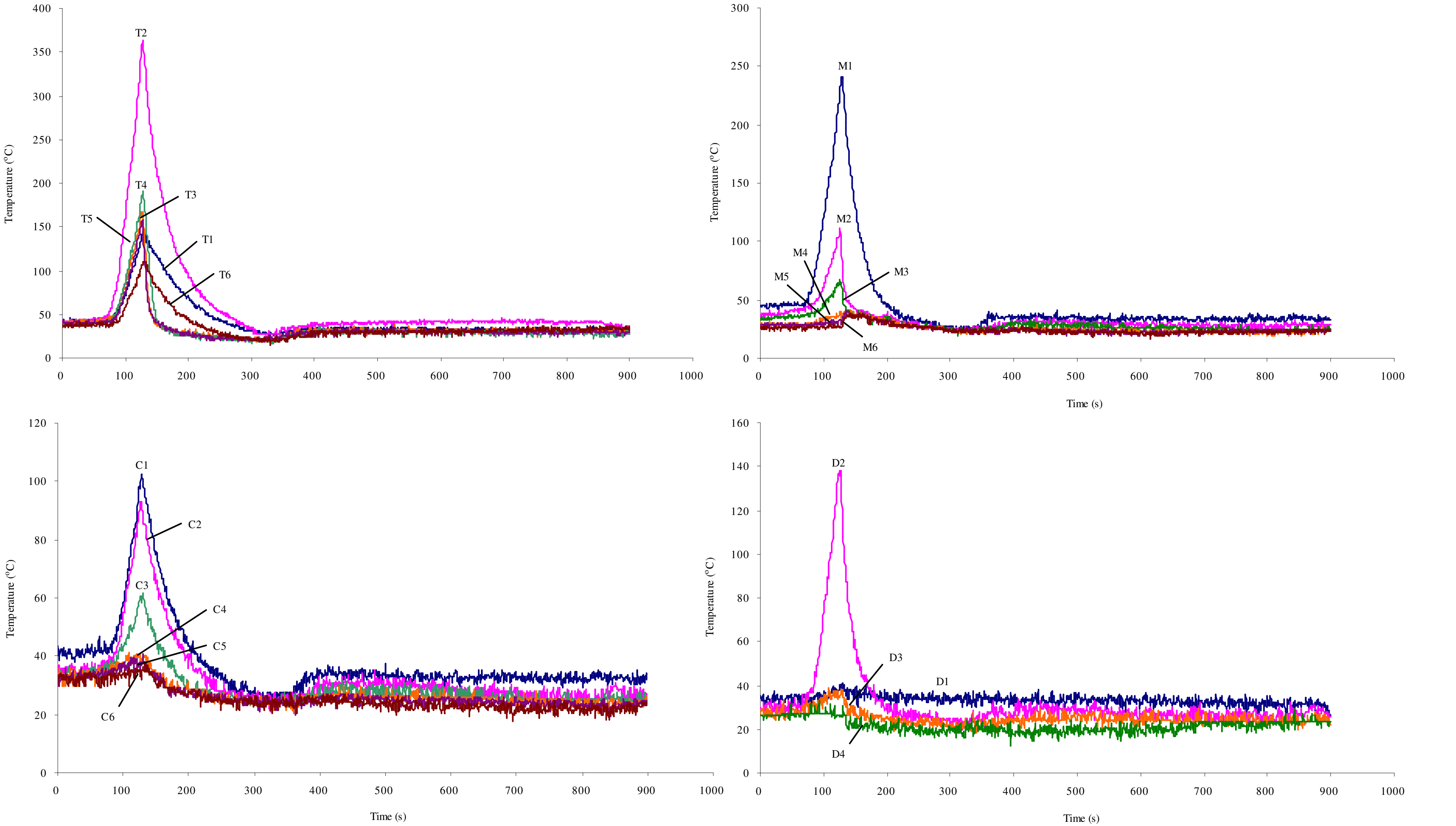


Figure 9.9b: Result of room temperature in test B4

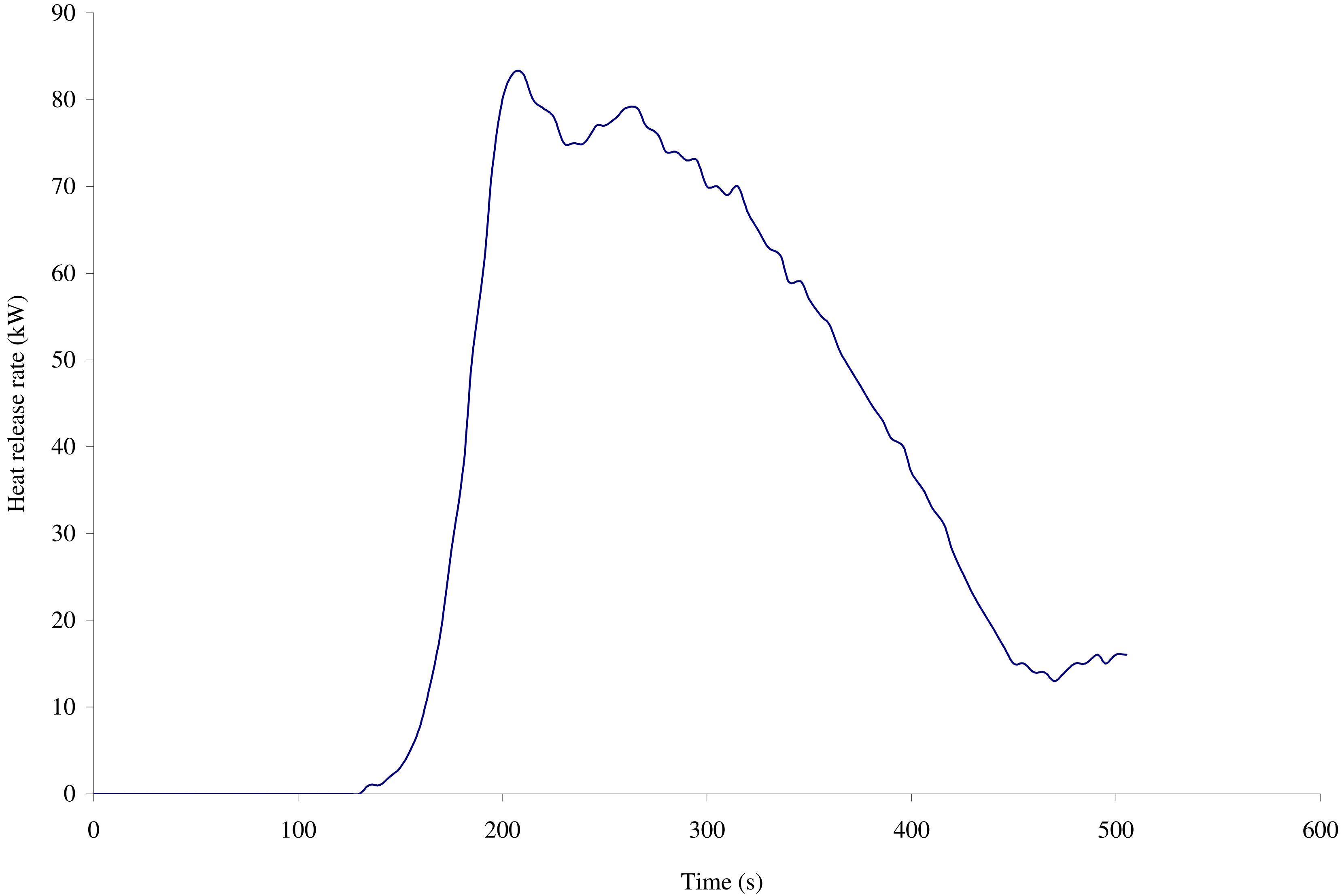


Figure 9.9c: Result of HRR in test B4

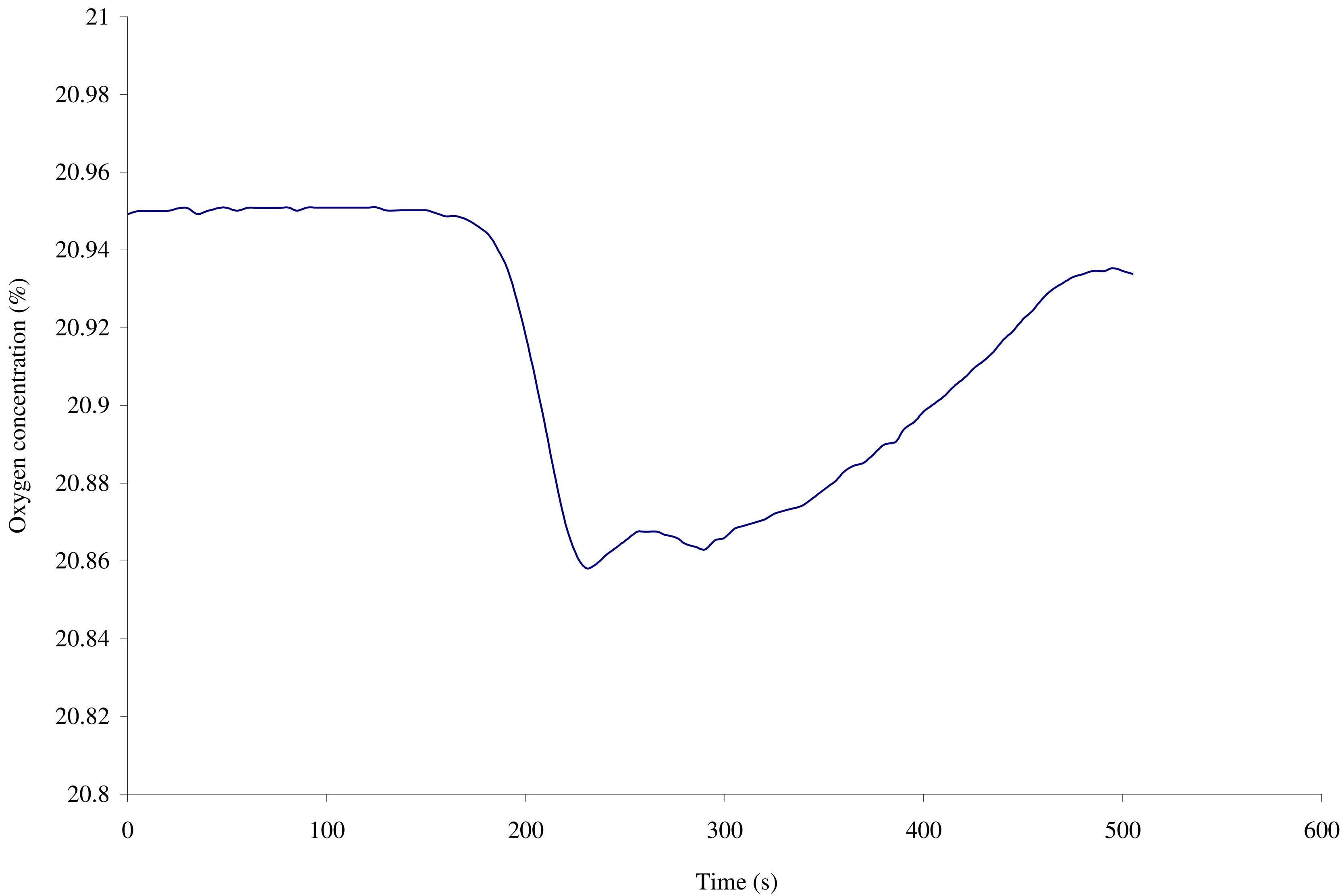


Figure 9.9d: Result of oxygen level in test B4

Figure 9.10: The hood

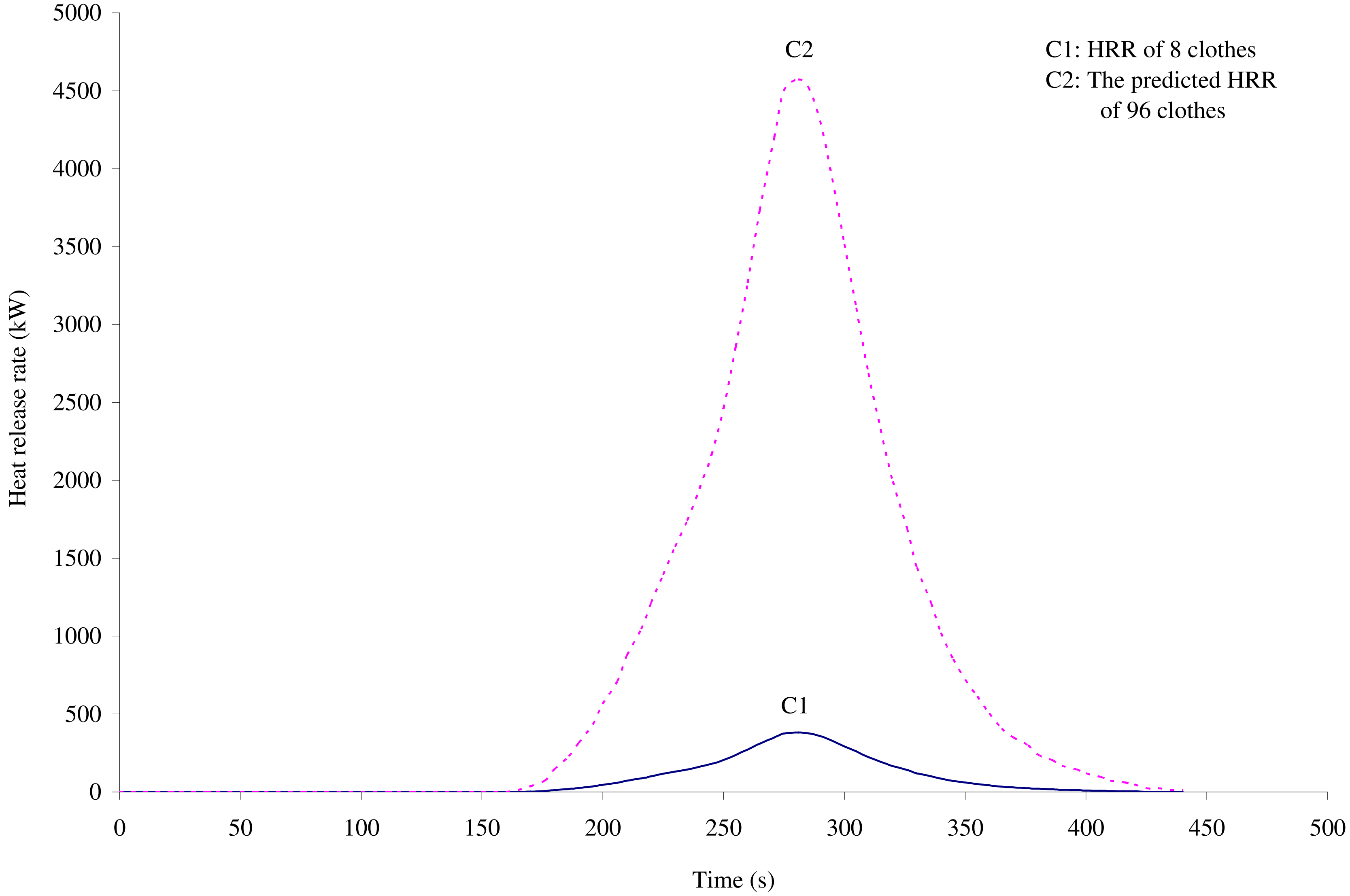


Figure 9.11a: Result of HRR in test B5

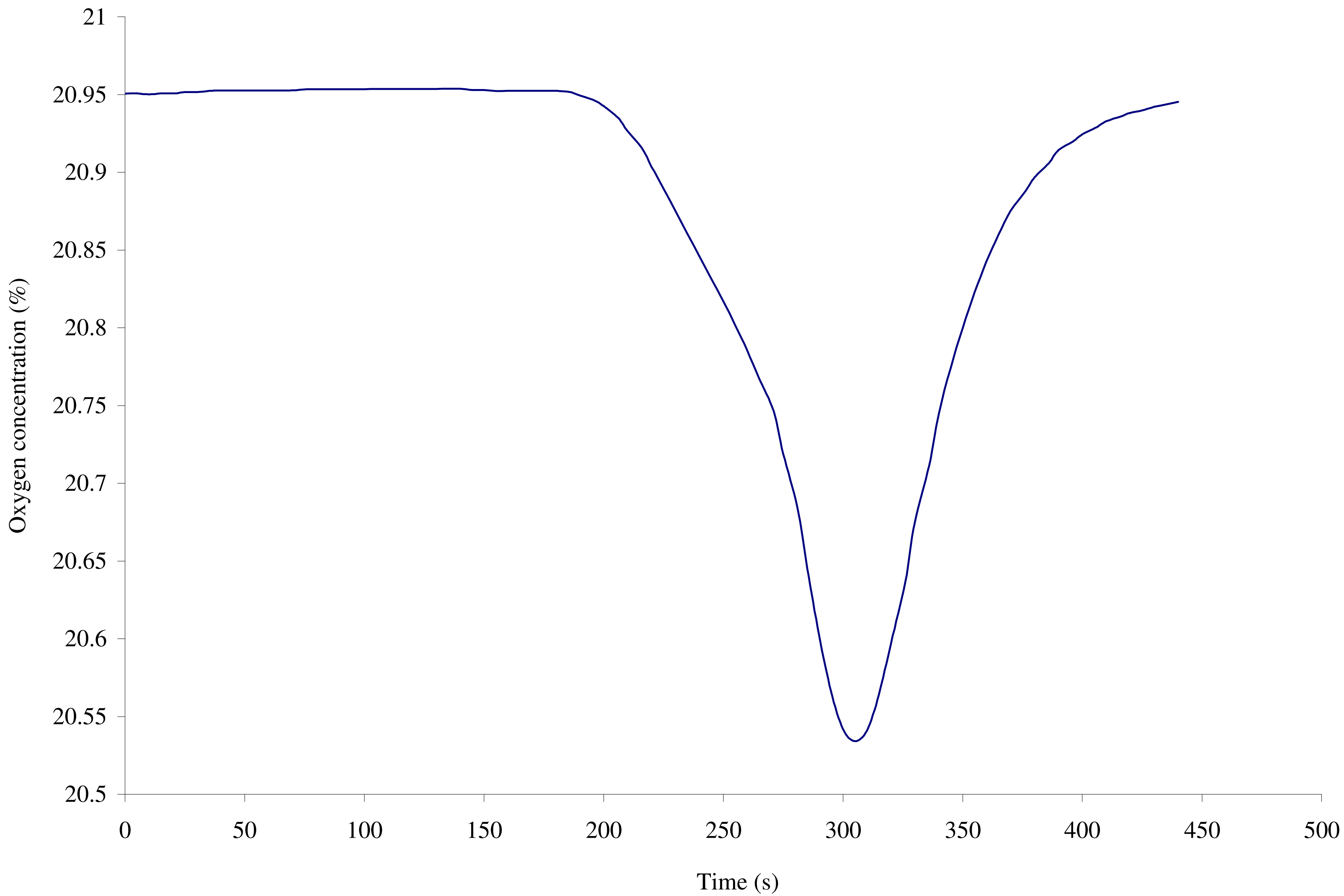
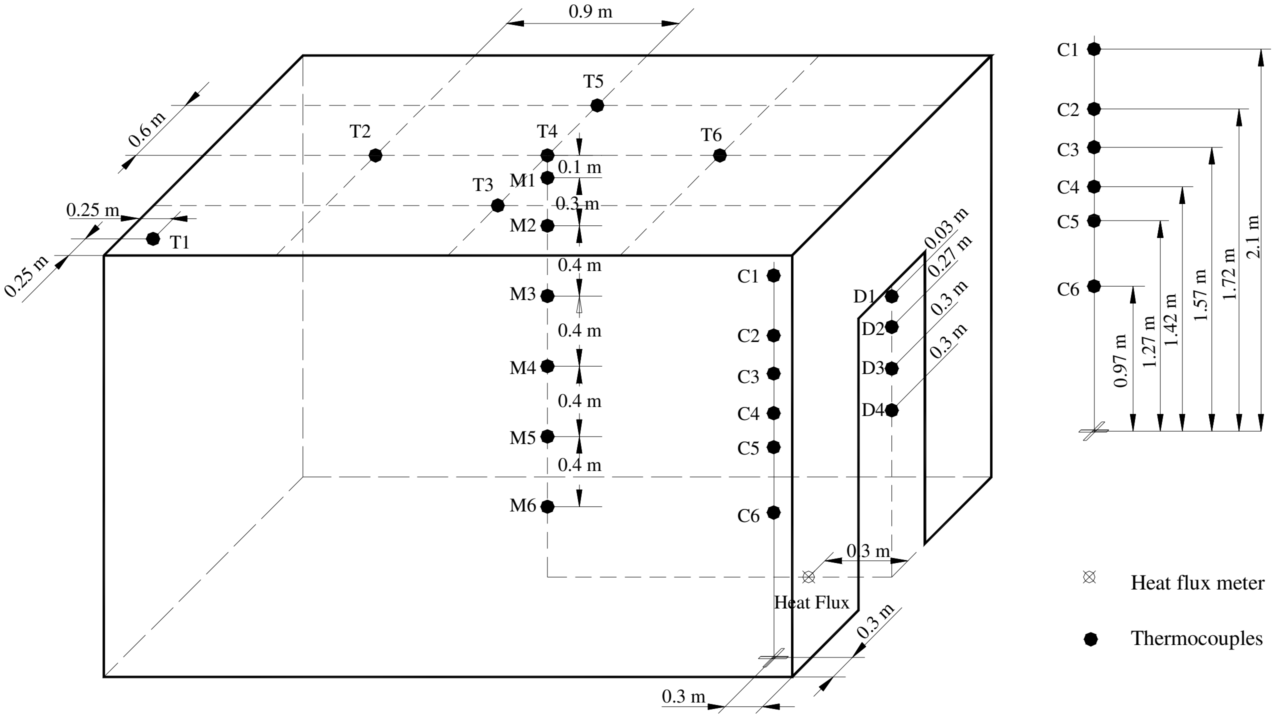


Figure 9.11b: Result of oxygen level in test B5



Thermocouple trees

Figure 9.12: Layout of test B6

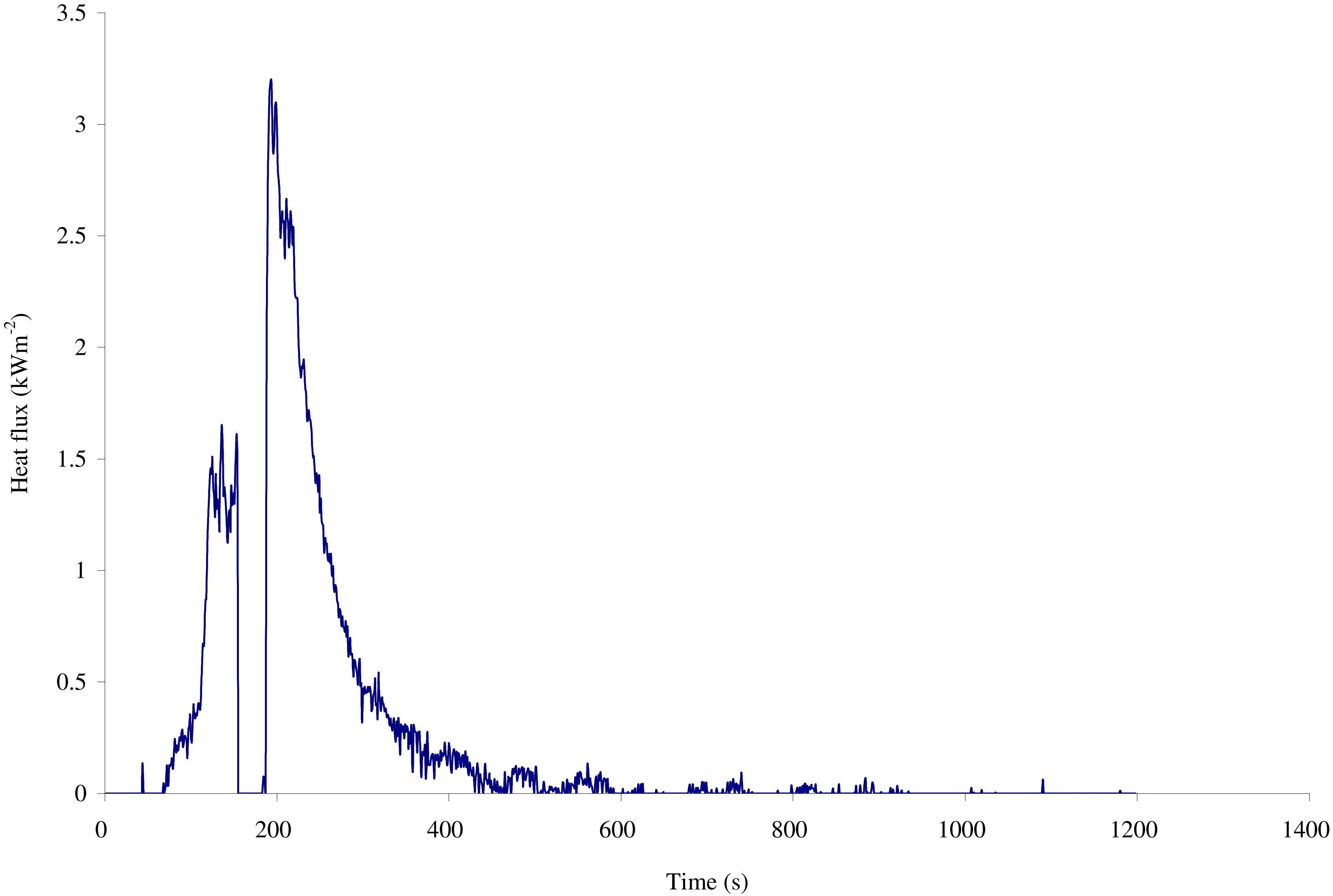


Figure 9.13a: Result of heat flux in test B6

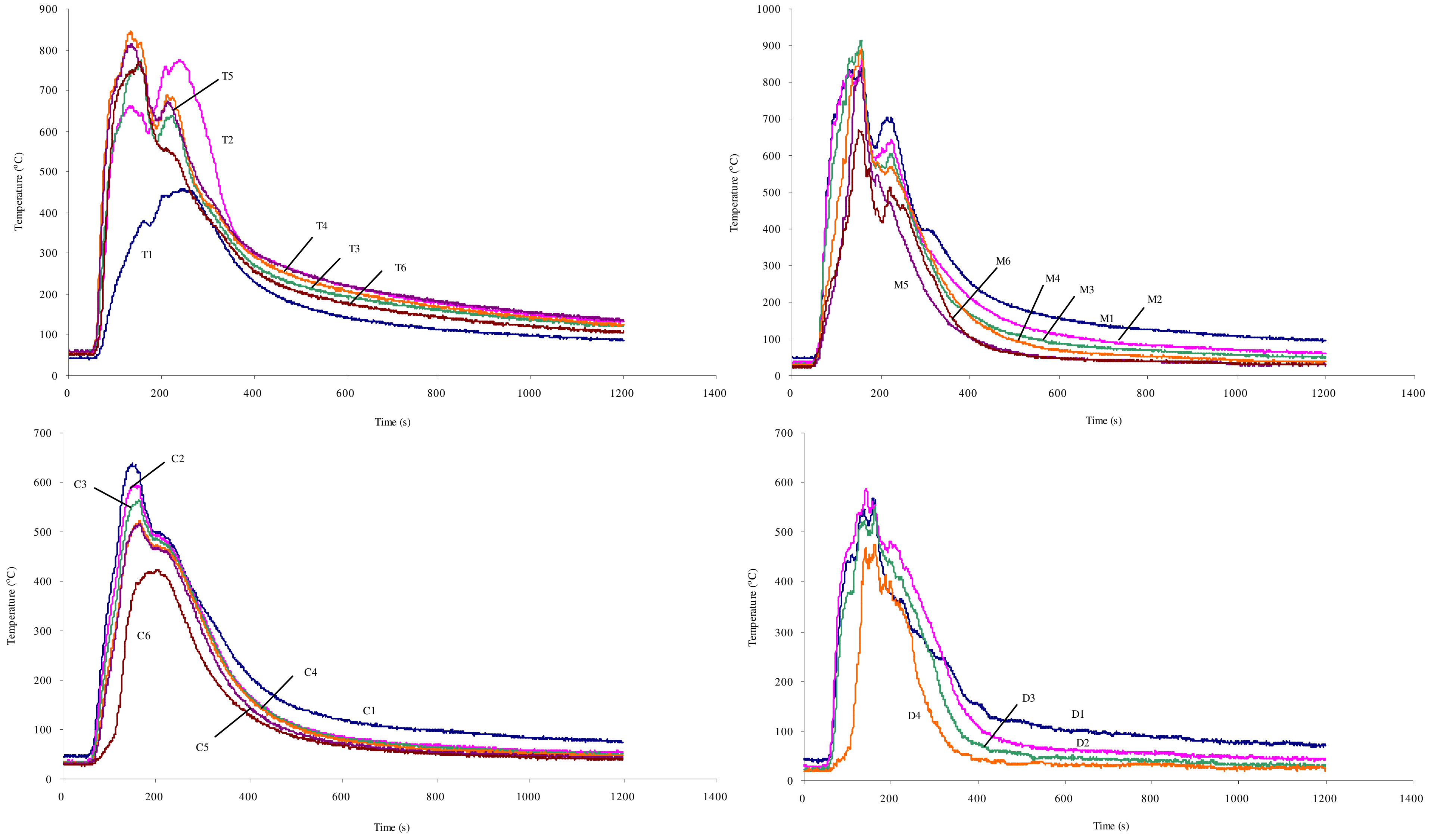


Figure 9.13b: Result of room temperature in test B6

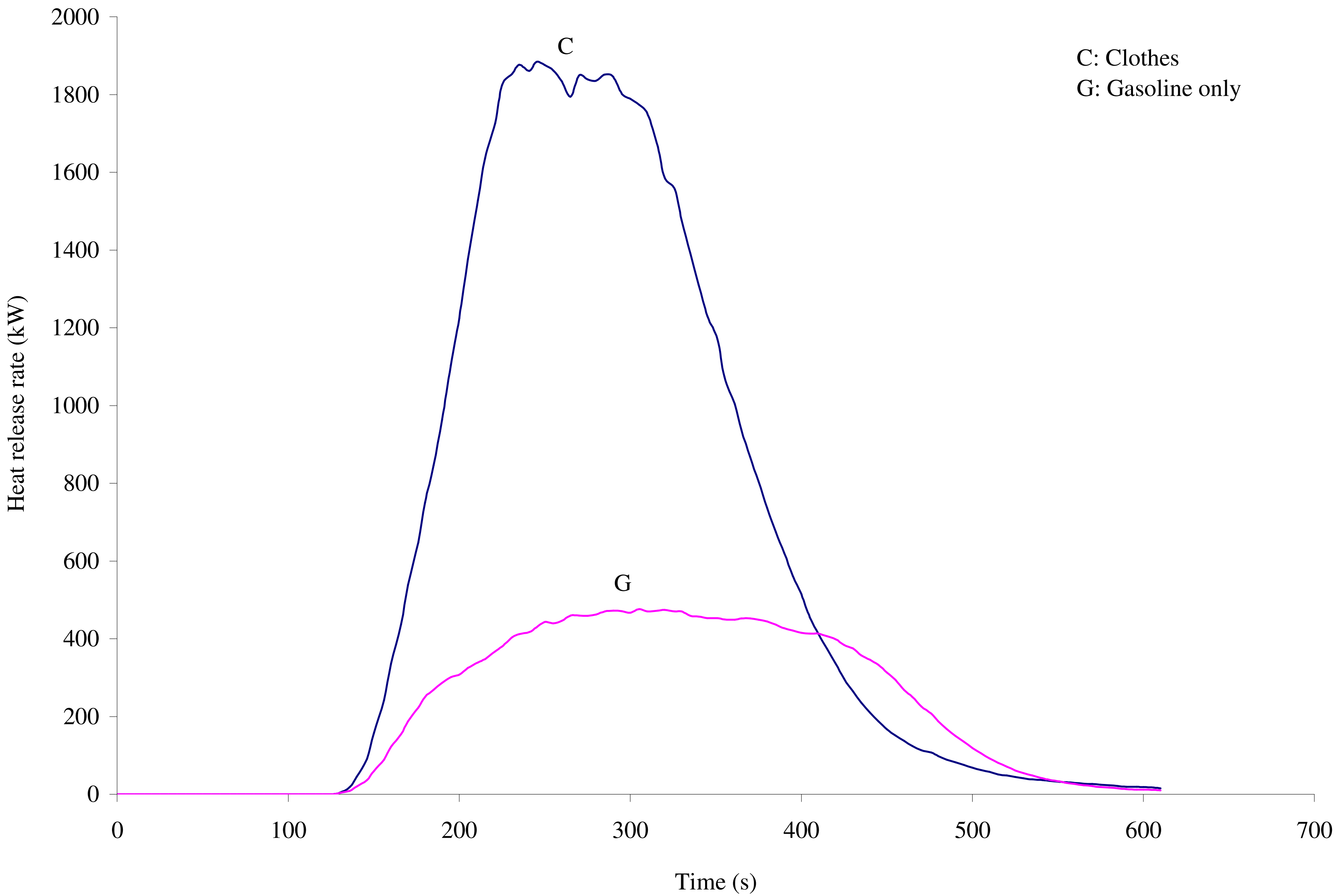


Figure 9.13c: Result of HRR in test B6

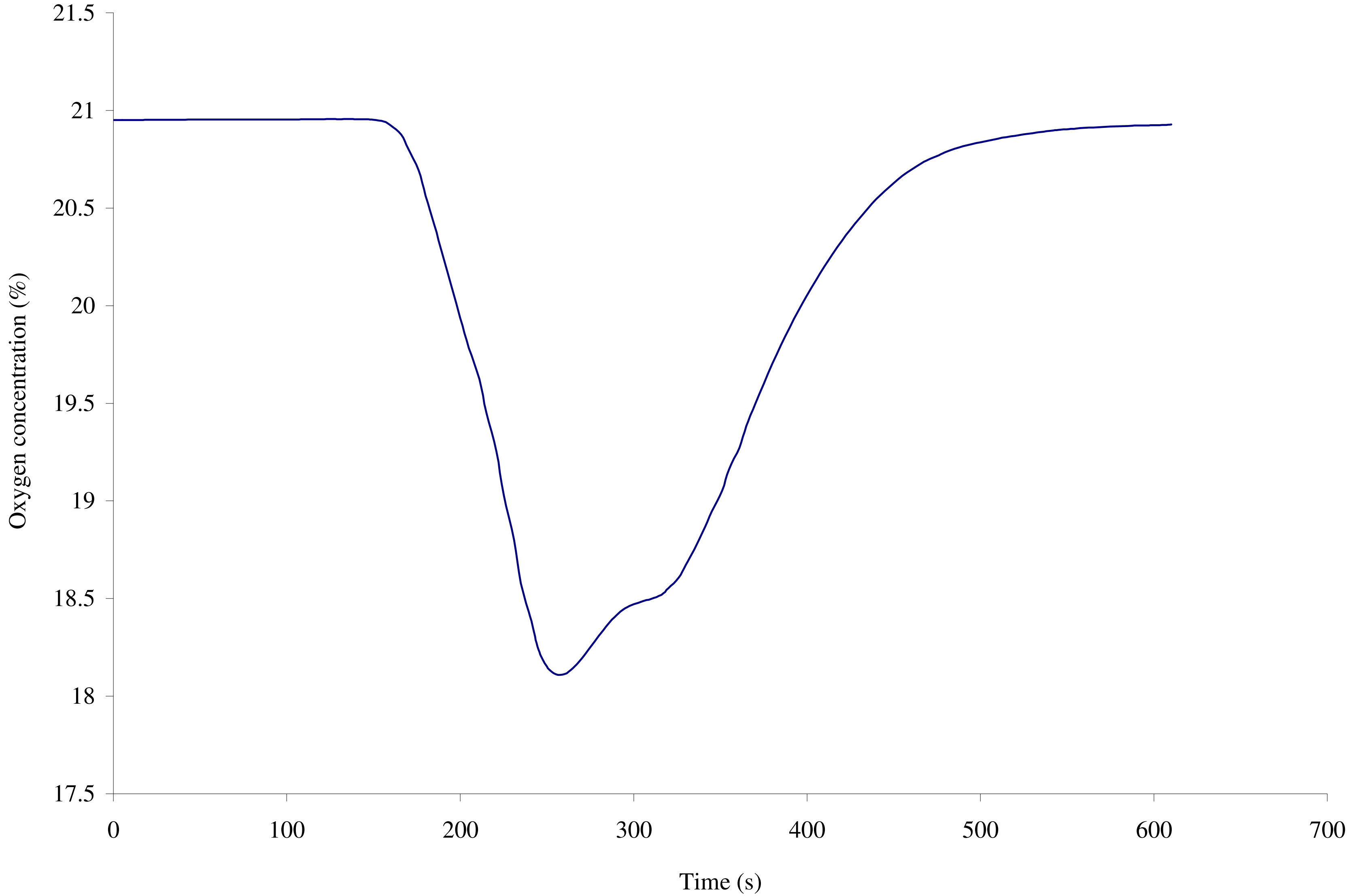
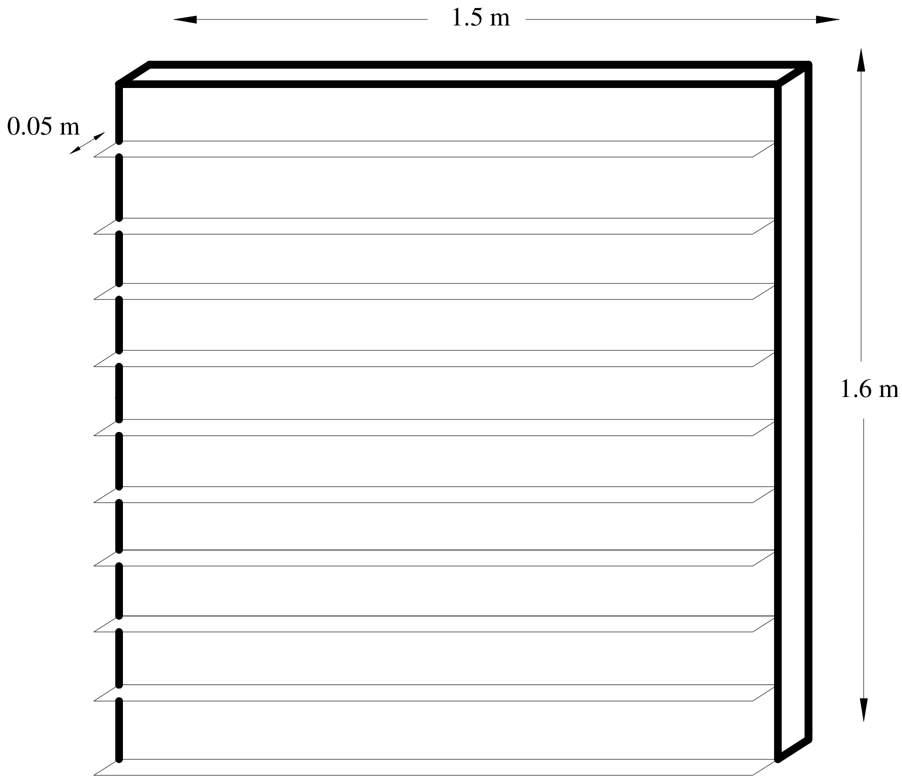
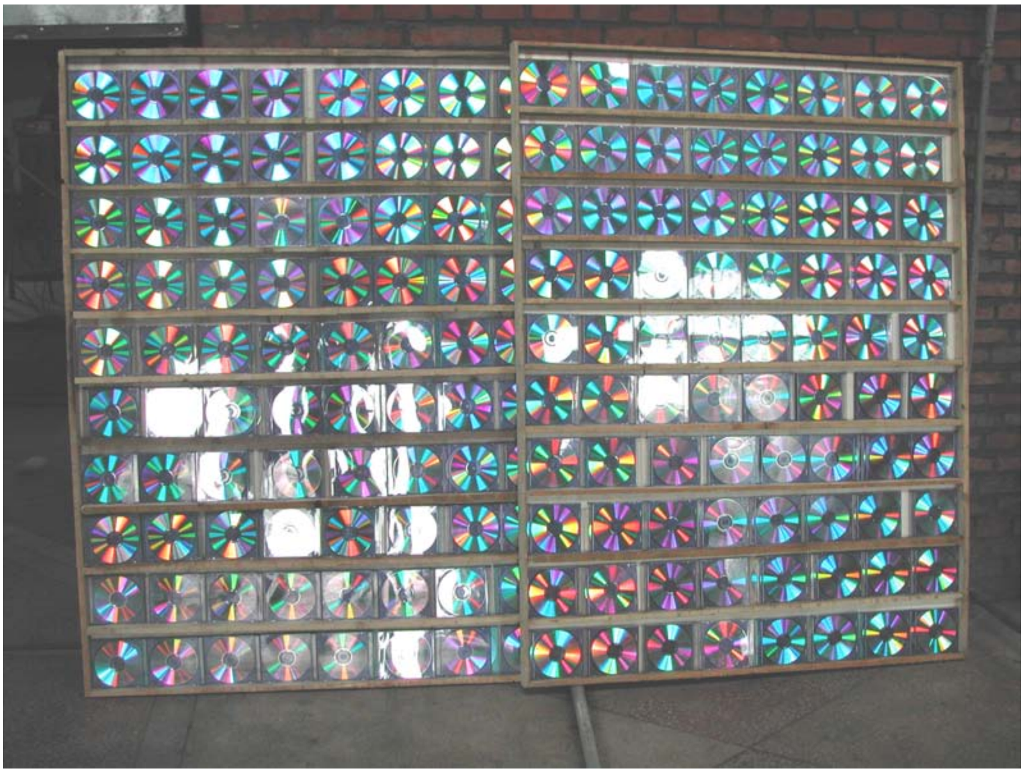


Figure 9.13d: Result of oxygen level in test B6



(a) Schematic diagram of CD display



(b) Arrangement of CDs

Figure 9.14: CD display

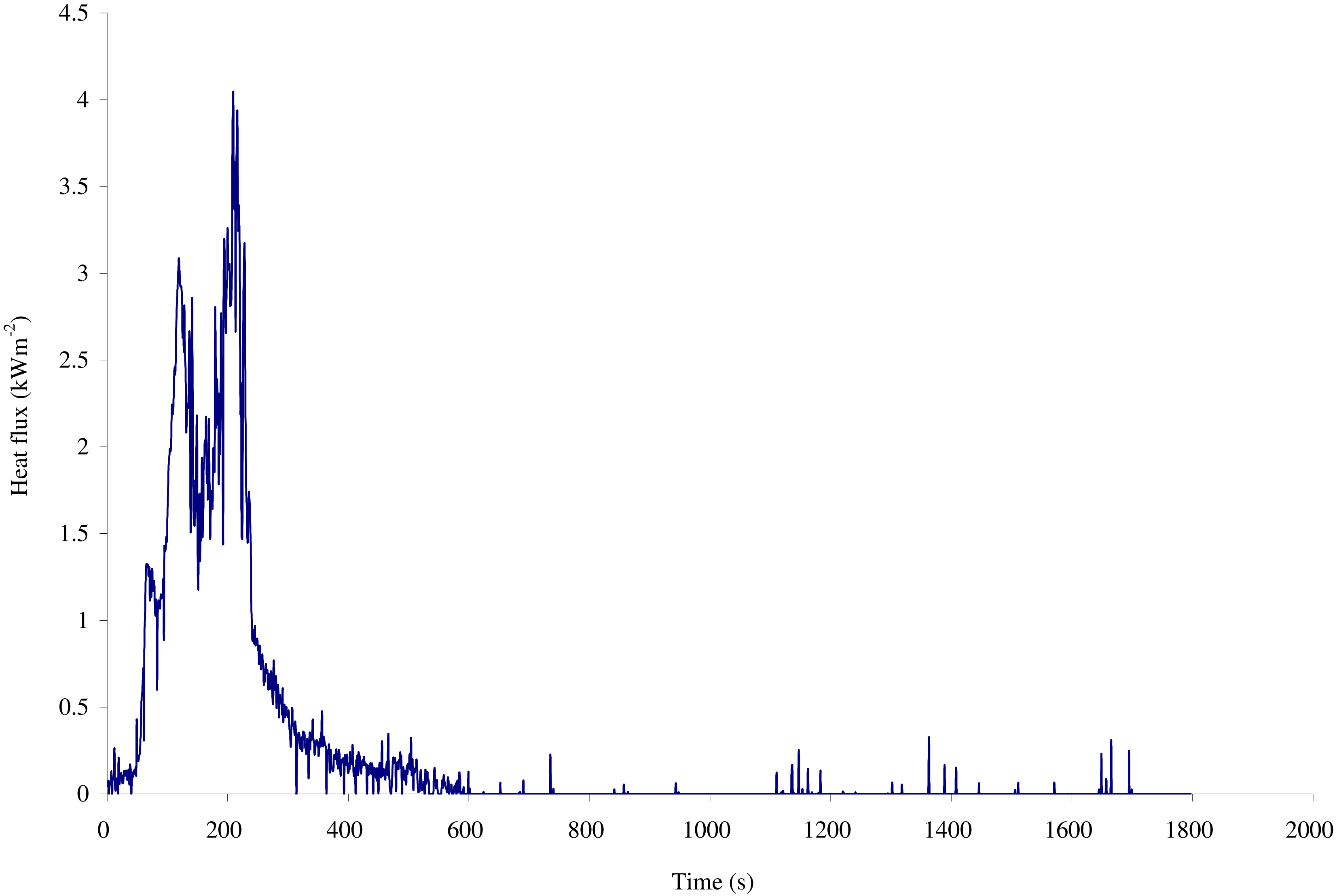


Figure 9.15a: Result of heat flux in test C1

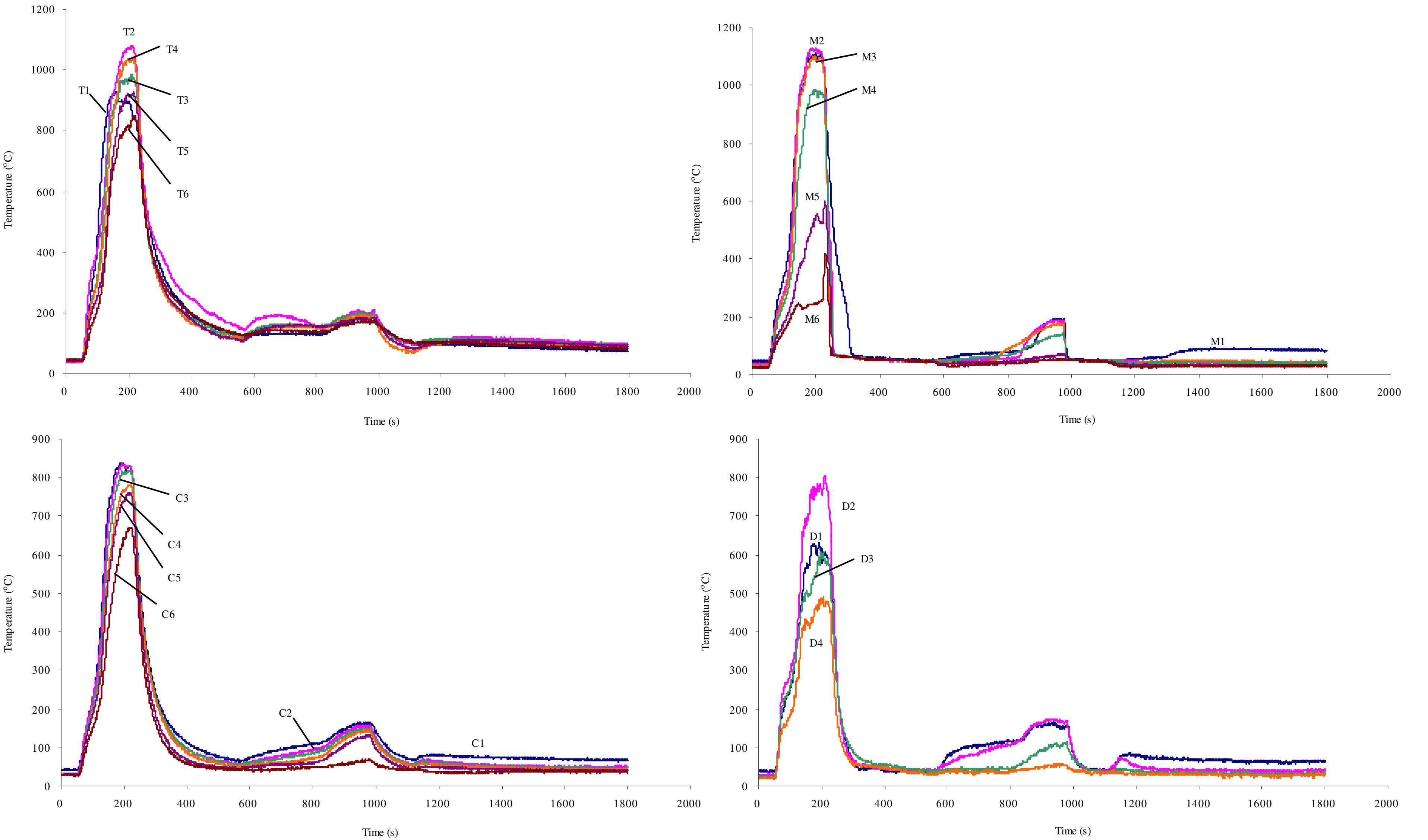


Figure 9.15b: Result of room temperature in test C1

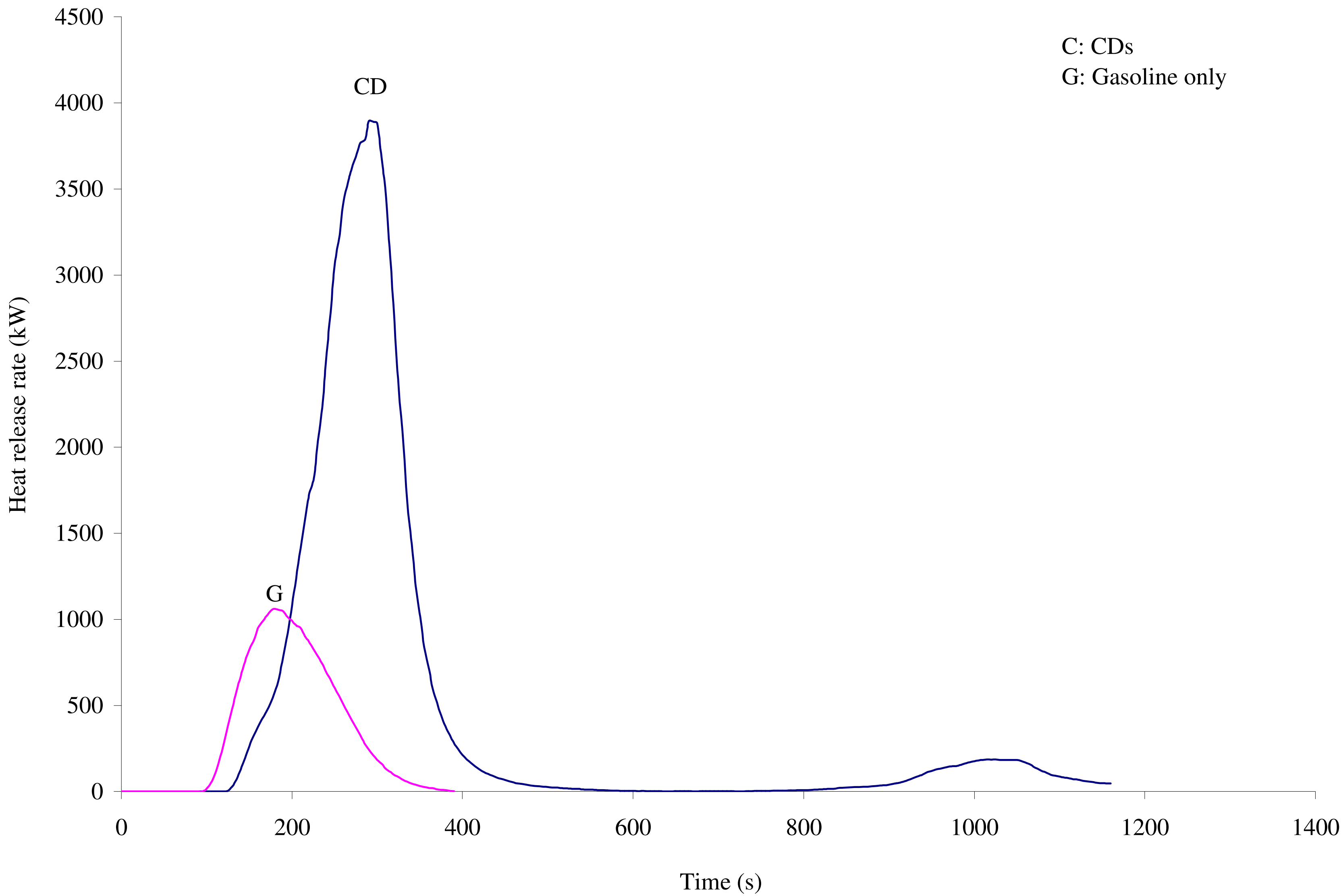


Figure 9.15c: Result of HRR in test C1

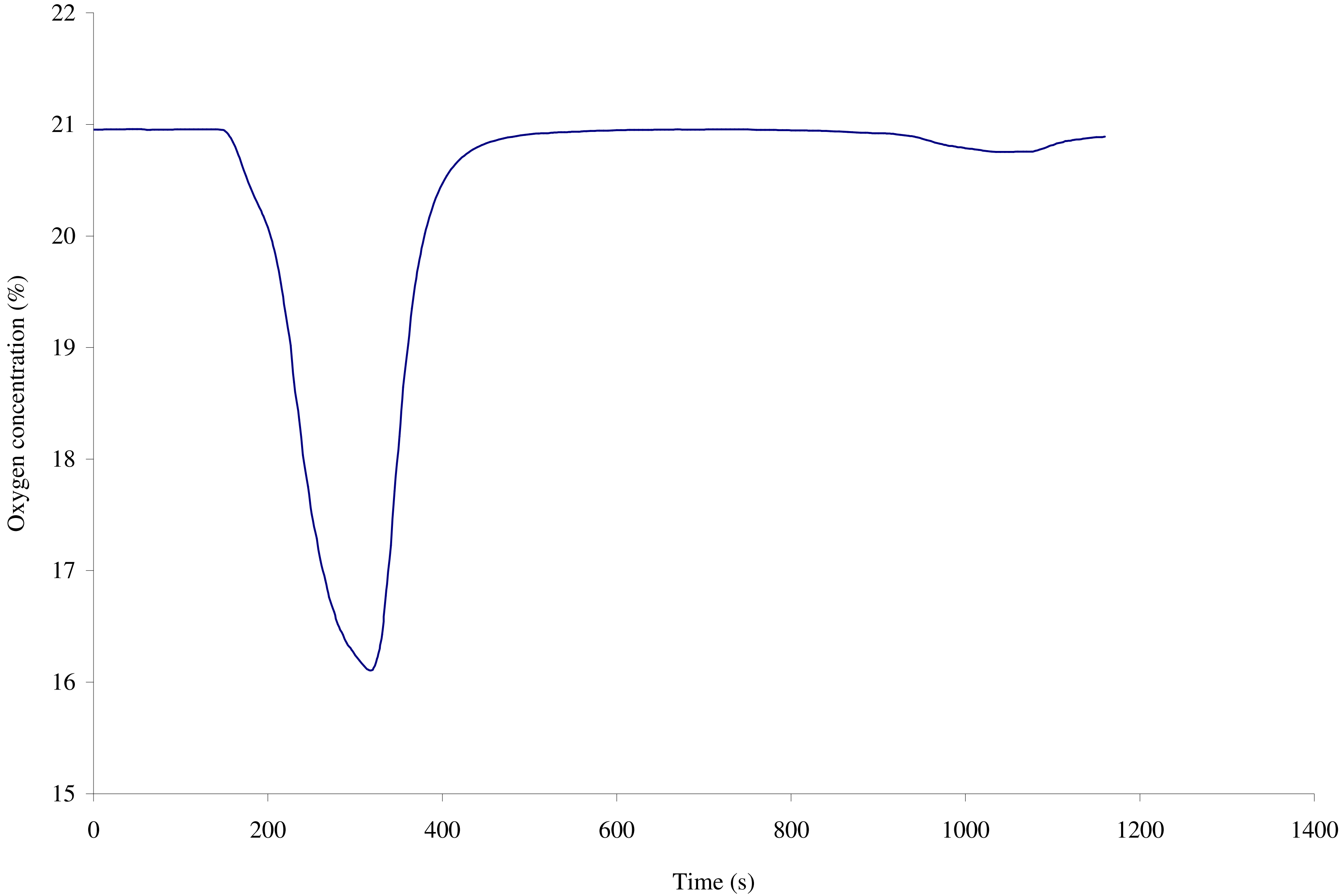


Figure 9.15d: Result of oxygen level in test C1

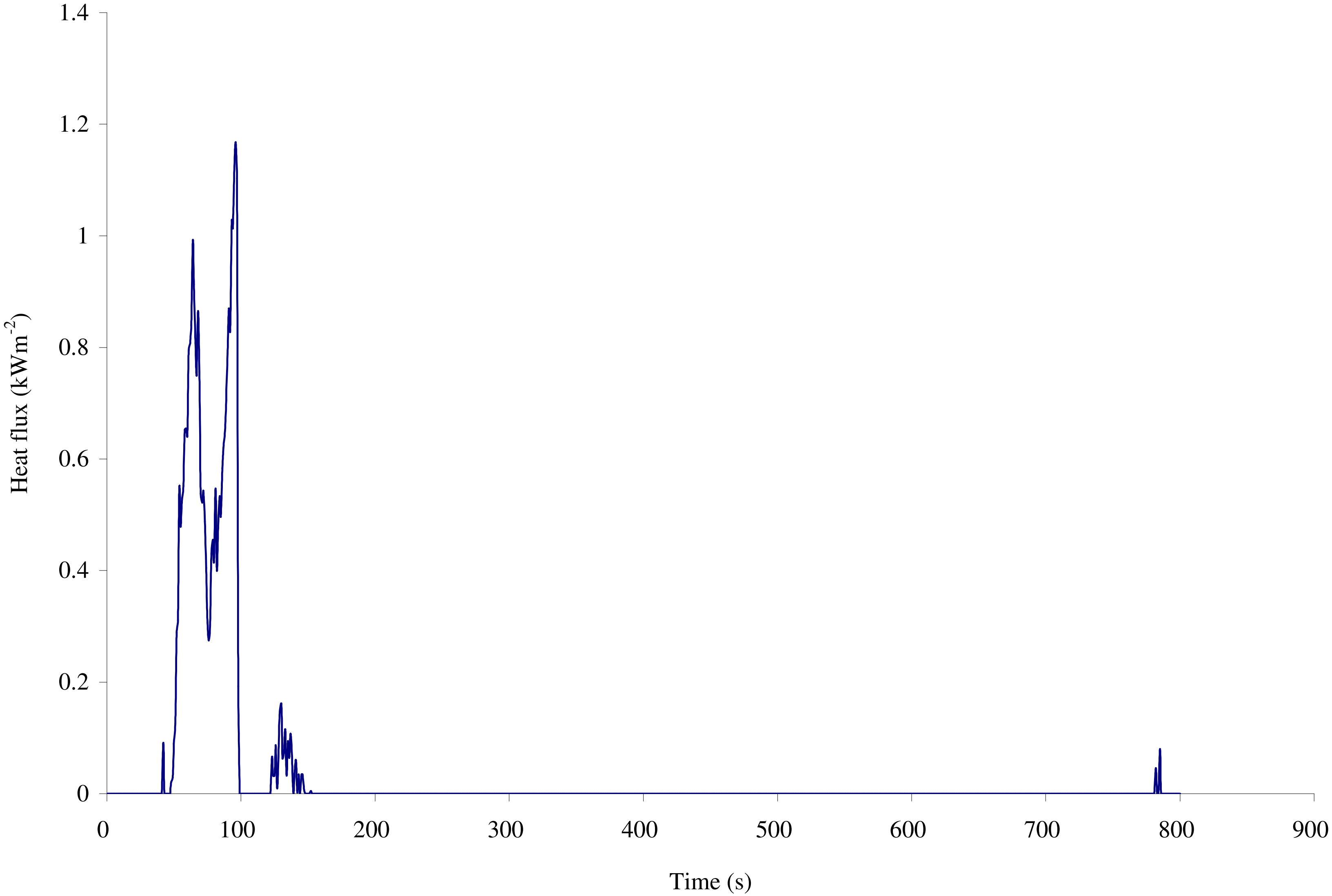


Figure 9.16a: Result of heat flux in test C2

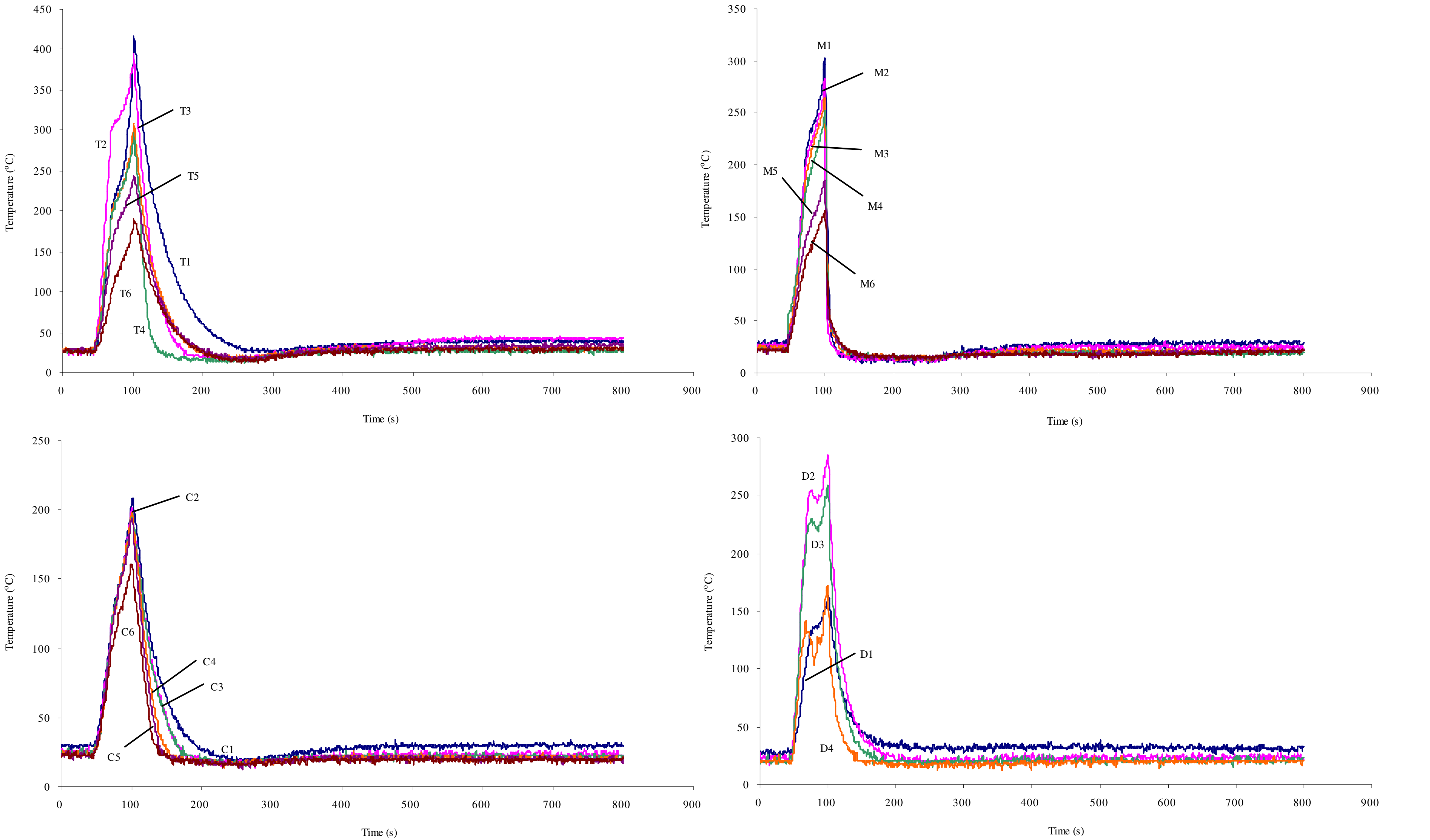


Figure 9.16b: Result of room temperature in test C2

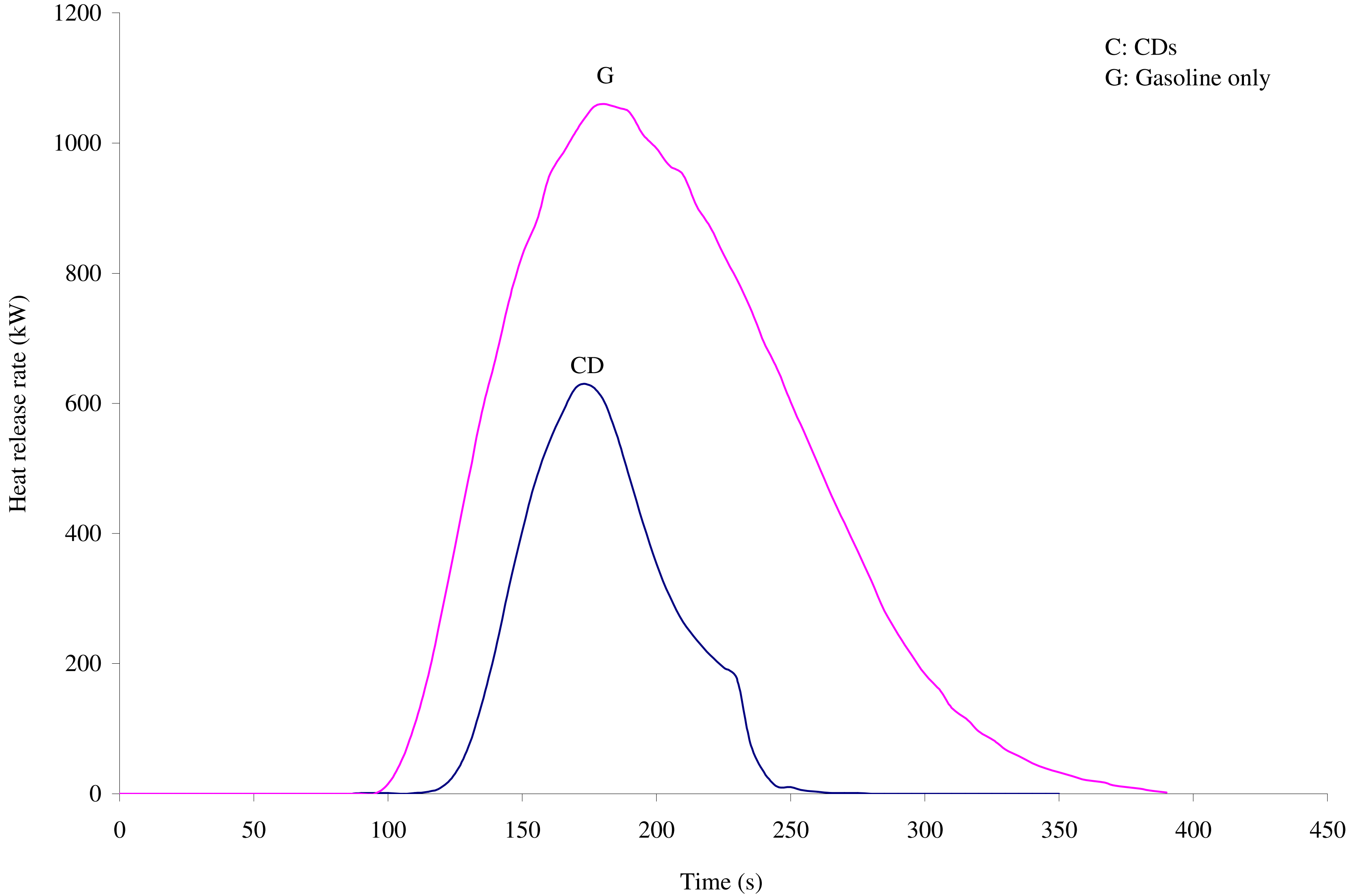


Figure 9.16c: Result of HRR in test C2

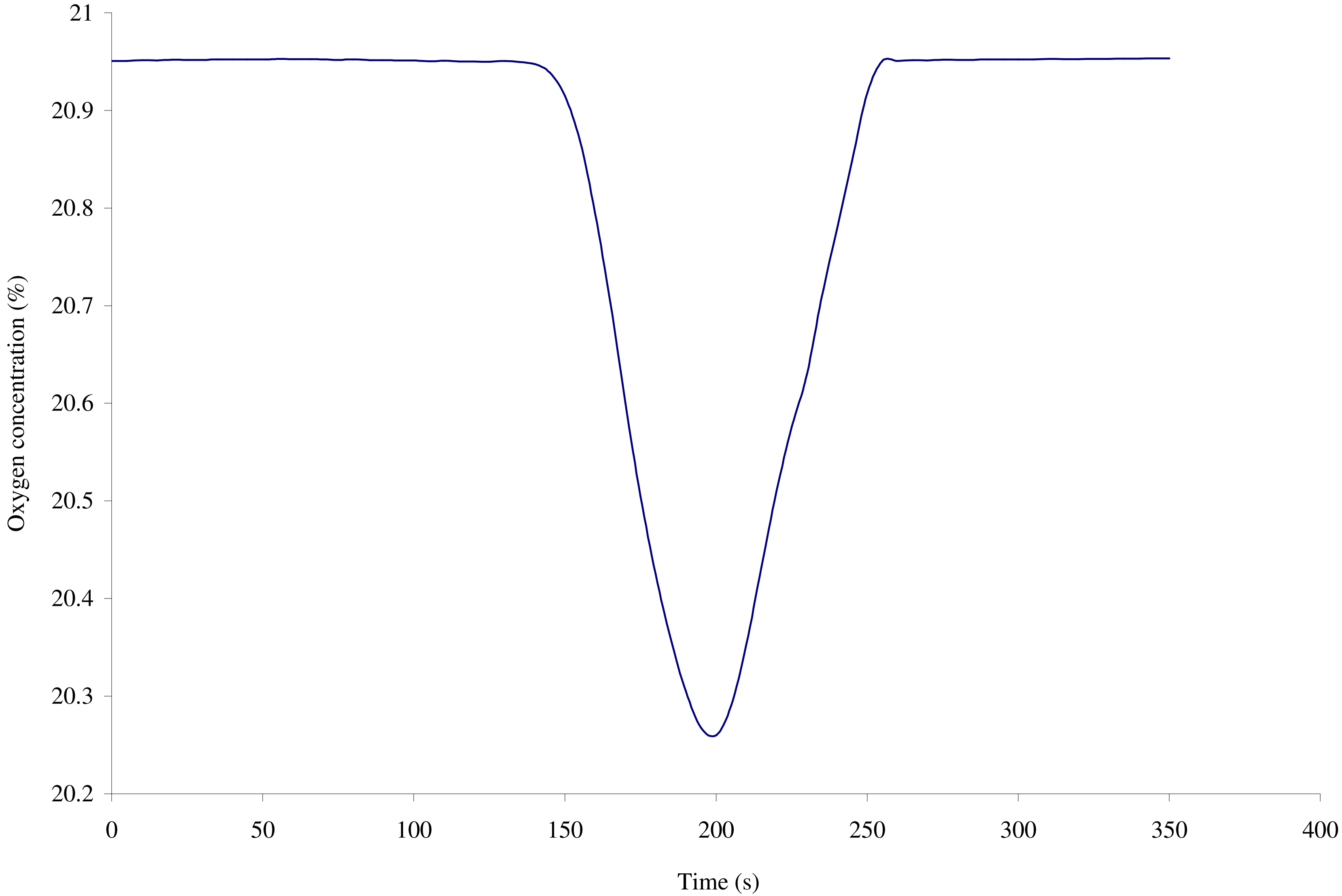


Figure 9.16d: Result of oxygen level in test C2

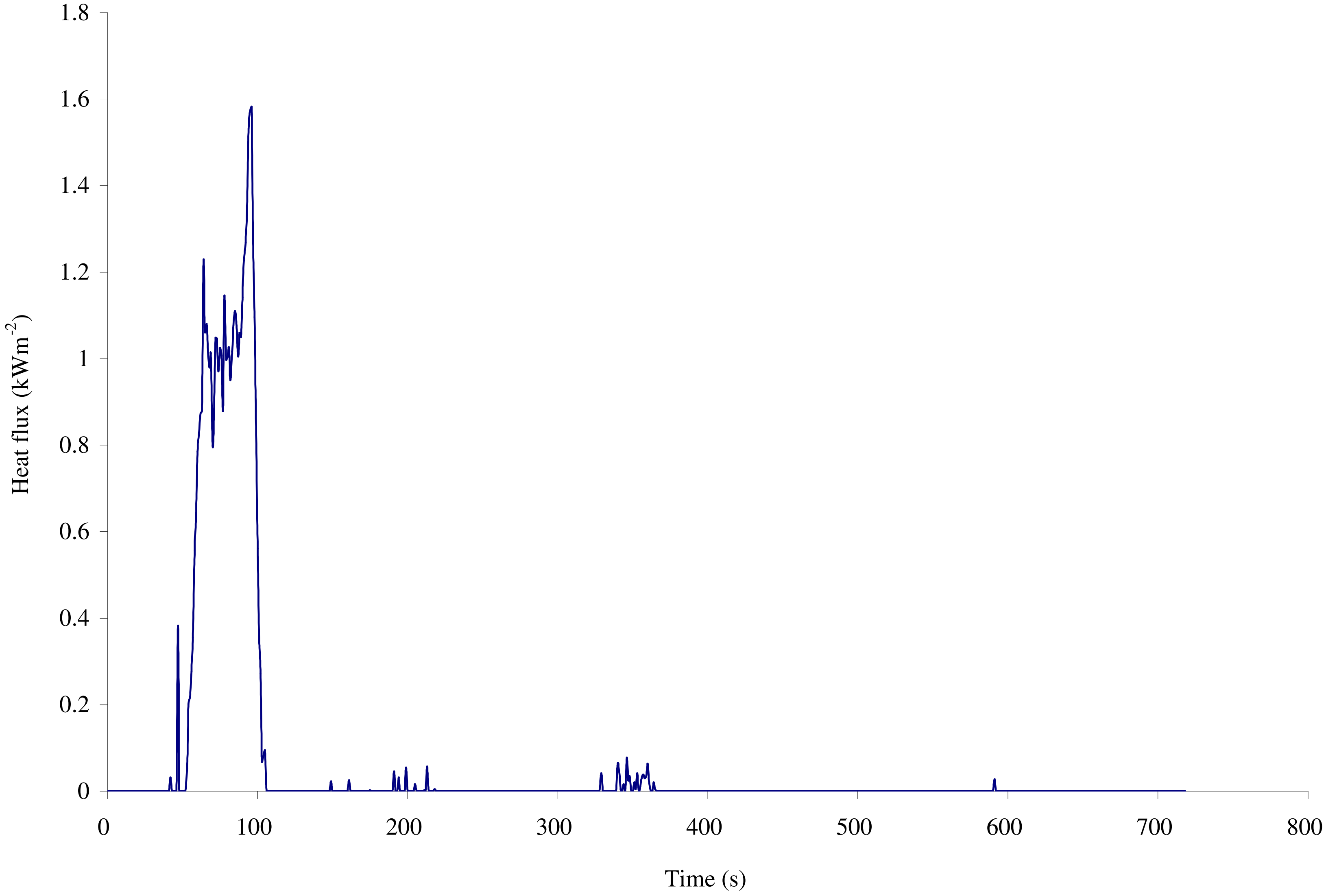


Figure 9.17a: Result of heat flux in test C3

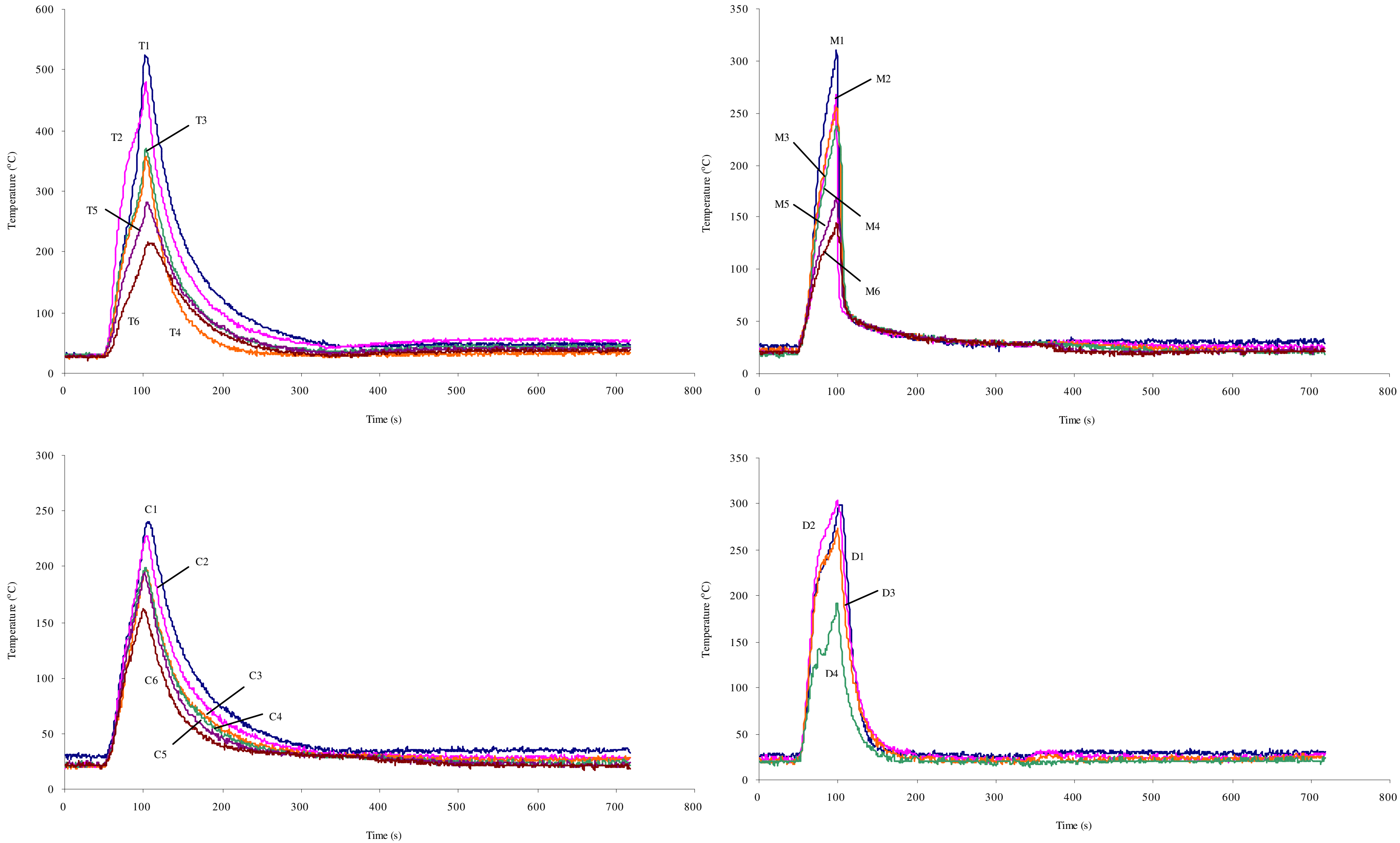


Figure 9.17b: Result of room temperature in test C3

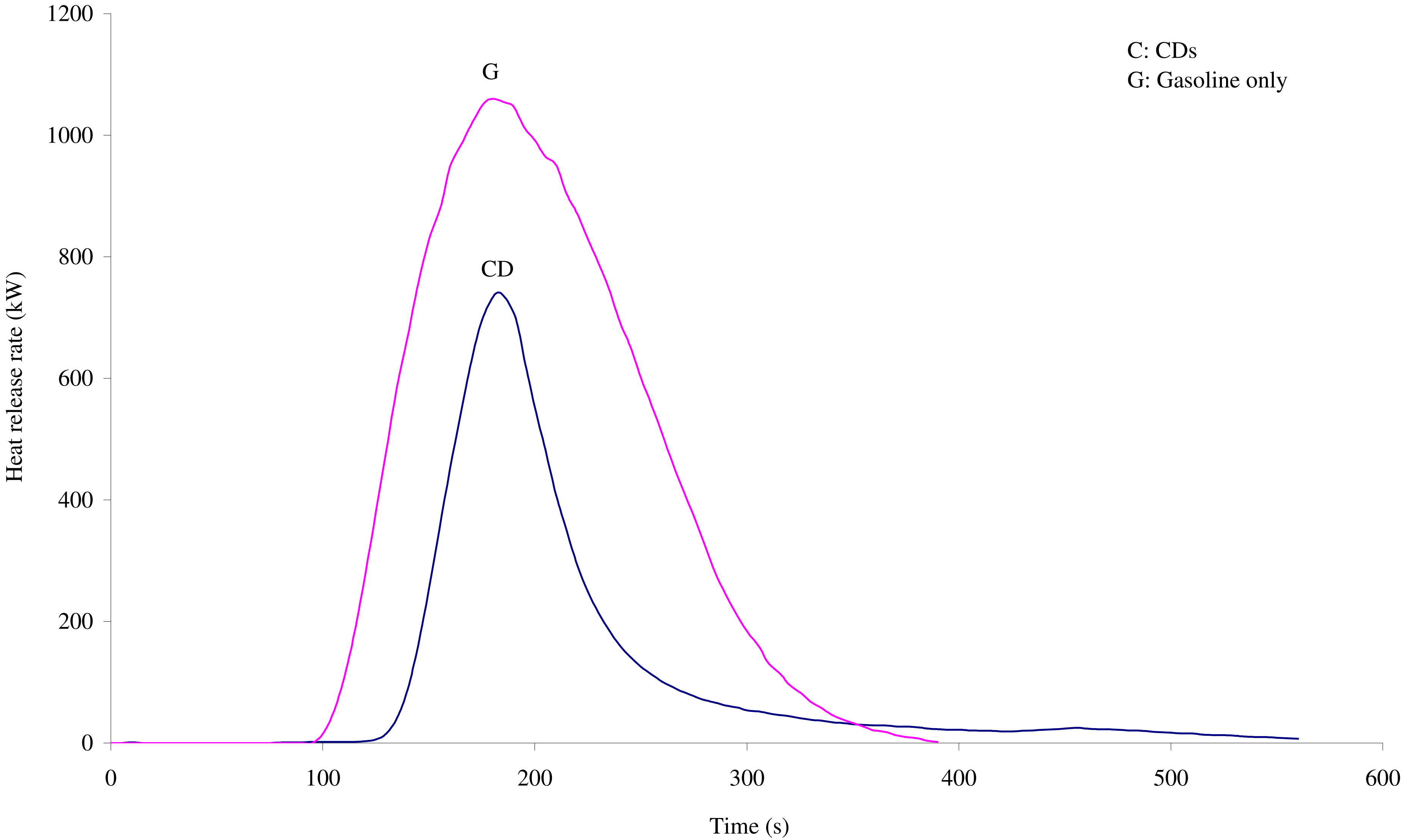


Figure 9.17c: Result of HRR in test C3

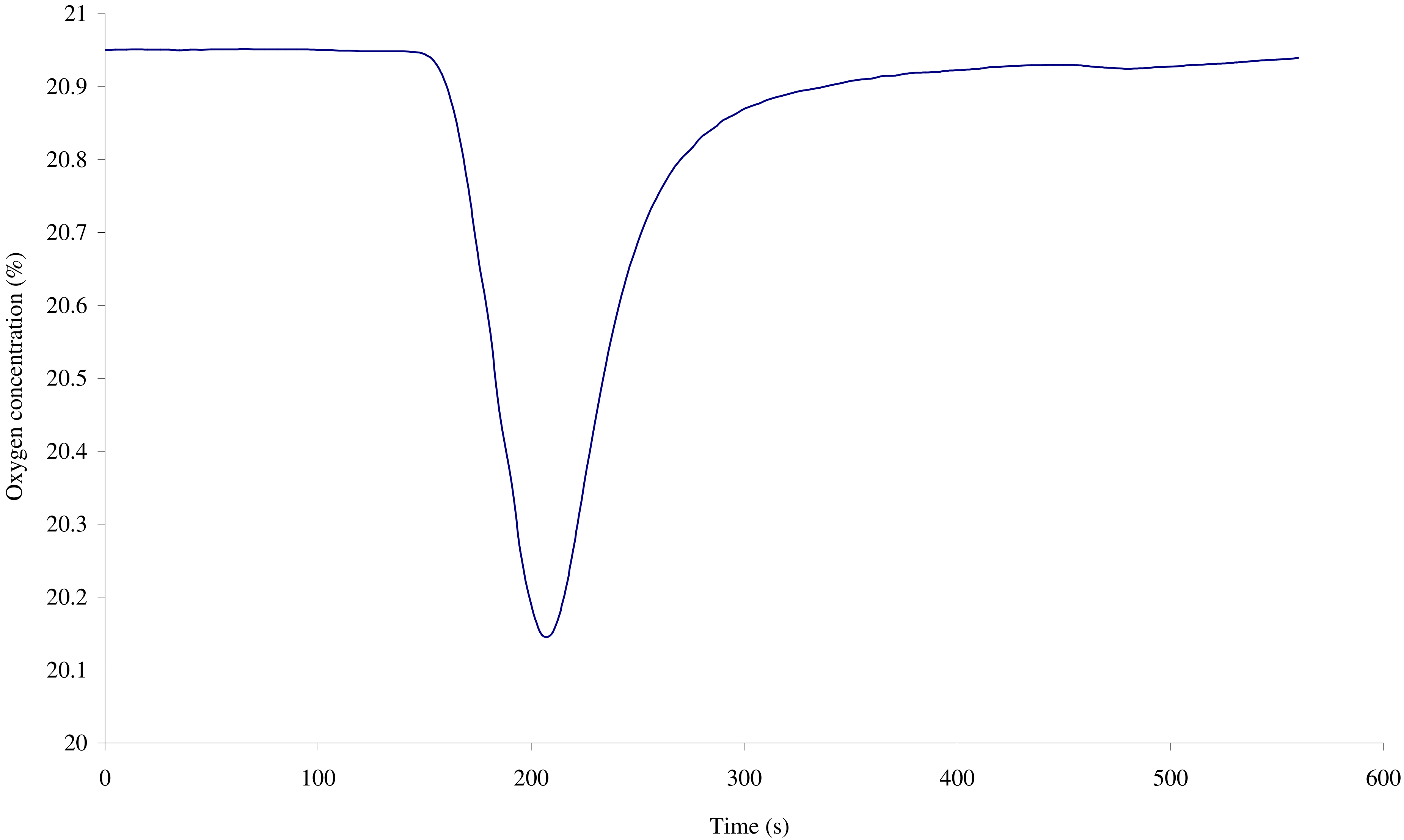
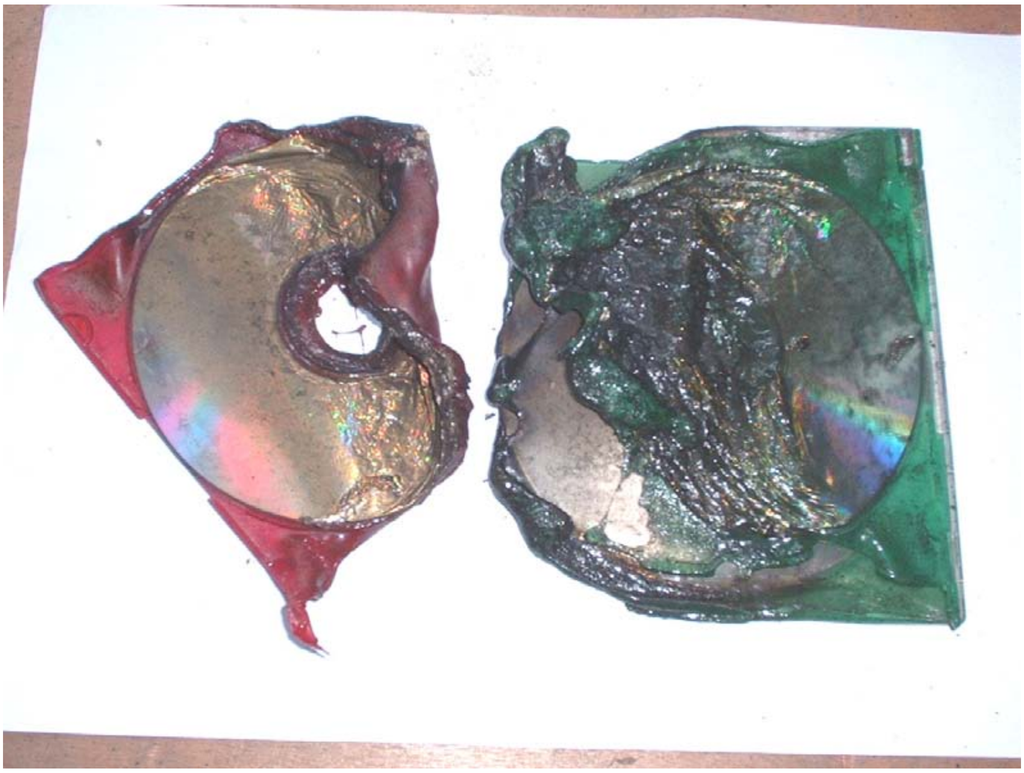


Figure 9.17d: Result of oxygen level in test C3

(a) The CD was not damaged



(b) The CD was melted together with the box

(c) The CD boxes were melted and stuck together

Figure 9.18: CDs and CD boxes

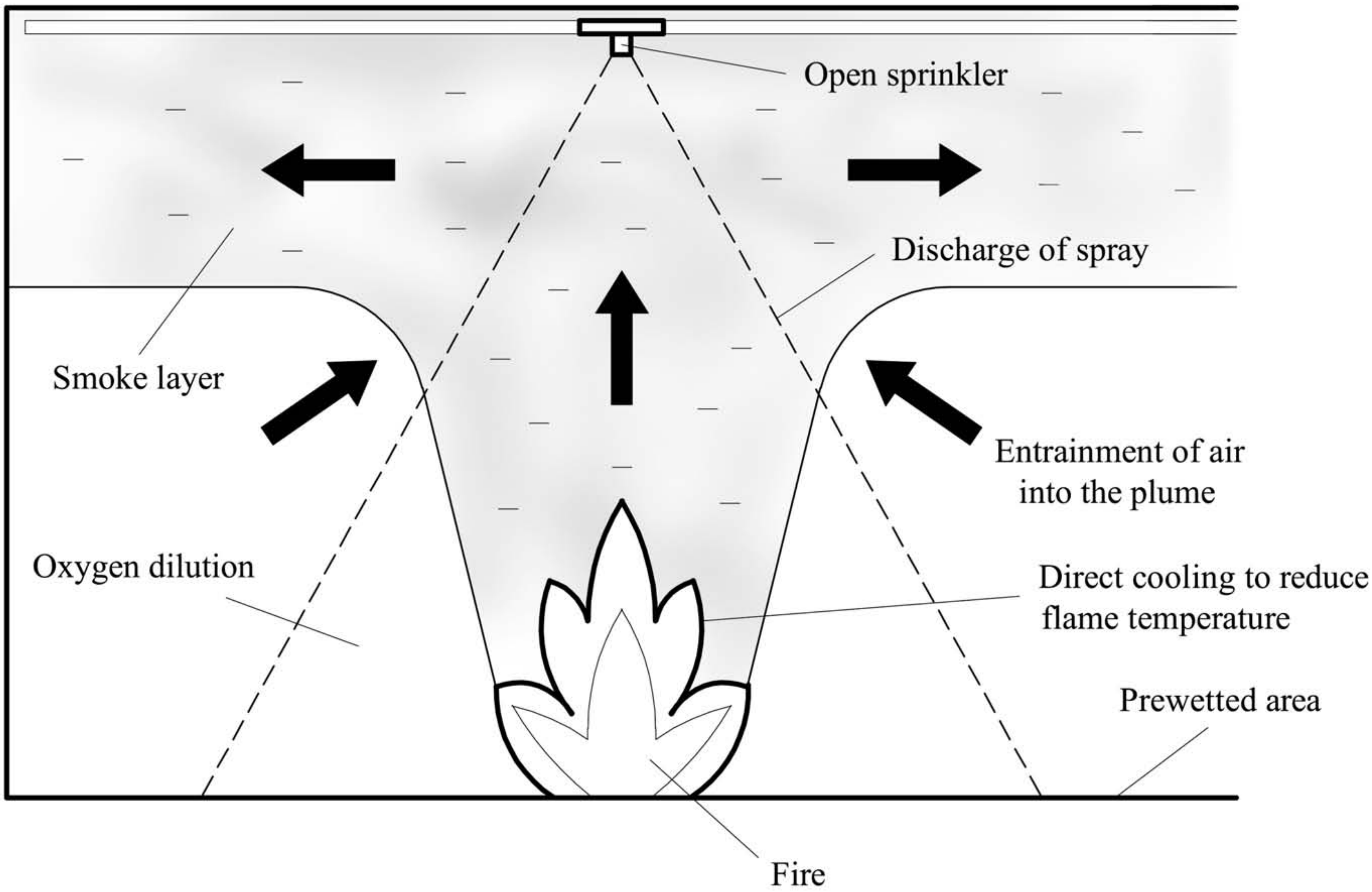


Figure 11.1: Extinguishing mechanism of deluge system

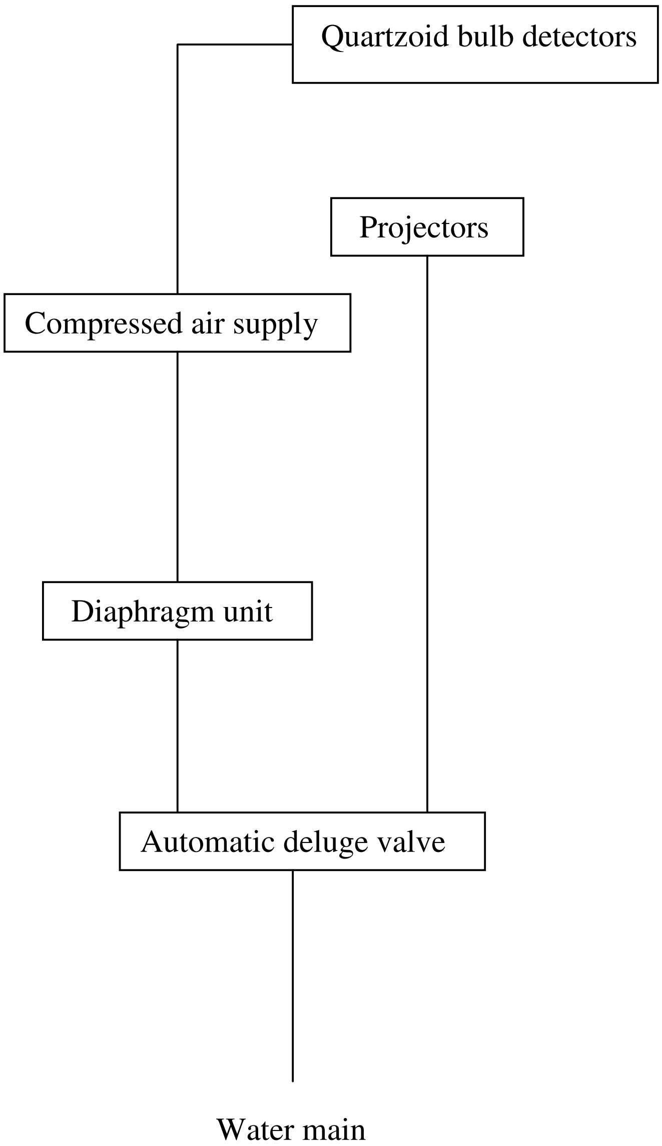


Figure 11.2: Block diagram of a deluge system

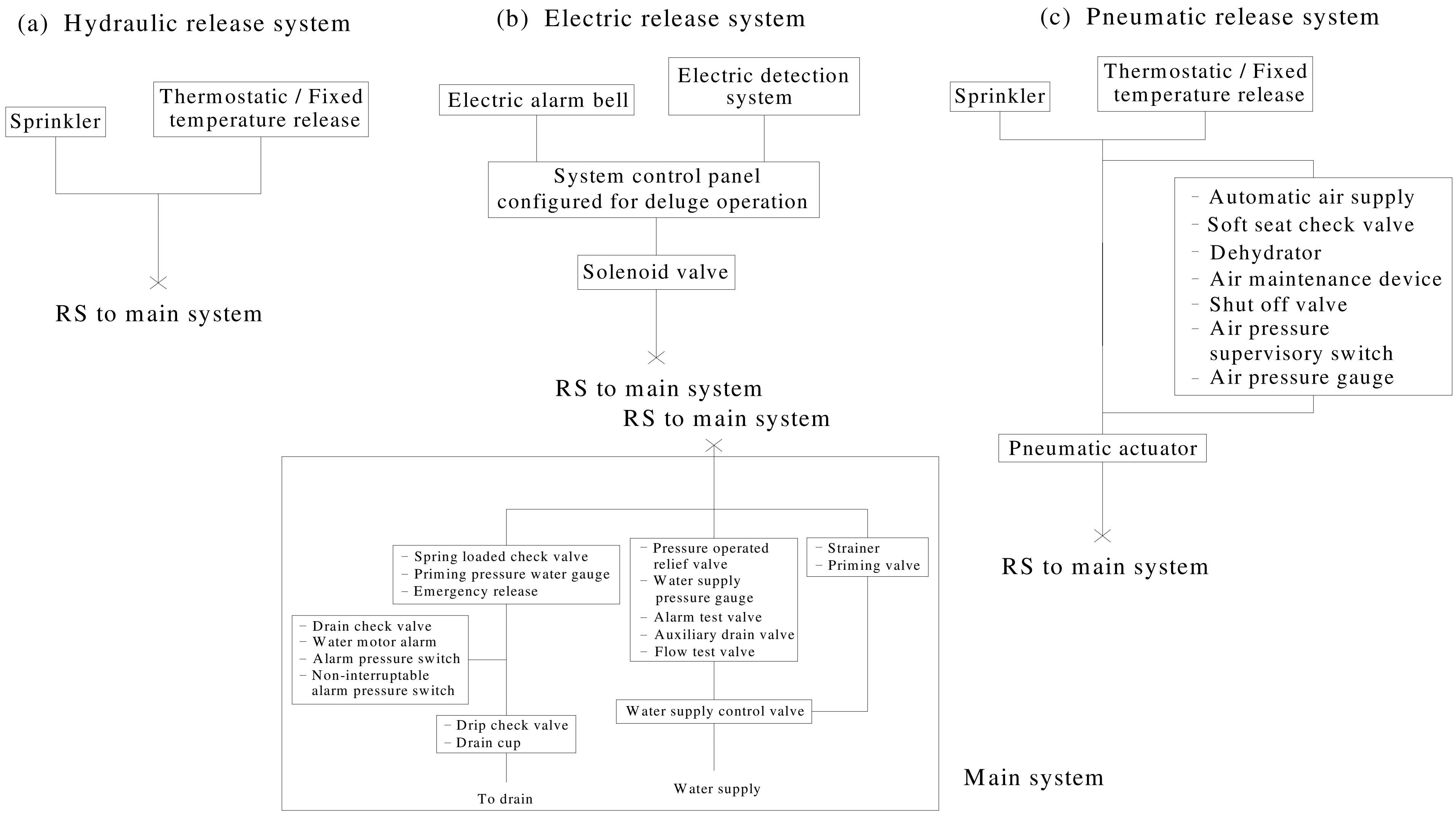


Figure 11.3: Block diagram of a deluge system controlled by different types of release systems

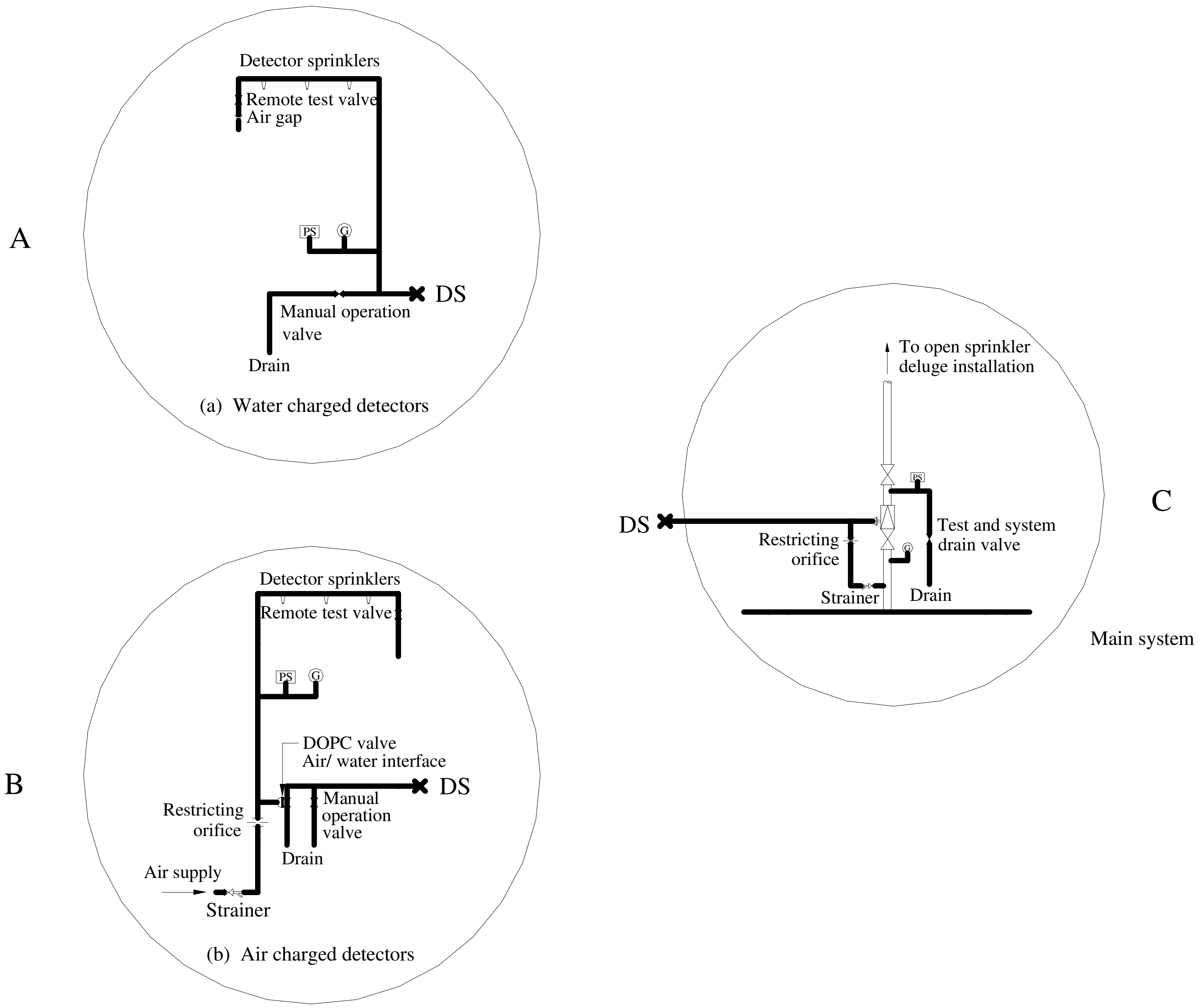


Figure 11.4: Deluge system using different types of detectors

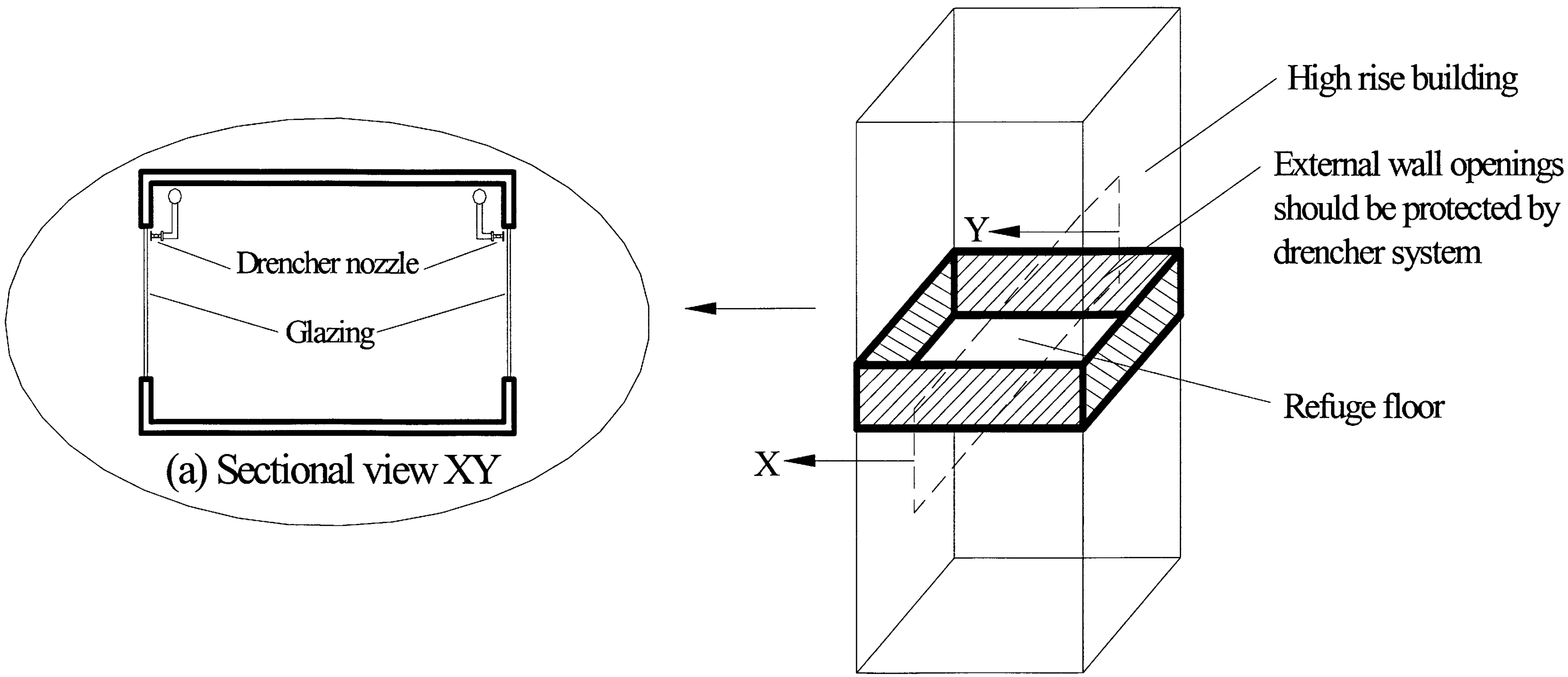


Figure 11.5: Diagram of a typical drencher system in Hong Kong

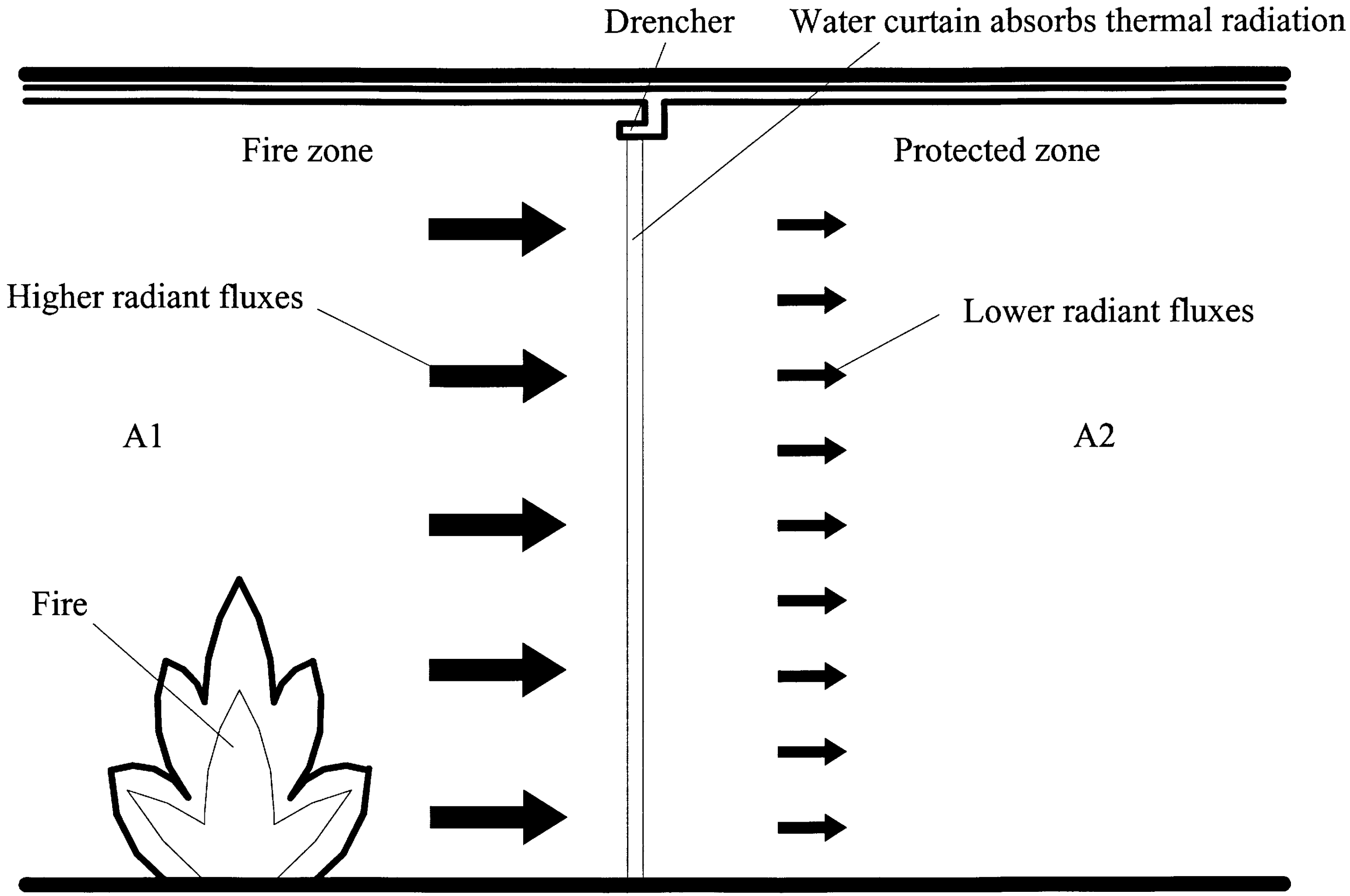


Figure 11.6: Working principle of the drencher system

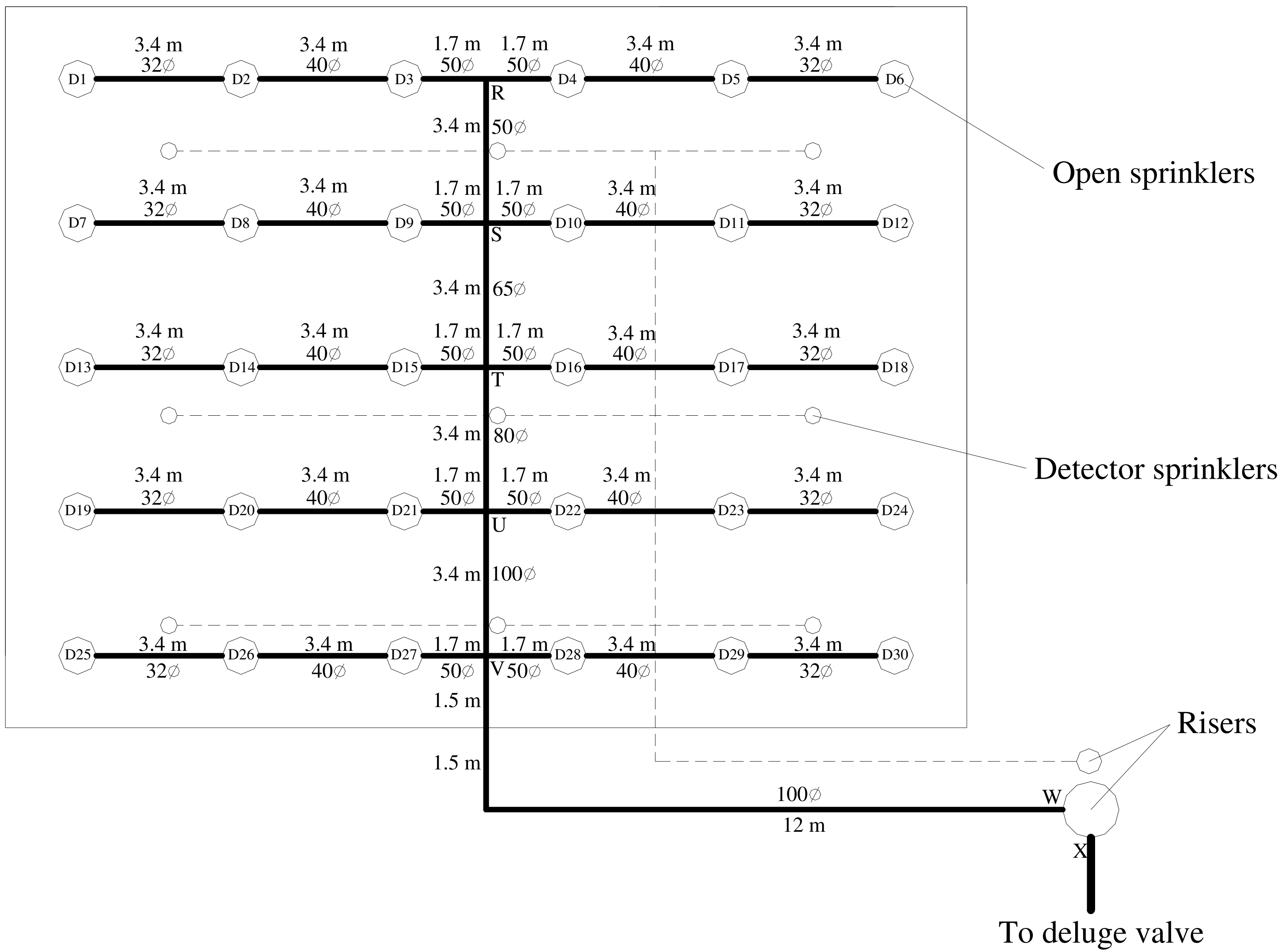


Figure 11.7: Layout of deluge system and detection system in an aircraft hanger

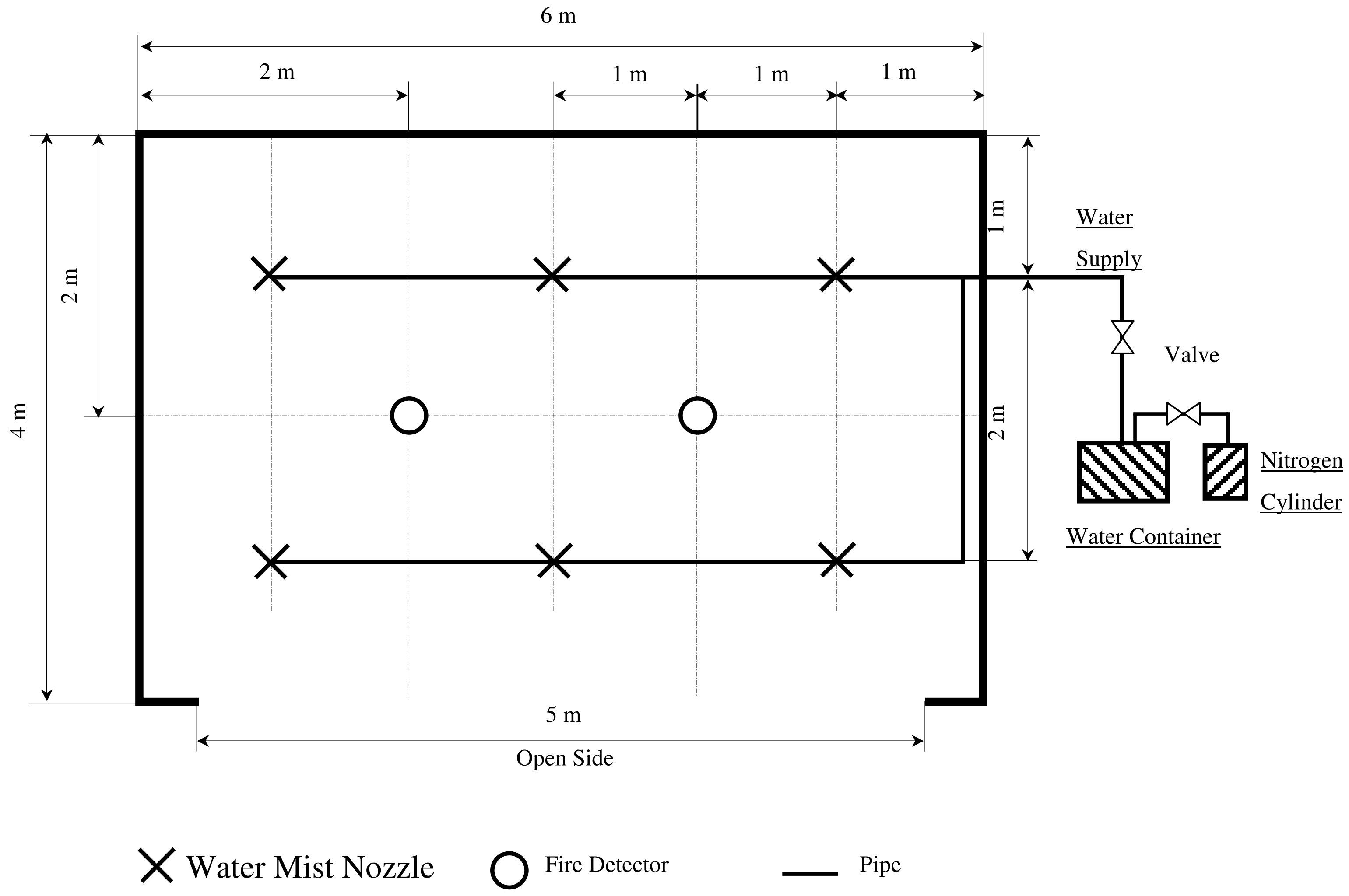


Figure 11.8: WMFSS application in a small retail shop (top view)

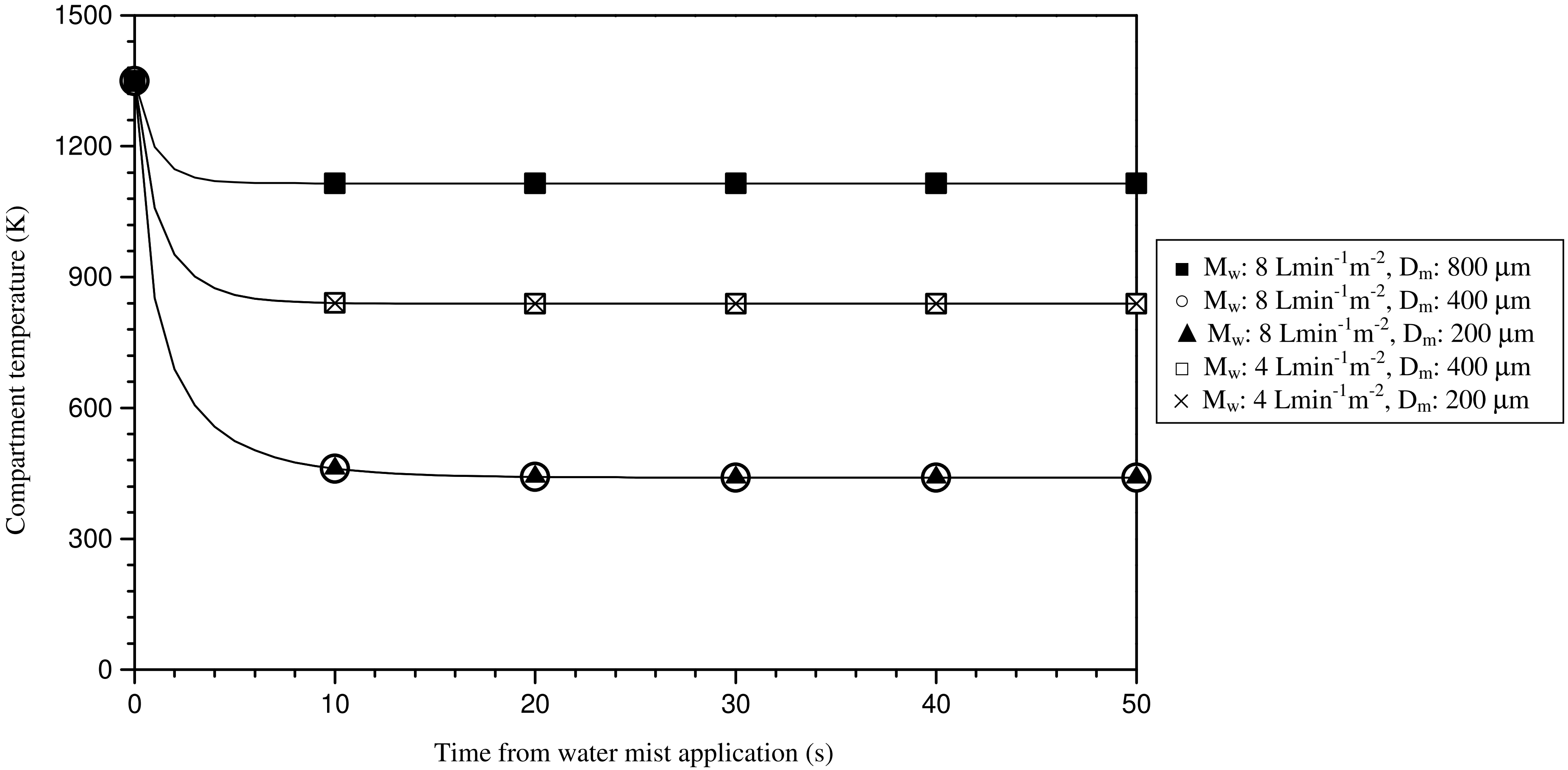


Figure 11.9: Gas temperature in the shop after water mist application (H_d: 2.1 m)

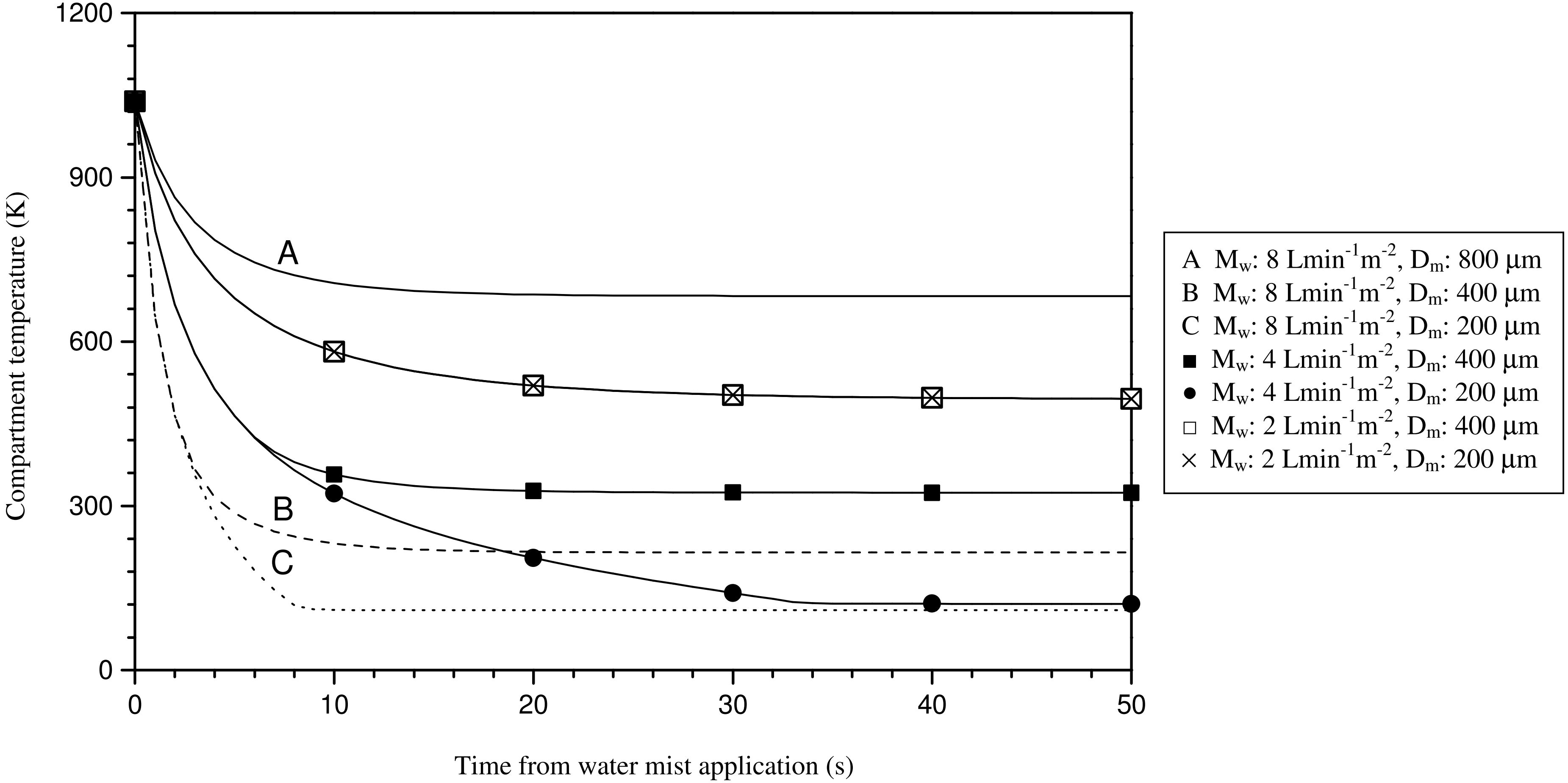


Figure 11.10: Gas temperature in the shop after water mist application (H_d: 1 m)

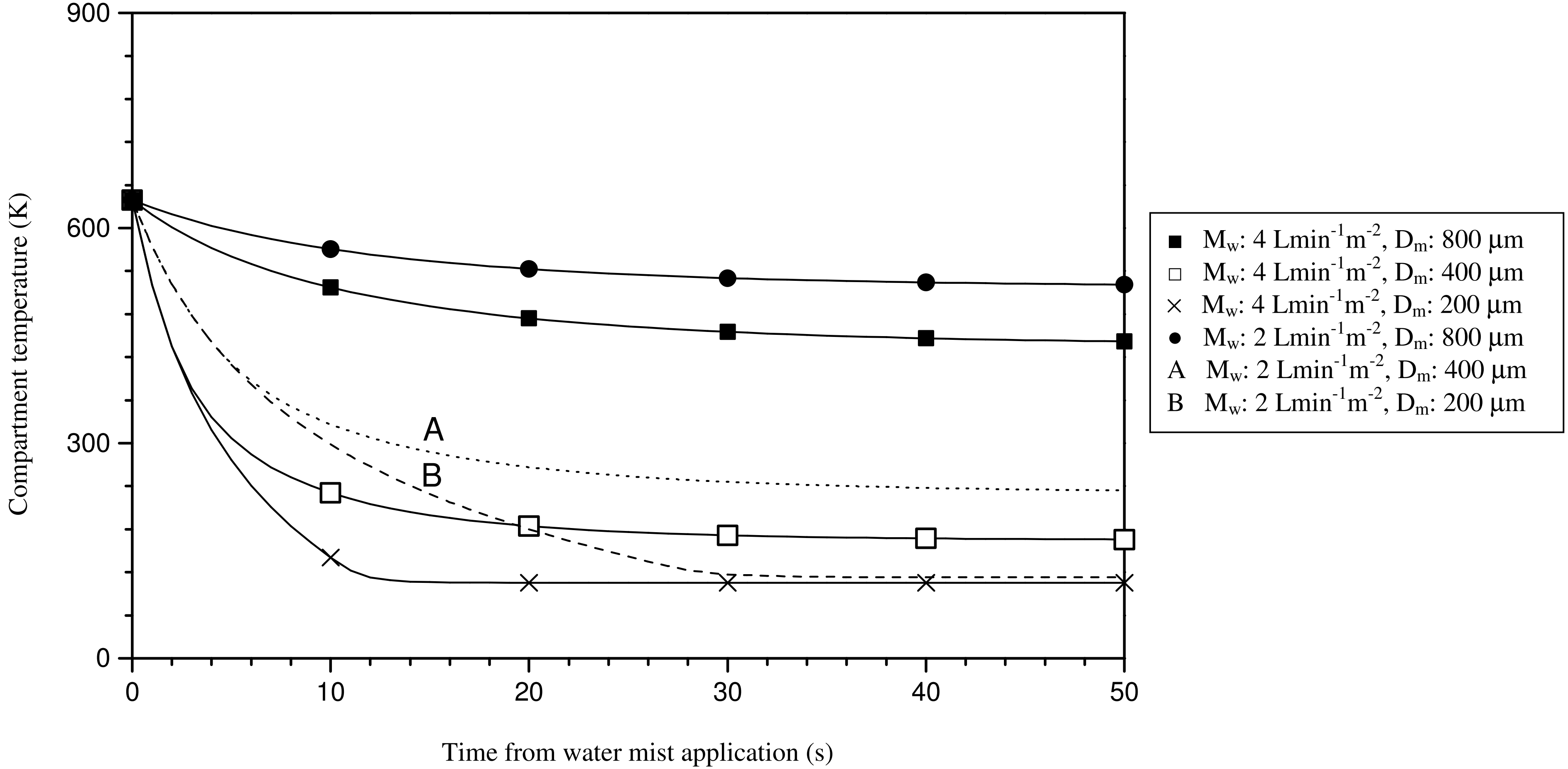


Figure 11.11: Gas temperature in the shop after water mist application (H_d: 0.5 m)

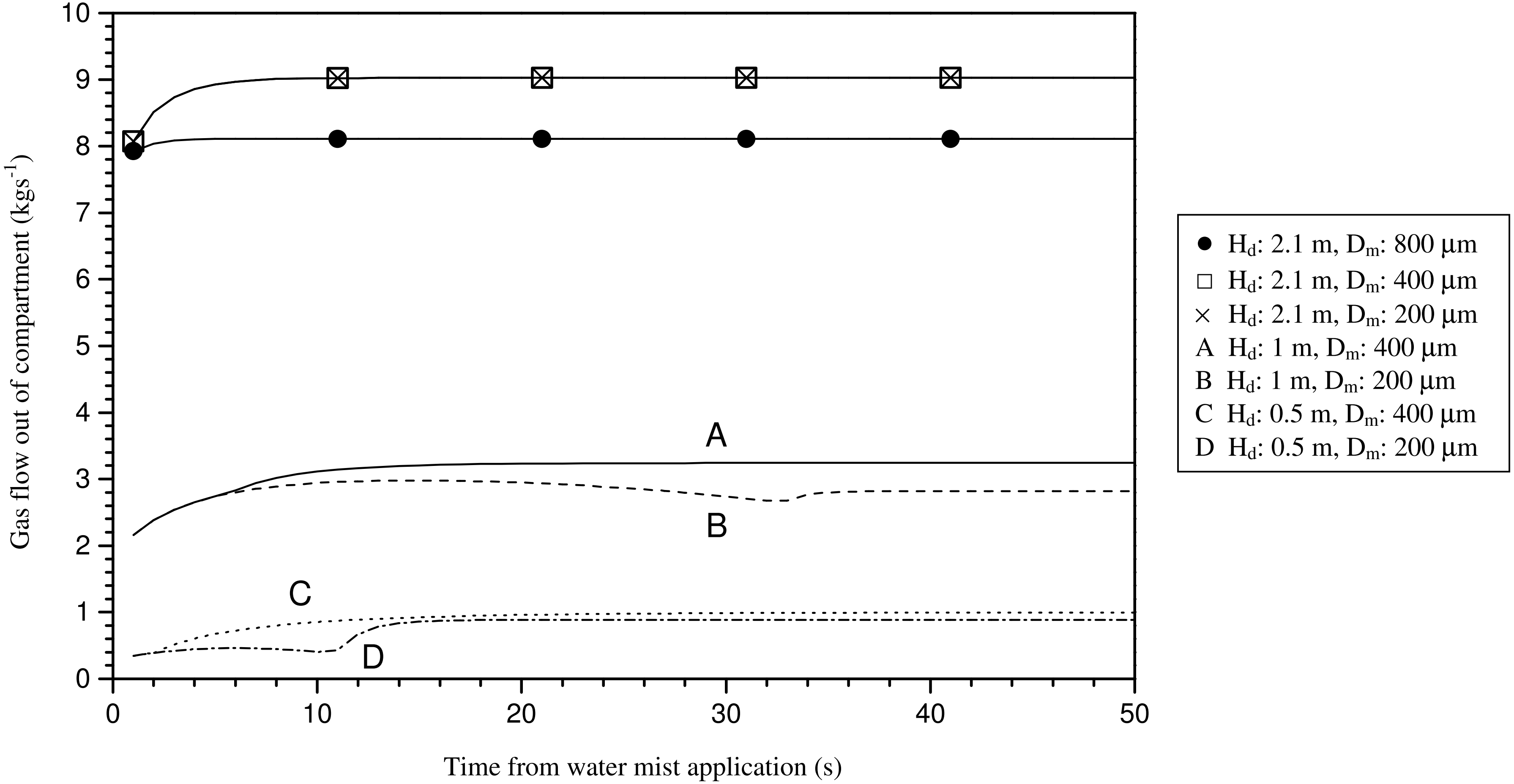
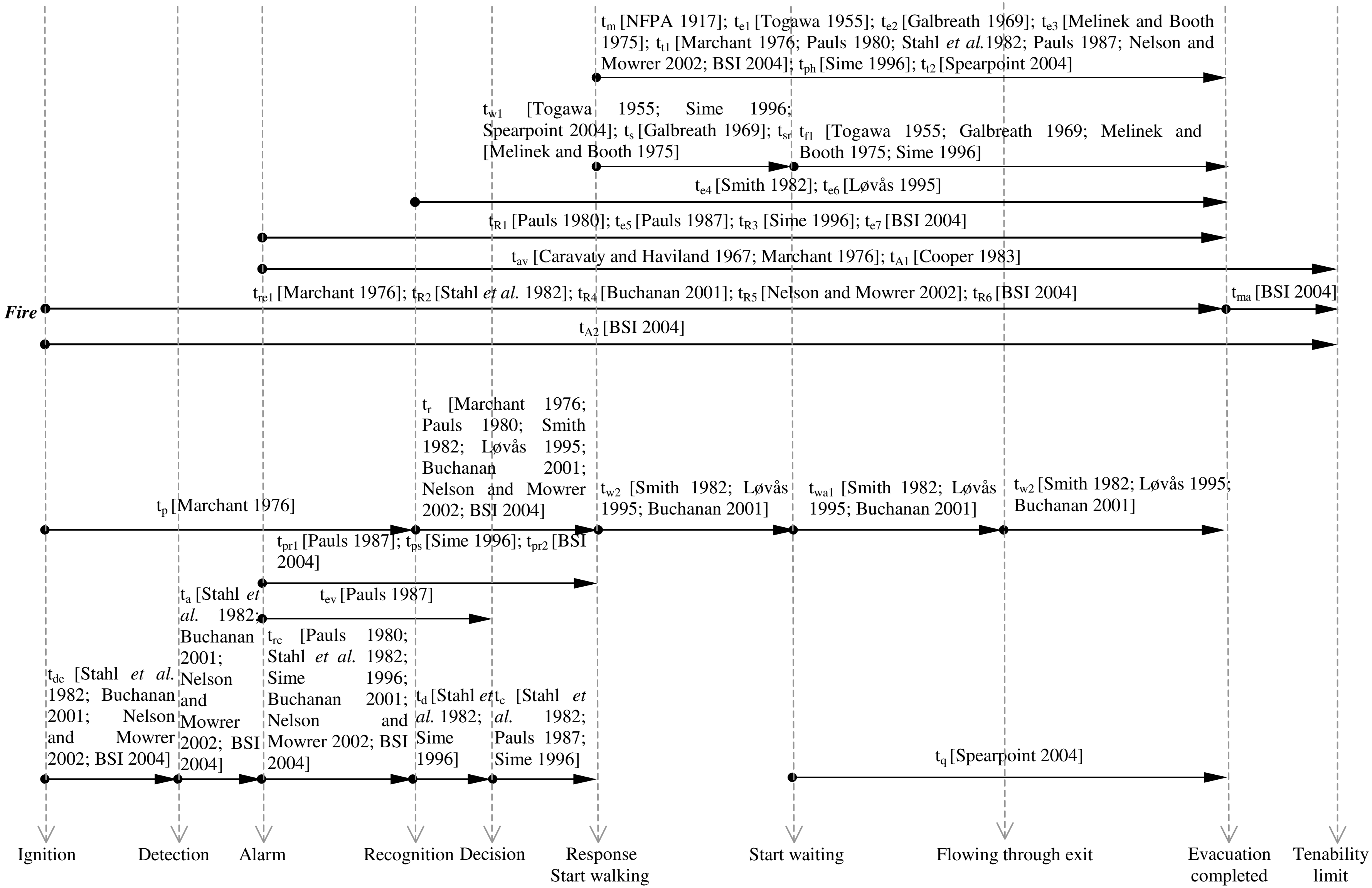


Figure 11.12: Gas flow rate out of the compartment after water mist application (M_w: 4 $Lmin^{-1}m^{-2}$)



BSI = British Standards Institution, NFPA = National Fire Protection Association

Figure C.1: Time line of fire development and evacuation process

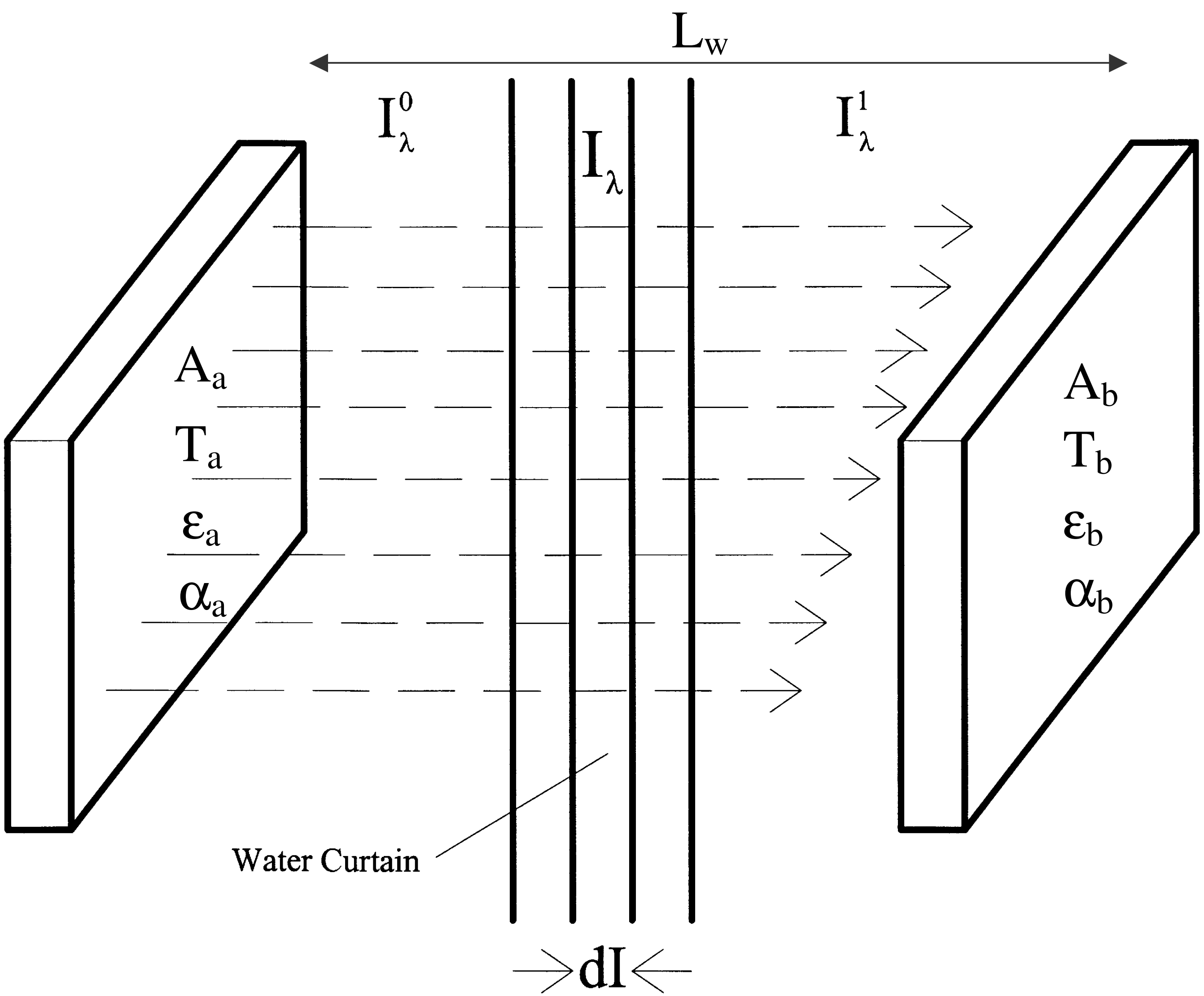


Figure F.1: Schematic diagram of the attenuation model

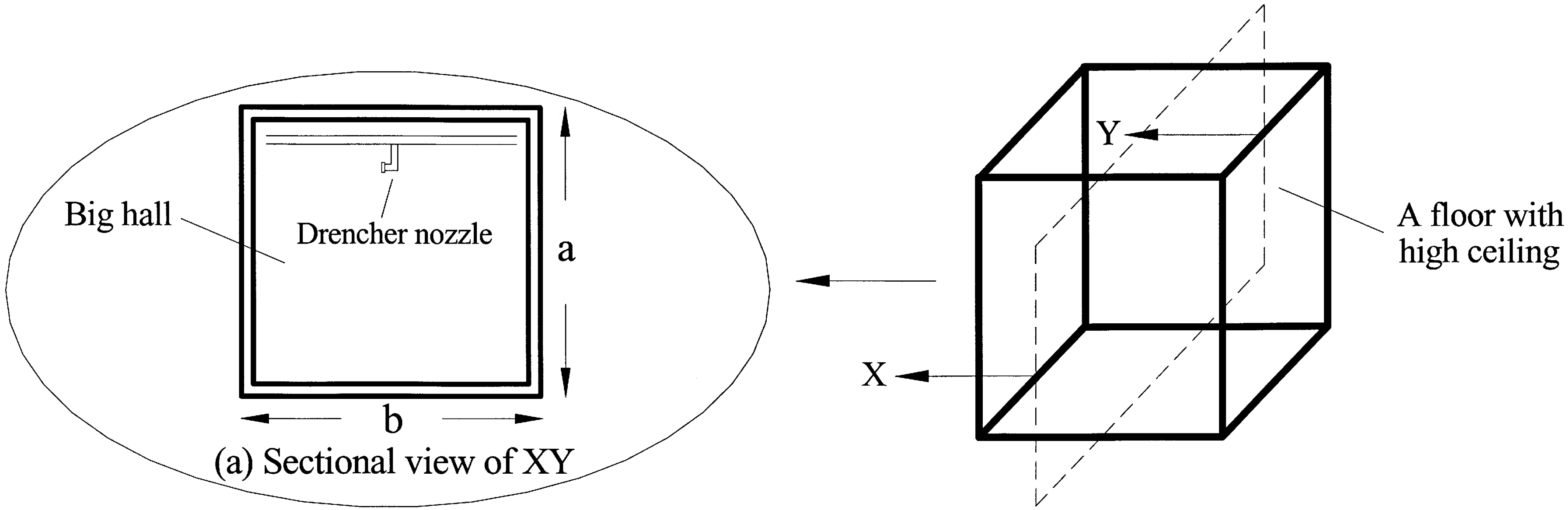


Figure G.1: Diagram of drencher nozzle installed inside a big hall for case F1

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Appendix A: Examples on fire safety objectives

- Life safety objectives of staff and occupants

  Evacuation of occupants is affected by many factors, such as age, social affiliation and responsiveness, mental ability and mobility [British Standards Institution 1999]. Further, evacuation pattern of airport terminal and railway stations would be affected by the baggage carriage, distributions of occupants and familiarity with the building.

  - Age

    Age of people is a major factor in affecting evacuation, especially for young children and older people who rely on the actions of others to effect their evacuation. For example, young children do not know the things happened and the method to evacuate in case of an emergency. They would become very nervous, frightened or just crying. As a result, the assist from elder persons to evacuate is required.

    On the other hand, response and movement of older persons are slow and the assist by other persons who are familiar with the building, such as staff, is very important during their evacuation.

- Social affiliation

  Behaviour of persons would be easily affected by a group of people. If a lot of people towards an escape route, the other passengers would also follow this route. However, this may not the nearest escape route. Therefore, signs such as flashing lights should be easily noticeable for indicating the escape route. Emergency announcements should also be made easily audible to everywhere to control the flow of people.

- Responsiveness

  Responsiveness of occupants to an emergency situation is affected by many psychological factors, such as the mental and physical state, response to the warning given by detection system and whether they feel threatened from the emergency. If the occupants are asleep, their awareness to the environment would be reduced and hence their response times to the fire alarm are delayed. Therefore, more indication such as broadcast the evacuation messages through the Public Address (PA) system should be given to the passengers to initiate the intention of passengers to evacuate when an emergency is occurred.

- Physical and mental ability and mobility

  It is unavoidable that a proportion of occupants would be mentally or physically disabled. Some of them would be immobile and need the assist from other occupants or staff. Their initial responses would be slower and needed more time to recognize that an emergency is occurred. The movement of them is also affected by their disability and the building elements such as width of the escape route and doors, ramps and whether disabled lifts are provided instead of staircases.

- Baggage carriage

For some places such as the airport terminal and railway stations, majority of escaping passengers will take their baggage in case of an emergency. If the baggage is large or heavy, this will not only hinder the evacuation, but also affect the escape of other occupants. Therefore, attention should be paid on the amount of baggage carried by each passenger. Size, amount and weight of the baggage should be limited.

- Distribution of occupants

Occupants would not be evenly distributed inside a building. Therefore, population density for some parts of building is high. When there is an emergency occurred, the escape route would be blocked and increased the risk of occupants being subject to fire and smoke. In order to limit the people within each part of building, adequate compartmentation should be provided to inhibit the spread of fire. However, some buildings with special architectural features, such as the airport terminal, compartmentation is not available inside the big hall. As a result, other methods should be considered to increase the safety of occupants.

- Familiarity with the building

  Occupant response is influenced by their familiarity with the building. Occupants such as the staff would have a knowledge of the nearest and alternative escape route. However, the occupants who are not familiar with the escape route can only leave by the route they entered the building. Therefore, they depend on the signs and the emergency announcements in order to evacuate to a safe refugee area.

- Life safety objectives of fire fighting personnel

  It is necessary to minimize the risk for fire fighting personnel when they exposed to fire and smoke inside the infected areas. The fire suppression system, such as automatic sprinkler system, should be operated at the right time. However, water should not be discharged too early before evacuation as the steam produced will hurt the occupants.

- Property protection objectives

  For the property protection, it is divided into three parts: the structure, its contents such as the shops inside the building, and interruption of the business. For the structure and its contents, they have different susceptibility to fire damage caused by heat and smoke. Linings, fixtures and fittings, services and contents are likely to be damaged by a post-flashover fire. The cost for the refurbishment work would be high.

The value of a fire-damaged object can be considered not only a straight financial replacement cost, but also the loss of asset and productive time. Time lost in replacing key fire-damaged objects should be included. Interruption to the business inside a building will also affect the public image and cause a huge amount of monetary losses. Therefore, it is necessary to employ certain methods to limit the monetary losses or spatial extent of damage, for example, to select the materials with a certain FRP, provide specific protection such as fire shutter and contingency planning in order to detect the fire as early as possible to allow manual or automatic extinguishment.

- Objectives on minimum disturbance to normal operation

Fire damage should be limited to prevent undesirable effects on a building and the availability and lead time for obtaining replacement parts. As the airport is under busy operation, interruption to the airport service should be avoided. Even an accidental fire occurs, part of the airport should be able to operate. Therefore, the fire area should be limited, say by control the flammable contents inside the building. It is better to employ some professionals to inspect the building structure after a fire happened, in order to certify that it will not be collapsed suddenly after continuing the business.

- Objectives on environmental concerns

Environmental protection is also a concern due to toxicity of combustible products; and contamination by fire protection runoff water. Although the environmental effect is localized and temporary [e.g., Bukowski and Babrauskas 1994], it should not be neglected. If large quantities of contaminants are expected, the fire protection system should operate well so as to detect a fire and initiate appropriate response prior to reaching a predetermined mass loss from burning materials or quantity of fire suppression agent discharged.

Appendix B: Parameters involved in FRAME

- Potential risks

Potential risks of building and its content (P), occupants (P_1) and activities (P_2) can be expressed in terms of the fire load factor q_f, fire spread factor i, area factor g_a, level factor e, venting factor v and access factor z_a as:

$$P = q_f \times i \times g_a \times e \times v \times z_a \qquad \text{… (B.1)}$$

$$P_1 = q_f \times i \times e \times v \times z_a \qquad \text{… (B.2)}$$

$$P_2 = i \times g_a \times e \times v \times z_a \qquad \text{… (B.3)}$$

Fire load factor q_f indicates the amount of combustibles present in a shop; fire spread factor i describes the ability of fire spreading; area factor g_a indicates horizontal influences of a fire; level factor e indicates vertical influences of a fire; venting factor v indicates influences of heat and smoke by comparing venting capacity with the sources of smoke; and access factor z_a indicates the difficulty for fire fighters to reach the fire area.

- Acceptance levels

Acceptance levels for loss of property (A), threat to people (A_1) and threat to business (A_2) are calculated from the activation factor a which is related to the number of fire sources; evacuation time t_{eva} which is affected by the priority given to human safety; volume number c which indicates the severity of loss; environment factor r_e related to the severity of fire spread; and dependence factor d_f which shows the impact on business. This set of values defines the numerical values which measure the acceptability of fire, so as to determine the risk tolerated in case of fire. Maximum value of the acceptance level is equal to 1.6.

$$A = 1.6 - a - t_{eva} - c \quad \text{… (B.4)}$$

$$A_1 = 1.6 - a - t_{eva} - r_e \quad \text{… (B.5)}$$

$$A_2 = 1.6 - a - c - d_f \quad \text{… (B.6)}$$

- Initial risks

Initial risk R_o is calculated by the structural fire resistance factor F_o which indicates the fire resistance of the structural elements inside a building, potential risk of building and its content P and acceptance level for loss of property A. R_o determines the level of protection such as risk separation, smoke venting and fire proofing required.

$$R_o = \frac{P}{A \times F_o} \quad \text{… (B.7)}$$

- Protection levels

Protection levels for building and its content (D), occupants (D_1) and operation of business (D_2) are determined by the water supply factor W_s, i.e. ability of water supplies, normal protection factor N_p, i.e. ability of normal protection, special protection factor S, i.e. ability of special protection, fire resistance factor F_r, i.e. ability of fire resistance, escape factor U, i.e. ability of escape protection and salvage factor Y, i.e. ability of salvage possibilities.

D, D_1 and D_2 are calculated by:

$$D = W_s \times N_p \times S \times F_r \quad \ldots \text{(B.8)}$$

$$D_1 = N_p \times U \quad \ldots \text{(B.9)}$$

$$D_2 = W_s \times N_p \times S \times Y \quad \ldots \text{(B.10)}$$

These elements determine the quality and quantity of fire protection available for retail shops. As the protection levels are inversely proportional to fire risks, values of these should be as high as possible.

- Fire Risks

Fire risks (R, R_1 and R_2) are calculated by the associated potential risk P, acceptance level (A, A_1 and A_2) and protection level (D, D_1 and D_2) to determine whether there is an equilibrium between risk and protection. For building with adequate fire protection, values of R, R_1 and R_2 would be less than 1.

Fire risk R for building and its content:

$$R = \frac{P}{A \times D} \qquad \text{… (B.11)}$$

Fire risk R_1 for occupants:

$$R_1 = \frac{P_1}{A_1 \times D_1} \qquad \text{… (B.12)}$$

Fire risk R_2 for the business activities:

$$R_2 = \frac{P_2}{A_2 \times D_2} \qquad \text{… (B.13)}$$

Appendix C: A Review on different time concepts

Importance of evacuation in hazard assessment

Evacuation time is an important time concept for recognizing the time required by all occupants to move from the hazard area to a safe region when they recognize the danger and start to evacuate. The margin of safety, which is the difference between the calculated value of the required evacuation time and available time of occupants to escape from the building, i.e. Required Safe Egress Time (RSET) and Available Safe Egress Time (ASET), can be used to determine the life safety in building.

A time line relating the evacuation process is shown in Figure C.1. In case of an emergency, different occupant groups would be merged before the exits [Thompson and Marchant 1995b]. Due to the reduction of flow rate at exits, congestion is likely to occur before the exits if large numbers of occupants were evacuated simultaneously. Queuing would occur and waiting effects in queues should not be ignored as it will affect the movement of occupants and lengthen the evacuation time. The time can be altered by the crowd density, selection of exits, and number and width of the exits used.

Time line concepts

Different time concepts of occupants have to be classified in evacuation. The concepts on evacuation time, RSET, ASET and time components included in evacuation such as pre-movement time, recognition time, response time, travel time, walking time and flow time were outlined.

- Evacuation time

The term "maximum emptying time" t_m (in min), i.e. the time for clearing the occupants within the building, was introduced in 1917 [National Fire Protection Association 1917]. It was the earliest time concept involved in the evacuation process and was considered to be the evacuation time as reviewed by Pauls [1987]. According to the National Bureau of Standards [1935], t_m can be reduced by utilizing a high flow rate in exit design. Based on the purported evacuation time in the theatre fire of Edinburgh in 1911, t_m for buildings was specified to 2.5 min [Her Majesty Stationery Office 1952].

Evacuation time is defined as the elapsed time that the occupants receive an alarm and arrive a destination where it is a safe location inside or outside the building [e.g. Ghosh 1997; Pauls 1987; Proulx 1995; Smith 1982]. It can be understood as the time interval between the raising of alarm and completion of evacuation [British Standards Institution 2004].

Evacuation was studied by Togawa [1955]. Examples were on the mass evacuation of buildings across the openings of department stores, theatres and station premises; moving out from elevators; and getting off from buses and trains. Railway station will have a high passenger loading during rush hours. Scenarios of passengers to escape from train, moving in platform and passing through the exit were analyzed to determine the evacuation time of passengers in the railway station [Togawa 1955].

A formula for calculating the evacuation time t_{e1} (in s) of passengers to escape from the station platform was derived [Togawa 1955]. Taking a train with the total number of passengers N_{a1} and n doors of width B_i (in m) for the i^{th} door (where i = 1,….,n) as an example, time T_o (in s) is the period between the occupants moving out from the train and the queues start to form at platform exit. The number of passengers N_1 who can escape can be expressed in terms of the flow rate of people moving out the i^{th} train door f_{pi} (in person $m^{-1}s^{-1}$), and percentage ϕ_i (in %) of the number of passengers gathered at the i^{th} door to the number of passengers going to other doors:

$$N_1 = \sum_{i=1}^{n} \int_0^{T_o} f_{pi}(t) B_i \phi_i(t) dt \qquad \text{… (C.1)}$$

After T_o, flow time t_{f1} (in s) of passengers who can pass through the platform exit is expressed in terms of the width of platform exit B' (in m) and flow rate of people f_p' (in person $m^{-1}s^{-1}$) passing through the exit:

$$t_{f1} = \frac{1}{f_p\text{'}B\text{'}}\left(N_{a1} - N\right) \qquad \text{… (C.2)}$$

Evacuation time t_{e1} (in s) can be expressed as a sum of the time period T_o for passengers to move out the train and begin to queue up before the platform exit, and flow time t_{f1} of passengers who can pass through the platform exit after T_o:

$$t_{e1} = T_o + t_{f1} \qquad \ldots \text{(C.3)}$$

A relatively simple expression can be derived for T_o and t_{f1} by assuming all passengers escaped from the train door which is the furthest from the platform exit [Togawa 1955]. Suppose the distance from the last train door to the platform exit is k_s (in m) and the walking velocity of the crowd is v_1 (in ms^{-1}), T_o is taken as the walking time t_{w1} (in s) of passengers travelled to the platform exit:

$$T_o \approx t_{w1} = \frac{k_s}{v_1} \qquad \ldots \text{(C.4)}$$

Equation (C.2) of t_{f1} can be simplified by taking all passengers passing through the platform exit without jamming:

$$t_{f1} = \frac{N_{a1}}{f_p 'B'} \qquad \ldots \text{(C.5)}$$

An approximate formula of t_{e1} can be expressed as:

$$t_{e1} = t_{w1} + t_{f1} \qquad \ldots \text{(C.6)}$$

The above expression of t_{e1} derived by Togawa [1955] was pinpointed on the station platform. It is only applicable to the platforms with a single floor. In applying t_{e1} to tall buildings, travel time in staircases should be considered.

Evacuation of multi-story buildings was studied by Galbreath [1969]. Two time periods were defined in the evacuation time t_{e2} (in s), i.e. walking time t_s (in s) of occupants required to travel the staircase, and the flow time t_{f1} required for the occupants to discharge from the base of stairs and passing through the exit.

$$t_{e2} = t_s + t_{f1} \qquad \ldots \text{(C.7)}$$

This equation holds when T_o is shorter than t_s.

The effect of different occupant loadings in multi-story buildings was considered by Melinek and Booth [1975]. Consider a building of i floors, where i = 1,..r,..m, the flow time t_{f1} (in s) of occupants on the r^{th} floor and above to enter the staircase can be expressed by the number of occupants Q_{nj} on the r^{th} floor and above, where j = r,….,m; flow rate f_1 (in person $m^{-1}s^{-1}$) per unit width of the staircase and width of the staircase b' (in m) as:

$$t_{f1} = \frac{\sum_{j=r}^{m} Q_{nj}}{f_1 \times b'} \qquad \ldots \text{(C.8)}$$

Evacuation time t_{e3} (in s) of occupants from the r^{th} floors and above can be expressed in terms of the flow time t_{f1} (in s) and walking time t_{sr} (in s) for the unimpeded crowd on the r^{th} floor to reach the ground floor.

$$t_{e3} = t_{sr} + t_{f1} \qquad \ldots \text{(C.9)}$$

Psychological effects of the occupants during evacuation were not considered in t_{e1}, t_{e2} and t_{e3}. Once the occupants recognized the occurrence of a fire, they are assumed to escape immediately. However, the response time t_r (in s) of the occupants to the warning prior to beginning evacuation was considered by Smith [1982] in determining the evacuation time t_{e4} (in s). t_{e4} will be regulated by the longest time of an occupant to exit the building. The longest time includes the response time t_r, walking time t_{w2} (in s) and waiting time t_{wa1} (in s) at each queue to exit.

$$t_{e4} = t_r + t_{w2} + t_{wa1} \qquad \text{… (C.10)}$$

Psychological effects of occupants during evacuation were further elaborated by Pauls [1987]. Two major components, pre-movement time t_{pr1} (in s) taken up by relatively complex behaviour that precedes egress, and time for some individuals to move along the most direct egress route, i.e. travel time t_{t1} (in s), should be included in the calculation of evacuation time t_{e5} (in s).

$$t_{e5} = t_{pr1} + t_{t1} \qquad \text{… (C.11)}$$

t_{pr1} can be expressed in terms of the evaluation time t_{ev} (in s) of occupants to recognize the fire and the decision to take action, and the coping time t_c (in s) that diverts the occupants from the most direct egress route to take action, i.e. inform others, assist others or fight the fire.

$$t_{pr1} = t_{ev} + t_c \qquad \text{… (C.12)}$$

The calculation of t_{t1} is similar to t_{e1} [Togawa 1955], which is involved the walking time t_{w1} to move along the egress route and the flow time t_{f1} to pass through the opening of the egress system.

$$t_{t1} = t_{e1} = t_{w1} + t_{f1} \qquad \ldots \text{(C.13)}$$

An evacuation model was established by Løvås [1995]. The components of the evacuation time t_{e6} (in s) are similar to t_{e4} [Smith 1982], which are expressed in terms of t_r, t_{w2} and t_{wa1}.

$$t_{e6} = t_{e4} = t_r + t_{w2} + t_{wa1} \qquad \ldots \text{(C.14)}$$

Human behaviour, queuing effect and occupant loading had been considered in British Standard [British Standards Institution 2004] for calculating the evacuation time t_{e7} (in s). Two cases were specified for t_{e7} with respect to different occupant density [e.g. Purser 2003; Purser and Bensilum 2001].

Case 1: Low occupant density

The enclosure is sparsely populated with a population density less than 1/3 of the design population [Purser 2003; Purser and Bensilum 2001]. Due to the low occupant density, walking speed to the exits is unimpeded. Pre-movement time in this case would become longer as the occupants can not aware the fire or get the information from others [Purser 2003; Purser and Bensilum 2001]. Therefore, t_{e7} is expressed in terms of the pre-movement time t_{p99} (in s) and walking time t_{w3} (in s) of the last few occupants. t_{w3} is equal to the unimpeded walking speed multiplied by the average or maximum travel distance.

$$t_{e7} = t_{p99} + t_{w3} \quad \ldots \text{(C.15)}$$

Case 2: High occupant density

The enclosure has the maximum design population. For the high occupant loading, the pre-movement time is shorter as occupants can recognize the occurrence of fire easily through the communication with others and evacuate together [Purser 2003; Purser and Bensilum 2001]. Therefore, t_{e7} can be expressed in terms of the pre-movement time t_{p1} (in s) and walking time t_{w4} (in s) of the first few occupants, and flow time t_{f1} of the total number of occupants to pass through the available exits.

$$t_{e7} = t_{p1} + t_{w4} + t_{f1} \quad \ldots \text{(C.16)}$$

- Required Safe Egress Time (RSET)

"Time required for escape" t_{re1} (in s) is the time taken for an individual or building population to reach safety, which can be understood as the target time for ensuring complete evacuation and all occupants remain safe for any portion of the time spent inside the building [Caravaty and Haviland 1967; Marchant 1976a, b; Togawa 1955]. Psychological effects of occupants were considered by Marchant [1976a, b]. t_{re1} can be expressed in terms of the elapsed time from ignition to perceive that a fire exists, i.e. perception time t_p (in s), elapsed time from recognition to the beginning of safety action, i.e. response time t_r and elapsed time from initiation of action to reach a safe place, i.e. travel time t_{t1}:

$$t_{re1} = t_p + t_r + t_{t1} \qquad \text{… (C.17)}$$

The term "Required Safe Egress Time" (RSET) was identified by Pauls [1980]. Three terms were involved in RSET t_{R1} (in s) [Pauls 1980], i.e. recognition time t_{rc} (in s) from being alerted by a cue to know that there is a fire, response time t_r from knowing that there is an emergency to begin escape and travel time t_{t1} for beginning to escape from the building.

$$t_{R1} = t_{rc} + t_r + t_{t1} \qquad \text{… (C.18)}$$

RSET t_{R2} (in s) was illustrated by Stahl *et al.* [1982]. t_p and t_r utilized in t_{re1} [Marchant 1976a, b] were further divided into a number of discrete time intervals [Stahl *et al.* 1982]. t_p can be expressed in terms of the detection time t_{de} (in s) required for sensing a stimulus from fire environment, notification time of sensation t_a (in s) and recognition time t_{rc} required to become aware of this sensation as a potential life threat, while t_r was understood as the time t_d (in s) required to evaluate the quality and extent of life threat and coping time t_c required to initiate effective actions. The travel time t_{t1} needed to escape from the building was represented by the time required to follow-through and complete the actions leading to safety.

$$t_{R2} = t_{de} + t_a + t_{rc} + t_d + t_c + t_{t1} \quad \dots \text{(C.19)}$$

RSET was defined by Cooper [1983] as the length of time subsequent to alarm, which is required for the occupant to escape safely from the threatened spaces. It can be understood as the overall time required for the occupants to evacuate the building in response to a cue [Hinks 1985; Maclennan 1986; Sime 1984]. According to Sime [1996], RSET t_{R3} (in s) can be divided into two parts, i.e. psychological time component t_{ps} (in s) and physical time component t_{ph} (in s).

$$t_{R3} = t_{ps} + t_{ph} \quad \dots \text{(C.20)}$$

Times involved in t_{ps} are related to human behaviour when there is a fire, i.e. recognition time t_{rc} from people being alerted by a cue to recognize that there is a fire, decision time t_d related to the decisions to take actions, and coping time t_c which includes actions after recognition, such as warn the others and fight the fire.

$$t_{ps} = t_{rc} + t_d + t_c \quad \dots \text{(C.21)}$$

The time components involved in t_{ph} are the physical movement of occupants during evacuation. t_{ph} can be expressed in terms of the walking time t_{w1} and flow time via exits t_{f1}, which is similar to t_{e1} [Togawa 1955].

$$t_{ph} = t_{e1} = t_{w1} + t_{f1} \quad \dots \text{(C.22)}$$

RSET t_{R4} (in s) was sub-divided by Buchanan [2001] into a number of discrete time intervals. As occupants have undergone hazards once a fire started, detection time t_{de} and notification time t_a were involved in t_{R4}. Except t_{de} and $t_{a,}$ recognition time t_{rc}, response time t_r, movement time t_{w2} and waiting time t_{wa1} were also considered in the calculation.

$$t_{R4} = t_{de} + t_a + t_{rc} + t_r + t_{w2} + t_{wa1} \qquad \text{… (C.23)}$$

RSET t_{R5} (in s) raised by Harold *et al.* [2002] was similar to that raised by Buchanan [2001]. t_{R5} involved the time from fire ignition to detection t_{de}, time from detection to notification of occupants in case of fire t_a, time from notification until occupants decide to take action t_{rc}, and the time for decision to take action until evacuation commences t_r. t_{de} and t_a will be affected by the fire detection system and fire alarm system, while t_{rc} and t_r are related to the individual and collective responses of occupants until they start to evacuate. Instead of the walking time and waiting time, the travel time t_{t1} of occupants is comprised in t_{R5} as:

$$t_{R5} = t_{de} + t_a + t_{rc} + t_r + t_{t1} \qquad \text{… (C.24)}$$

For the earlier versions of British Standards, such as draft code of practice [British Standards Institution 1994] and technical report [British Standards Institution 1999], RSET is interpreted as “escape time”. The escape time [British Standards Institution 2004] is the period between ignition and the time in which all the occupants are able to reach a place of safety. For RSET, it is the calculated time available between the ignition of a fire and the time at which occupants in a specified place of building are able to reach a place of safety [British Standards Institution 2004]. RSET t_{R6} (in s) of occupants [British Standards Institution 2004] is similar to t_{R5} [Harold *et al*. 2002], which also includes the terms t_{de}, t_{a}, t_{rc}, t_{r} and t_{t1}.

$$t_{R6} = t_{R5} = t_{de} + t_{a} + t_{rc} + t_{r} + t_{t1} \quad \dots \text{(C.25)}$$

- Available Safe Egress Time (ASET)

The Available Safe Egress Time ASET t_{av} (in s) is interpreted as the "Time available" t_{av} (in s) in the previous years [Caravaty and Haviland 1967], which is the time required for toxic environment to reach a critical or untenable state. It is also understood [Marchant 1976a, b] as the elapsed time from ignition of a fire to the development of untenable environmental conditions.

ASET was developed by Cooper [1983] as the time interval between the initiation of alarm and the time of onset of hazardous conditions. Occupants would be safe under the fire conditions if they can escape from the threatened spaces successfully prior to the time when the hazardous conditions start to prevail. ASET t_{A1} (in s) can be expressed in terms of the detection time t_{de}, notification time t_{a} and the time of onset of hazardous conditions t_{h} (in s) as:

$$t_{A1} = t_{h} - t_{de} - t_{a} \quad \dots \text{(C.26)}$$

ASET [e.g. British Standards Institution 1997; Hinks 1985; Løvås 1995; Sime 1986] can be realized as the time available for safe egress before the fire-induced conditions inside the building become untenable. As mentioned in British Standard [British Standards Institution 2004], ASET is the calculated time available between the ignition of a fire and the time at which the tenability criteria are exceeded in a specified place of building. The criterion is set up as the maximum exposure to hazards that can be tolerated without causing incapacitation. All occupants should be able to evacuate before ASET is reached.

ASET t_{A2} (in s) [British Standards Institution 2004] can be expressed in terms of t_{R5} and the time difference between t_{A2} and t_{R6}, i.e. the margin of safety t_{ma} (in s):

$$t_{A2} = t_{R6} + t_{ma} \qquad \text{… (C.27)}$$

The time taken for an individual or building population to reach a place of safety should not exceed the time required for the environment to reach the critical or untenable state [e.g. Caravaty and Haviland 1967; Cooper 1983; Marchant 1976a, b]. A building is of safe design if ASET > RSET. The value of t_{ma} should be larger than zero. It is essential to identify t_{ma} for ensuring life safety, provided that occupants are evacuated in a safe condition without causing serious injuries or deaths. A safety index (SI) [Shields *et al.* 1992] can be derived with respect to t_{ma} and t_{R6} as:

$$SI = \frac{t_{ma}}{t_{R6}} \quad \ldots \text{(C.28)}$$

SI is used as a benchmark to identify the life safety of occupants in a building. The increased values of index indicate the increased levels of safety, while the increased levels of risk are indicated by the reduced values of SI.

- Pre-movement time

Pre-movement time t_{pr1} (in s) can be understood as the time taken up by the relatively complex behaviour during evacuation [Pauls 1987]. Two components, i.e. the period of recognition time and decision time t_{ev}, and coping time t_c, are involved in t_{pr1}.

$$t_{pr1} = t_{ev} + t_c \quad \ldots \text{(C.29)}$$

Pre-movement time is the time interval between the warning of fire being given (by an alarm or by direct sight of smoke or fire) and the first move being made towards an exit [British Standards Institution 1999, 2004]. The time will be affected by the flow of people. For example, the rate of people entered the exits will be different when the occupants are moving together or at different times. Pre-movement time t_{pr2} (in s) [British Standards Institution 2004] can be expressed in terms of the recognition time t_{rc} and response time t_r as:

$$t_{pr2} = t_{rc} + t_r \quad \ldots \text{(C.30)}$$

The pre-movement time [British Standards Institution 2004] is consisted of three phases.

- The time from raising of the alarm to the movement of the first few occupants to begin their travel phase, i.e. pre-movement time of the first occupants t_{p1}.

- The subsequent distribution of the pre-movement times for the occupants to begin their travel phase. This can be expressed as a distribution of the individual times, i.e. pre-movement time occupant distribution t_{p50} (in s).

- The time from raising of a general alarm to the movement of the last few occupants to begin their travel phase, i.e. pre-movement time of the last few occupants t_{p99}.

t_{pr2} of all occupants [British Standards Institution 2004] can also be expressed in terms of t_{p1} and t_{p99} as:

$$t_{pr2} = t_{p1} + t_{p99} \qquad \text{… (C.31)}$$

It was pointed out by Spearpoint [2004] that the evacuation time will be dominated by travel time, when the pre-movement time is short. If the pre-movement time is long, the travelling and waiting effects in evacuation will become a small percentage and hence appear to be less important. For a very long pre-action, pre-movement time dominates the evacuation time even the occupant loading is high. When the pre-movement time lies between these two extremes, evacuation time will be affected by the occupant loading and pre-movement time of each occupant [Spearpoint 2004].

Pre-movement time of occupants is a factor in affecting the formation of queue [Spearpoint 2004]. Rate of people joining the queues will be different when the occupants are moving together or different times [Spearpoint 2004]. If the people are moving together with identical travel speed, occupants will arrive the exit simultaneously and hence constitute the jamming situations.

According to Proulx and Fahy [1997], the mean response time of an office building is 30 to 60 s. In a furniture warehouse, most of the occupants will respond within a 30 s period if the evacuation is initiated by pre-recorded voice messages [Frantzich 2001]. As audio and visual advisory systems are provided in the airport terminal, the magnitude of pre-movement time for the airport terminal of Hong Kong can be taken as 30 s (0.5 min).

- Travel time

Travel time is the time for the person to move from a point of origin and finally his/her evacuation is considered complete [Chartered Institution of Building Services Engineers 1997; Owen *et al.* 1996; Pauls 1987]. As mentioned in the British Standard [British Standards Institution 2004], travel time is the time needed once the movement of an occupant towards an exit has begun and all occupants reach a place of safety at last. Travel distance is an important factor in affecting the travel time. It can be used to calculate the travel time when the travel speed is known.

In the British Standard [British Standards Institution 2004], three components were considered in the travel time t_{t1}. These are the walking time t_{w1}, i.e. average time required for occupants to move from their starting location to a protected escape route or outside the building; time to queue formation at exits t_{qf} (in s), i.e. time from raising of a general alarm to that when queues are formed at exits; and flow time t_{f1}, i.e. time required for people to pass through a particular exit.

$$t_{t1} = t_{w1} + t_{qf} + t_{f1} \qquad \text{… (C.32)}$$

Travel time t_{t2} (in s) is expressed only in terms of the walking time t_{w1} and queuing time t_q by Spearpoint [2004], where the flow time was not included.

$$t_{t2} = t_{w1} + t_q \qquad \text{… (C.33)}$$

The ASET of airport terminal can be determined by the CFD model such as FDS [McGrattan 2004] for identifying the tenability criteria such as the smoke level, temperature, radiant heat flux and visibility inside the departure hall and arrival hall. However, FDS is not well developed during this study period. There is no reference value of ASET for the airport terminals. Although 300 s (5 min) adopted in the local codes [Buildings Department Hong Kong 1996b] is a figure used to compile the discharge value high rise building egress under total evacuation situation, it is an unique value as quoted by the local codes for the targeted evacuation time for sprinklered buildings.

According to the simulation results of TET as shown in Tables 7.3 and 8.3 to 8.6, the occupants in the departure level and arrival level can be evacuated within 300 s (5 min) in normal condition, while the TET of occupants will be exceeded under the fire condition. This indicated that the discharge value of exits and staircases is capable of allowing all the occupants to evacuate within the specific time period under normal condition, i.e. 300 s (5 min). However, the fact that one of the staircases or exits being blocked and cannot be utilized in case of fire may not be considered in the evacuation design of the airport terminals, such that the TET of occupants is exceeded under the fire condition. Therefore, 270 s is considered as a benchmark and adopted as the evacuation target time, i.e. the time for the last occupant to leave the terminal building, in the evacuation analysis for evaluating the evacuation design of the departure level and arrival level of the airport terminal under the normal and fire conditions. With the pre-movement time of the airport terminal presumed to be 30 s, the travel time of the occupants in the airport terminal of Hong Kong should be less than 240 s.

- Other time components

  - Recognition time

Recognition time is realized as the time to recognize the dangerous situation by Sime [1986]. In British Standards [British Standards Institution 1999, 2004], recognition time is defined as the period after an alarm or cue is evident but before the occupants start to respond. The time ends when the occupants have accepted that there is a need to respond [e.g. British Standards Institution 1999, 2004; Løvås 1994; Sime 1986].

Before the activation of an alarm, occupants may engage in different activities such as waiting for check-in or check-out, working and shopping. Length of the recognition period can be varied seriously, depending on the types of building, nature of occupant, and alarm and management system [British Standards Institution 1999, 2004].

  - Response time

After the occupants have accepted that there is an emergency occurred, they need to take time to respond [Melinek and Booth 1975]. Response time is defined as the time to receive and interpret the information of emergency and make preparations for evacuation [e.g. Kendik 1983; Melinek and Booth 1975; Smith 1982]. As mentioned in British Standards [British Standards Institution 1999, 2004], response time is the period after the occupants recognize the alarms or cues and begin to respond before the start of the travel phase of evacuation.

Occupants near the emergency location would be more aware of the risk, they would react and evacuate earlier than those far away from the hazardous areas [Melinek and Booth 1975]. Response time can be significantly reduced by providing clear, prompt and accurate information to occupants [Chartered Institution of Building Services Engineers 1997]. Many factors will affect the response of occupants, such as the level of occupants committed to other activities, their mental and physical state, extent to which they are trained to respond to warnings, the level they feel endangered by fire, their role and responsibilities [British Standards Institution 1999, 2004].

- Walking time

Walking time is the time for the movement towards safety [Sime 1986]. In other words, it is the time to walk from the most remote point in a building to the exit [Thompson and Marchant 1995a]. Walking time is the time needed for all occupants in a specified part of building to move to an exit [British Standards Institution 1999]. It depends upon the walking speed of each occupant and their distance from an exit [e.g. Fruin 1971].

According to the British Standard [British Standards Institution 2004], walking time is the time taken for a person to walk from their starting position to the nearest exit, assuming the walking speed is unrestricted. It represents the minimum time required to walk to the exit as no allowance is made for the possibility of impeded walking due to high levels of occupant density within the enclosure [British Standards Institution 2004].

- Flow time

Flow time [e.g. Fruin 1971; Kendik 1983; Melinek and Booth 1975] is the total time taken for a number of people to pass through an element in the egress route. It is a function of the crowd flow capacity of a particular circulation element and the number of people to be moved through it [Pauls 1987].

According to the British Standard [British Standards Institution 2004], flow time is the time for the occupants to evacuate from an enclosure, assuming all occupants are available at exits and the use of exits is optimal. It is determined by the flow capacity of exits and represented by the total time required for the occupants to flow through the exits.

Queuing and waiting time

When people arrive the exit and identify that it is obstructed, occupants will slow down their pace and reduce the walking velocity gradually in order to keep a comfortable distance between themselves and the others [Graat *et al.* 1999;

Hankin and Wright 1958]. They will become stationary if there is no space for them to move [Thompson and Marchant 1995a]. Waiting period is commenced. Occupants will wait in the queues until they can move forward.

- Occurrence of queuing

  Waiting lines are formed when the current demand for service exceeds the current capacity to provide services [Conway and Maxwell 1961; Hillier *et al.* 1964]. In evacuation, queues are developed when the rate of occupants passing through the exit is slower than the rate of people arrived the exit [Watts 1987].

  Occupants from different areas would be merged before the exit [Thompson and Marchant 1995c]. If the rate of people arrived the exit is larger than the maximum flow rate that the exit can be sustained, queues will be developed [Thompson and Marchant 1995c].

  Two types of queues, i.e. ordered queue and bulk queue, would be formed before the exits. For an ordered queue, the priority of queuing is on the basis of 'first come, first served', while bulk queue is characterized by an unordered and deficiency of the queue discipline [Fruin 1971]. Some people would be lacked of patience and overtaken the front person to reach the exit [Gwynne *et al.* 1998a, b]. If they cannot overtake the person, they would only stand around the ordered queue and wait to pass the queue and enter the exit [Hankin and Wright 1958]. Formation of bulk queues affects the flow rate of exit such that the occupants need to use a longer time to pass through the exit [Spearpoint 2004]. On the other hand, the close pack of bulk queue will cause people anxiously waiting or competing to enter the exit [Pauls 1987]. Crushing force between people is increased, the panic situation will occur when the occupants cannot leave the building rapidly or enter a safe area [Melinek and Booth 1975].

- Background of waiting time

As mentioned by Togawa [1955], “waiting time” can be understood as the delaying time of the crowd to pass through the platform exit. Although Togawa’s approach was based on the studies in mass rail transit system and might not be applicable for the calculation of waiting time in the departure hall, arrival hall and retail areas of the airport terminal, it can become a reference for us to recognize the parameters involved in the waiting time for the jamming condition occurred before the platform exit of the Airport Express in the terminal buildings.

A formula of the number of passengers φ who will be jammed before the platform exit was indicated [Togawa 1955]. It is the difference between the number of passengers y_1 escaping from the train with respect to time T_1 (in s), and the number of passengers y_2 who can pass through the platform exit. y_1 and y_2 are expressed in terms of f_{pi}, B_i, ϕ_i and T, for i = 1,....., n; while f_p’, B’ and T_o are included in y_2.

$$y_1 = \sum_{i=1}^{n} \int_0^{T_1} f_{pi}(t) B_i \phi_i(t)\, dt \qquad \ldots \text{(C.34)}$$

$$y_2 = \sum_{i=1}^{n} \int_0^{T_o} f_{pi}(t) B_i \phi_i(t)\, dt + (T_1 - T_o) f_p ' B' \qquad \ldots \text{(C.35)}$$

φ can be expressed in terms of y_1 and y_2 as:

$$\begin{aligned} \varphi &= y_1 - y_2 \\ &= \sum_{i=1}^{n} \int_0^{T_1} f_{pi}(t) B_i \phi_i(t)\, dt - \left(\sum_{i=1}^{n} \int_0^{T_o} f_{pi}(t) B_i \phi_i(t)\, dt + (T_1 - T_o) f_p ' B' \right) \\ &= \sum_{i=1}^{n} \int_{T_o}^{T_1} f_{pi}(t) B_i \phi_i(t)\, dt - (T_1 - T_o) f_p ' B' \qquad \ldots \text{(C.36)} \end{aligned}$$

By differentiating φ, two values of T_1 can be obtained, i.e. the time T_o for the crowd begins to wait at platform exit, and the time T_m (in s) when maximum number of passengers queue up at exit.

$$\frac{d\varphi}{dT_1} = \sum_{i=1}^{n} f_{pi}(T_1) B_i \phi_i(T_1) - f_p ' B' = 0 \qquad \ldots \text{(C.37)}$$

The Russian approach of crowd movement [Predtechenskii and Milinskii 1969] also puts a great emphasis on queuing. The number of occupants Q_n, area of horizontal projection of people H_1 (in m^2) and traffic capacity C' (in $m^2 min^{-1}$) would be involved in the waiting period τ' (in min) of occupants during queuing. H_1 is calculated by the width w (in m) and thickness t' (in m) of a person, while C' can be expressed in terms of the density of flow D' (in

m^2m^{-2}), speed of flow s (in ms^{-1}) and width of flow δ (in m), and D' is obtained by H_1, δ and the length of flow l' (in m).

$$H_1 = \frac{\pi}{4}(wt') \qquad \text{… (C.38)}$$

$$C' = D' \times s \times \delta \qquad \text{… (C.39)}$$

$$D' = \frac{Q_n \times H_1}{\delta \times l'} \qquad \text{… (C.40)}$$

Taking the occupants travelled from the corridor to a wider staircase as an example, traffic capacity of occupants in corridor and staircase are C_c (in m^2min^{-1}) and C_s (in m^2min^{-1}) respectively. τ' with respect to C_c and C_s can be expressed as:

$$\tau' = Q_n \times H_1 \left(\frac{1}{C_s} - \frac{1}{C_c} \right) \qquad \text{… (C.41)}$$

Delay time in queues can be interpreted as the period required for occupants to stand in a stationary position [Fruin 1971]. It is also understood as the time that a person has to wait to enter the exit [Watts 1987].

Appendix D: Physical aspects of deluge system

- Size of orifice

Assuming the area coverage by an open sprinkler is A_p (in m^2), minimum flow rate Q (in $Lmin^{-1}$) from the system is expressed in terms of design density of discharge D_e (in $mmmin^{-1}$) as:

$$Q = A_p \times D_e \qquad \text{… (D.1)}$$

Before determining the orifice size of open sprinkler, pipe size would be determined first. Pressure loss f (in bar) for water passing through the pipe is:

$$f = k \times l \times Q^{1.85} \qquad \text{… (D.2)}$$

where k factor is a constant which depends on type and size of pipe utilized, and l (in m) is the equivalent length of pipe and fitting.

Working pressure P_w (in bar) for the system is given by the required pressure to deliver the flow P_w' (in bar) as:

$$P_w = P_w' + f \qquad \text{… (D.3)}$$

In order to determine the size of orifice, constant K should be estimated by applying sprinkler characteristic equation in terms of P_w (in bar) and Q (in

Lmin^{-1}):

$$K = \frac{Q}{\sqrt{P_w}} \qquad \text{… (D.4)}$$

Pressure loss P_x (in kPa) can be expressed in terms of frictional loss f' (in kPa) and flow rate produced by orifice plate Q_x (in Lmin^{-1}) as:

$$P_x = 100\, f' \left(\frac{500}{Q_x} \right) \text{ for pipe sizes 50 mm and 65 mm} \qquad \text{… (D.5)}$$

$$P_x = 100\, f' \left(\frac{5000}{Q_x} \right) \text{ for pipe sizes 80 mm to 200 mm} \qquad \text{… (D.6)}$$

Orifice size can be determined by P_x and K, such as those appeared in Tables C1 and C2 of AS 2118.1 [Australian Standard 1995a].

- Response of the detectors

Sprinklers can be used as detectors and installed on pressurized inert gas, air or liquid lines in deluge system. As for sprinkler systems, thermal sensitivity is important. Response of thermal sensing element can be quantified by "Response Time Index" (RTI) (in $m^{\frac{1}{2}}s^{\frac{1}{2}}$) [National Fire Protection Association 1992] expressed in terms of time constant τ (in s) and velocity of hot air V_h (in ms^{-1}) in plunge test as:

$$RTI = \tau (V_h)^{\frac{1}{2}} \qquad \ldots \text{(D.7)}$$

Time constant τ is given by mass m_e (in g), specific heat capacity C_e (in $Jg^{-1o}C^{-1}$) of thermal sensing element, convective heat transfer coefficient h_e (in $Js^{-1}m^{-2o}C^{-1}$) and the surface area of element exposed to hot air A_e (in m^2):

$$\tau = \frac{m_e C_e}{h_e A_e} \qquad \ldots \text{(D.8)}$$

Therefore,

$$RTI = \left(\frac{m_e C_e}{h_e A_e} \right) V_h^{\frac{1}{2}} \qquad \ldots \text{(D.9)}$$

- Heat absorption rate of spray

Heat absorption rate Q_h (in kW) by the spray of open sprinkler is given by total heat release rate of fire Q_c (in kW), rate of convective heat loss through openings Q_{con} (in kW), heat loss rate through walls, floor and ceiling by conduction Q_o (in kW) and radiative heat loss through openings Q_r (in kW) [Society of Fire Protection Engineers and National Fire Protection Association 1995] as:

$$Q_h = Q_c - Q_{con} - Q_o - Q_r \qquad \ldots \text{(D.10)}$$

However, it is quite difficult to determine Q_c, Q_{con}, Q_o and Q_r, and so Q_h is calculated directly by the following parameters:

$$q_h = h_t a_s \left(\frac{dT}{dt} \right) \quad \text{… (D.11)}$$

where q_h (in Ws^{-1}) is the heat absorption rate by a single water droplet [Chow and Cheung 1994; Drysdale 1999], h_t (in $Wm^{-2}K^{-1}$) is the heat transfer coefficient of each droplet, a_s (in m^2) is the surface area of droplet, and $\frac{dT}{dt}$ (in Ks^{-1}) is equal to the rate of change of temperature between droplet and envelope of cone spray.

Heat transfer coefficient of each droplet can be expressed in terms of thermal conductivity of air k_a (in $Wm^{-1}K^{-1}$), Nusselt number Nu which indicates the dimensionless temperature gradient at droplet surface [Incropera and Dewitt 1996] and the mean droplet diameter D_x (in mm):

$$h_t = Nu \left(\frac{k_a}{D_x} \right) \quad \text{… (D.12)}$$

Equations for Nu and D_x are expressed in terms of viscosity of hot air flow μ_a (in Nsm^{-2}), viscosity of water μ_w (in Nsm^{-2}), Reynolds number of water droplets Re, Prandlt number Pr, diameter of nozzle D_i (in mm) and Weber number $W_{e.}$

$$Nu = 2 + \left(0.4\,(Re)^{\frac{1}{2}} + 0.06\,(Re)^{\frac{2}{3}} \right) + Pr^{2.4} \left(\frac{\mu_a}{\mu_w} \right)^{\frac{1}{4}} \qquad \text{… (D.13)}$$

$$D_x = 3.21\,D_i\,(W_e^{-\frac{1}{3}}) \qquad \text{… (D.14)}$$

W_e can be expressed in terms of D_i, density of water ρ (in kgm^{-3}), discharge velocity of nozzle V_d (in ms^{-1}) and water surface tension σ_w (in Nm^{-1}).

$$W_e = \frac{\rho V_d^{\,2} D_i}{\sigma_w} \qquad \text{… (D.15)}$$

with

$$V_d = \frac{U_p}{C_M} \qquad \text{… (D.16)}$$

U_p (in ms^{-1}) is initial droplet velocity and C_M is momentum coefficient. Taking C_M equal to 0.4,

$$V_d = 2.5\,U_p \qquad \text{… (D.17)}$$

On the other hand, V_d can also be expressed as:

$$V_d = \frac{16Q}{\pi D_i^{\,2}} \qquad \text{… (D.18)}$$

Substituting equation (D.9) into W_e,

$$W_e = \frac{\rho\,(256Q^2)}{\pi^2 D_i^{\,3}\sigma_w} \qquad \ldots \text{(D.19)}$$

Putting equation (D.19) into D_x,

$$D_x = 3.21\, D_i \left(\frac{\rho\,(256Q^2)}{\pi^2 D_i^{\,3}\sigma_w} \right)^{-\frac{1}{3}} \qquad \ldots \text{(D.20)}$$

As $\rho = 1000\ \text{kgm}^{-3}$,

$$D_x = 0.051\,(\pi^{\frac{2}{3}}\sigma_w^{\frac{1}{3}})\,(D_i^{\,2} Q^{-\frac{2}{3}}) \qquad \ldots \text{(D.21)}$$

D_x is proportional to $D_i^{\,2} Q^{-\frac{2}{3}}$. As the total surface area of a single droplet A_s is proportional to $\frac{Q}{D_x}$ [Society of Fire Protection Engineers and National Fire Protection Association 1995], therefore, A_s is proportional to $D_i^{\,2} Q^{\frac{5}{3}}$, and α is a constant.

$$A_s = \alpha\, D_i^{\,2} Q^{\frac{5}{3}} \qquad \ldots \text{(D.22)}$$

Substituting equation (D.21) into equation (D.22),

$$h_t = Nu\left(\frac{k_a}{0.051\,(\pi^{\frac{2}{3}}\sigma_w{}^{\frac{1}{3}})\,(D_i{}^2 Q^{-\frac{2}{3}})}\right) \qquad \ldots \text{(D.23)}$$

Putting equations (D.22) and (D.23) into equation (D.11),

i.e. $$q_h = Nu\,(Q^{\frac{7}{3}})\left(\frac{k_a\alpha}{0.051(\pi^{\frac{2}{3}}\sigma_w{}^{\frac{1}{3}})}\right)\left(\frac{dT}{dt}\right) \qquad \ldots \text{(D.24)}$$

Number of droplets per unit volume N is expressed in terms of parameter of drop size of spray r_p (in mm), angle of cone spray θ_c (in radian), mean velocity of droplets inside unit volume V_x (in ms^{-1}), distance between sprinkler and floor x' (in m) and diameter of cone spray at the location where water stream is changed to droplets D_c (in mm):

$$N = \frac{\left(\frac{3}{2}\right)V_d{}^2}{\pi r_p{}^3 D_i{}^2 \tan^2\left((\frac{\theta_c}{2})(\frac{V_x}{U_p})(\frac{x'}{D_c})\right)} \qquad \ldots \text{(D.25)}$$

Putting

$$\left((\frac{\theta_c}{2})(\frac{V_x}{U_p})(\frac{x'}{D_c})\right) = a \qquad \ldots \text{(D.26)}$$

Substituting equations (D.18) and (D.26) into N,

$$N = \frac{384Q^2}{\pi^3 {r_p}^3 {D_i}^6 \tan^2(a)^2} \qquad \text{… (D.27)}$$

By applying equations (D.11) and (D.27), the total heat absorption rate per unit volume is:

$$Q_h = \sum_{x=1}^{N} q_x$$

$$= \left(\frac{k_a \alpha}{0.051(\pi^{\frac{2}{3}})}\right) \sum_{x=1}^{N} Nu_x \left(\frac{Q^{\frac{7}{3}}}{{\sigma_w}^{\frac{1}{3}}}\right)_x \left(\frac{dT}{dt}\right)_x \qquad \text{… (D.28)}$$

where

$$N = \frac{384Q^2}{\pi^3 {r_p}^3 {D_i}^6 \tan^2(a)^2} \qquad \text{… (D.29)}$$

Appendix E: Pressure and flow rate required for deluge system

(a) Design criteria:

D_e = 7.5 mmmin^{-1}

As O_s = 15 mm, K = 80

(b) Area coverage A_p by an open sprinkler D1 = 3.4 m $\times$ 3.4 m

= 11.56 m^2

Flow rate Q_1 = 11.56 m^2 $\times$ 7.5 mmmin^{-1}

= 86.7 Lmin^{-1}

According to equation (D.4), Pressure P_{w1} at D1 is:

$$P_{w1} = \frac{86.7^2}{80^2} = 1.17 \text{ bar}$$

For the diameter of range pipe between D1 and D2 which is equal to 32 mm, k value is 2.33 $\times 10^{-6}$.

Frictional loss f_{12} = 2.33 $\times 10^{-6} \times 3.4 \times (86.7)^{1.85}$

= 0.031 bar

Required pressure P_{w2} and flow rate Q_2 at D2 is equal to

$$P_{w2} = P_{w1} + f_{12}$$

$= 1.17 + 0.031$

$= 1.2$ bar

$Q_2 = 80\sqrt{1.2}$

$= 87.7$ $Lmin^{-1}$

For the diameter of range pipe between D2 and D3 which is equal to 40 mm, k value is 1.11×10^{-6}.

Frictional loss $f_{23} = 1.11 \times 10^{-6} \times 3.4 \times (87.7)^{1.85}$

$= 0.015$ bar

Required pressure P_{w3} and flow rate Q_3 at D3 is equal to

$P_{w3} = P_{w2} + f_2$

$= 1.20 + 0.015$

$= 1.22$ bar

$Q_3 = 80\sqrt{1.22}$

$= 88.4$ $Lmin^{-1}$

(b) For the diameter of range pipe between D3 and point R which is equal to 50 mm, k value is 3.51×10^{-7}.

Frictional loss $f_{3R} = 3.51 \times 10^{-7} \times 1.7 \times (262.8)^{1.85}$

$= 0.018$ bar

Required pressure P_{wR} at point R is equal to

$P_{wR} = P_{w3} + f_{3R}$

$= 1.22 + 0.018$

$= 1.24$ bar

Assume P_{w3} is equal to P_{w4}, i.e. $Q_1 = Q_6 = 86.7$ $Lmin^{-1}$, $Q_2 = Q_5 = 87.7$ $Lmin^{-1}$ and $Q_3 = Q_4 = 88.4$ $Lmin^{-1}$. Flow rate discharge Q_{SR} from S to R is:

$Q_{SR} = (Q_1 + Q_2 + Q_3) \times 2$

$= (86.7 + 87.7 + 88.4) \times 2$

$= 525.6$ $Lmin^{-1}$

For the diameter of distribution pipe from point S to R, diameter and k value are 50 mm and 3.51×10^{-7} respectively.

Frictional loss $f_{SR} = 3.51 \times 10^{-7} \times 3.4 \times (525.6)^{1.85}$

$= 0.129$ bar

Required pressure P_{wS} at point S is equal to

$P_{wS} = P_{wR} + f_{SR}$

$= 1.24 + 0.128$

$= 1.37$ bar

K for D1, D2 and D3 = $\frac{262.8}{\sqrt{1.24}} = 236$. As the flow rate for D4, D5 and D6 is also 262.8 $Lmin^{-1}$, i.e. K for D4, D5 and D6 = 236.

Flow rate discharge Q_S from point S to the sprinklers from D7 to D12 is:

$$Q_S = (236\sqrt{1.37}) \times 2$$
$$= 552.5 \ Lmin^{-1}$$

Flow rate discharge Q_{TS} from point T to S is:

$$Q_{TS} = Q_{SR} + Q_S$$
$$= 525.6 + 552.5$$
$$= 1078.1 \ Lmin^{-1}$$

For the diameter of distribution pipe from point T to S, the diameter and k value are 65 mm and 9.90×10^{-8} respectively.

Frictional loss $f_{TS} = 9.90 \times 10^{-8} \times 3.4 \times (1078.1)^{1.85}$

$= 0.137$ bar

Required pressure P_{wT} at point T is equal to

$P_{wT} = P_{wS} + f_{TS}$

$= 1.37 + 0.137$

$= 1.51$ bar

Flow rate discharge Q_T from point T to the sprinklers from D13 to D18 is:

$Q_T = (236\sqrt{1.51})\times 2$

$= 580\ \text{Lmin}^{-1}$

Flow rate discharge Q_{UT} from point U to T is:

$Q_{UT} = Q_{TS} + Q_T$

$= 1078.1 + 580$

$= 1658.1\ \text{Lmin}^{-1}$

For the diameter of distribution pipe from point U to T, the diameter and k value are 80 mm and 4.51×10^{-8} respectively.

Frictional loss $f_{UT} = 4.51 \times 10^{-8} \times 3.4 \times (1658.1)^{1.85}$

$= 0.139$ bar

Required pressure P_{wU} at point U is equal to

$P_{wU} = P_{wT} + f_{UT}$

$= 1.51 + 0.139$

$= 1.65$ bar

Flow rate discharge Q_U from point U to the sprinklers from D19 to D24 is:

$$Q_U = (236\sqrt{1.65})\times 2$$
$$= 606.3 \text{ Lmin}^{-1}$$

Flow rate discharge Q_{VU} from point V to U is:

$$Q_{VU} = Q_{UT} + Q_U$$
$$= 1658.1 + 606.3$$
$$= 2264.4 \text{ Lmin}^{-1}$$

For the diameter of distribution pipe from point V to U, the diameter and k value are 100 mm and 1.27×10^{-8} respectively.

$$\text{Frictional loss } f_{VU} = 1.27 \times 10^{-8} \times 3.4 \times (2264.4)^{1.85}$$
$$= 0.069 \text{ bar}$$

Required pressure P_{wV} at point V is equal to

$$P_{wV} = P_{wU} + f_{VU}$$
$$= 1.65 + 0.069$$
$$= 1.72 \text{ bar}$$

Flow rate discharge Q_V from point V to the sprinklers from D25 to D30 is:

$$Q_V = (236\sqrt{1.72})\times 2$$
$$= 619 \text{ Lmin}^{-1}$$

Flow rate discharge Q_{WV} from point W to V is:

$$Q_{WV} = Q_{VU} + Q_V$$
$$= 2264.4 + 619$$
$$= 2883.4 \text{ Lmin}^{-1}$$

For the diameter of distribution pipe from point Y to X, the diameter and k value are 100 mm and 1.27×10^{-8} respectively.

$$\text{Frictional loss } f_{WV} = 1.27 \times 10^{-8} \times 12 \times (2883.4)^{1.85}$$
$$= 0.479 \text{ bar}$$

Required pressure P_{wW} at point W is equal to

$$P_{wW} = P_{wV} + f_{WV}$$
$$= 1.72 + 0.479$$
$$= 2.20 \text{ bar}$$

(c) Assume the diameter of distribution pipe from deluge valve to point X is 150 mm, i.e. k value of this pipe is 8.73×10^{-10}. Height difference h between the valve and point X is considered to be 12 m.

Frictional loss $f_{YX} = 8.73 \times 10^{-10} \times 12 \times (2883.4)^{1.85}$

$= 0.003$ bar

Required pressure P_{wX} at point X is equal to

$$P_{wX} = P_{wW} + f_{YX}$$

$$= 2.20 + 0.003$$

$$= 2.20 \text{ bar}$$

Appendix F: Physical aspects of drencher system

Factors to be considered in evaluating performance of a water curtain include radiant heat received at protected zone after passing through water curtain, radiant heat flux inside water curtain, transmission of unit intensity of radiation and wind effect on flame and water curtain:

- Transmission of heat

Suppose the surface of a fire of area A_a is radiating heat fluxes to another surface of area A_b (in m^2) after passing through the water curtain, which is a scattering-absorbing medium. Schematic diagram of attenuation model [Ravigururajan and Beltran 1989] is shown in Figure F.1. Following Lambert-Beer law, radiant heat Q_{ab} (in kW) received at A_b is given by parameter view factor F_{ab}, emissivity of A_a, ε_a, absorptivity of A_b, α_b, Stefan-Boltzmann constant σ, which is equal to 5.67×10^{-8} $Wm^{-2}K^{-4}$, temperature of A_a T_a' (in K), extinction coefficient of water k_{ext} (in m^{-1}) and distance between centres of surfaces A_a and A_b L_w (in m) [Coppalle *et al.* 1993; Ravigururajan and Beltran 1989]:

$$Q_{ab} = A_a F_{ab} \varepsilon_a \alpha_b \sigma T_a'^4 e^{-k_{ext} L_w} \quad \ldots \text{(F.1)}$$

In fact, k_{ext} (in m^{-1}) is the sum of absorption coefficient k_{abs} (in m^{-1}) and scattering coefficient k_{sca} (in m^{-1}) which can be expressed as the amount of water injected M_w (in kgm^{-3}), density of water ρ (in kgm^{-3}), extinction efficiency Q_{ext} and diameter of water droplet D_w (in μm):

$$k_{ext} = k_{abs} + k_{sca} \quad \ldots \text{(F.2)}$$

$$= \frac{3}{4}\left(\frac{M_w}{\rho}\right)\left(\frac{Q_{ext}}{D_w}\right) \quad \ldots \text{(F.3)}$$

- Radiant heat flux inside the water curtain

Radiant heat flux transfer inside water curtain I_λ (in Wm^{-2}) is expressed in terms of wavelength λ, heat flux before entering water curtain at temperature T $I^0_{\lambda,T}$ (in Wm^{-2}) and intensity diffused normally inside water curtain $I^1_{\lambda,T}(\Omega)$ (in Wm^{-2}) as [Coppalle *et al.* 1993]:

$$dI_\lambda = -(k_{abs} + k_{sca})I_\lambda dI + k_{abs} I^0_{\lambda,T} dI + k_{sca} dI \int_{4\pi} I^1_\lambda(\Omega)\frac{d\Omega}{4\pi} \quad \ldots \text{(F.4)}$$

Let

$$\omega = \frac{k_{sca}}{k_{ext}} \quad \ldots \text{(F.5)}$$

Substituting equations (F.2) and (F.3) into equation (F.4),

$$\frac{dI_\lambda}{dI} = -k_{ext} I_\lambda + (1-\omega)k_{ext} I^0_{\lambda,T} + \omega k_{ext} + \int_{4\pi} I^1_\lambda(\Omega)\frac{d\Omega}{4\pi} \quad \ldots \text{(F.6)}$$

- Transmission of unit intensity of radiation

For radiation of intensity I_o (in Wm^{-2}) incident on a layer of water curtain with thickness d (in m), transmitted radiant heat flux I_i (in Wm^{-2}) can be given by extinction cross-section of a single water droplet q (in μm^2) and number of water droplets per unit volume N [Heselden and Hinkley 1965; Thomas 1952]:

$$I_i = I_o e^{-qNd} \qquad \dots \text{(F.7)}$$

Assume all water droplets have the same size with droplet radius r (in μm), q is then equal to πr^2, giving N in terms of volume flow rate through unit horizontal area Q_v (in m^3s^{-1}) and downward component of drop velocity v_D (in ms^{-1}) as:

$$N = \frac{Q_v}{v_D}\left(\frac{3}{4\pi r^3}\right) \qquad \dots \text{(F.8)}$$

Substituting equation (F.8) into equation (F.7),

$$I_i = I_o e^{-\left(\frac{3Q_v d}{4v_D r}\right)} \qquad \dots \text{(F.9)}$$

Taking v_D and r as constants, equation (F.9) becomes:

$$I_i = I_o (e^{-GQ_v d}) \qquad \dots \text{(F.10)}$$

Q is then given in terms of constant G:

$$Q_v = \frac{\ln\left(\frac{I_o}{I_i}\right)}{Gd} \qquad \ldots \text{(F.11)}$$

- Wind effect

Blocking of thermal radiation will be affected when drencher system is used outside a building. This is because smaller water droplets, though having a better effect in blocking thermal radiation, will be affected by wind-induced motion. Air entrainment rate into a fire plume outside a building might be changed due to wind action, enhancing burning to give a bigger fire diameter D_f (in m) which depends on height of flame L_f (in m) and angle of deflection θ (in radian) [Drysdale 1999]:

$$D_f = L_f \cos\theta \qquad \ldots \text{(F.12)}$$

But L_f depends on the heat release rate Q_c (in kW),

$$L_f = 0.23\, Q_c^{2/5} - 1.02\, D_f \qquad \ldots \text{(F.13)}$$

Equations (F.12) and (F.13) give:

$$D_f = \frac{0.23\, Q_c^{2/5} (\cos\theta)}{1 + 1.02\cos\theta} \qquad \ldots \text{(F.14)}$$

θ can be expressed in terms of density of air ρ_a (in kgm^{-3}), density of fuel vapour ρ_f (in kgm^{-3}), heat of combustion H_c (in $kJkg^{-1}$), thermal capacity at constant pressure C_p (in $Jkg^{-1}K^{-1}$), ambient air temperature T_{at} (in K) and dimensionless windspeed per unit width V'_{wind}:

$$\sin\theta = \begin{cases} 1 & V'_{wind} < 1 \\ \left(V'_{wind}\right)^{-1/2} & V'_{wind} > 1 \end{cases} \qquad \text{… (F.15)}$$

where

$$V'_{wind} = V_{wind}\left(\frac{2C_p T_{at}\rho_a}{\pi\rho_f H_c}\right) \qquad \text{… (F.16)}$$

Note that the dimensionless windspeed V_{wind} can be expressed in terms of actual windspeed V (in ms^{-1}) and characteristic plume velocity U_c (in ms^{-1}):

$$V_{wind} = \frac{V}{U_c} \qquad \text{… (F.17)}$$

U_c is found experimentally to be related to Q_c as:

$$U_c = 1.9Q_c^{1/5} \qquad \text{… (F.18)}$$

Q_c is given in terms of combustion efficiency χ, rate of mass loss per unit area m_a (in $kgs^{-1}m^{-2}$) and fuel area A_{fu} (in m^2).

$$Q_c = \chi H_c m_a A_{fu} \qquad \ldots \text{(F.19)}$$

It is very difficult to control wind effect on fire in outside environment. For designing drencher system of outdoor use, an experimental investigation should be carried out on the amount of flow rate required for supplying water droplets in sufficient volume to absorb and scatter radiant heat flux in a much more effective way.

Having recognized the theoretical phenomenon, it is important to identify parameters in designing drencher system. In order to attain a certain level of minimization of radiant heat flux, following parameters should be considered:

- Attenuation factor

For determining the position requiring drencher system protection, it is important to calculate attenuation factor. This factor is related to radiation emitted from the source that water curtain or structural materials such as windows can withstand. First, I_i that is desired in protected zone should be determined. To find out I_i, heat flux transducer [Fong and Chan 2001] can be used to measure radiant fluxes in protected zonF. Different operating conditions such as utilization of curtains, different pressures, flow rates, types of nozzles and sizes of water droplets can be experimented to find out percentage of radiant heat flux reduced and maximum attenuation in radiative heat flux.

According to Australian Standard [1995b], attenuation factor F can be calculated as follows:

$$F = \frac{I_i}{I_s} \times \frac{100}{P_{eo}} \qquad \text{… (F.20)}$$

where [Chow and Cheung 1995; Raes 1973]

$$I_s = \frac{F_d}{t_e}$$

$$= \frac{A_t^{1/2} A_v^{1/2} h^{1/2}}{0.067 A_f} \qquad \text{… (F.21)}$$

I_s (in kWm^{-2}) is the average radiant heat intensity of fire source, F_d (in MJm^{-2}) is fire load density, t_e (in mins) is equivalent duration of fire, A_t (in m^2) is the total area of wall, A_v (in m^2) is the surface area of ventilation opening, h (in m) is the height of opening and A_f (in m^2) is floor area.

P_{eo} is the percentage of opening in a wall or roof and can be expressed in terms of dimensions of wall or roof W (in m) and H (in m), total area of openings A_o (in m^2) (plus 25% where applicable) within a wall or roof. An allowance of 25% is included to allow flame projecting beyond and enlarging openings.

$$P_{eo} = \frac{A_o}{W \times H} \times 100 \qquad \text{… (F.22)}$$

Aspect ratio A_r of wall and roof can be defined as W/H or H/W whichever is smaller.

- Position requiring drencher system protection

To determine the position for installing drencher system inside a building, limiting distance D_l (in m) is an important factor. For any distance from fire source shorter than D_l, radiant heat intensity would be greater than I_i. For the position where radiant heat is equal to limiting radiant heat intensity, i.F. limiting distance, drencher system should be installed.

$$D_l = C \times \sqrt{(W \times H)} \qquad \text{… (F.23)}$$

C is the dimensionless conversion factor given in Table B1 of AS 2118.2 [Australian Standard 1995b].

- Average discharge density over protected area

It is important to calculate the flow rate required for protection area. Discharge density for each nozzle Q_i (in $Lm^{-2}min^{-1}$) can be calculated in terms of flow rate Q_f (in $litresmin^{-1}$) and diameter of nozzle D_i (in m) [Australian Standard 1995b]:

$$Q_i = \frac{Q_f}{D_i^2} \qquad \text{… (F.24)}$$

Average discharge density Q_a (in $Lm^{-2}min^{-1}$) over protected area is expressed in terms of the number of drencher nozzles over protected area n' as:

$$Q_a = \frac{1}{n'} \sum_{j=1}^{n'} (Q_i)_j \qquad \text{… (F.25)}$$

- Pressure required over the protected area

Pressure P_o (in kPa) required to supply the flow for a drencher nozzle over protected area [Australian Standard 1995b] can be expressed in terms of Q_f and 'k' factor of drencher nozzle:

$$P_o = \frac{(Q_f)^2}{k} \qquad \text{… (F.26)}$$

Appendix G: Position and area requiring drencher system protection

Case F1: Internal source

Drencher system is acted as a partition in a big hall. Diagram of drencher nozzle installed inside a big hall is shown in Figure G.1.

(a) The hall is of width W_{w1} (in m), height W_{h1} (in m) and area $W_{w1} \cdot W_{h1}$ (in m^2), given an aspect ratio A_{r1} of W_{w1}/W_{h1} if W_{w1} is smaller than W_{h1}.

(b) Percentage of openings is P_{eo1}, which is equal to 100 %.

(c) Attenuation factor

$$F_1 = \frac{I_{i1}}{I_{s1}} \times \frac{100}{P_{eo1}} = \frac{I_{i1}}{I_{s1}} \times \frac{100}{100} = \frac{I_{i1}}{I_{s1}} \qquad \ldots \text{(G.1)}$$

(d) Find the dimensionless conversion factor C_1 from Table B1 of AS 2118.2 by using aspect ratio and attenuation factor. Interpolating C_1 when needed.

(e) Limiting distance

$$D_{l1} = C_1 \times \sqrt{W_{w1} \cdot W_{h1}} \qquad \ldots \text{(G.2)}$$

Drencher system should be situated in the limiting distance calculated.

Case F2: External source

Vertical sources of radiant heat, such as from wall openings in another building. Source of radiant heat is assumed to be situated D_s m away from protected zone.

(a) Assume fire is confined within one storey in other building, total window areas of the external wall of source building is equal to $W_{w2} \cdot W_{h2}$ (in m^2), where W_{w2} (in m) is width and W_{h2} (in m) is height. As 25% should be added to window areas, effective area becomes 1.25 $W_{w2} \cdot W_{h2}$. Aspect ratio A_{r2} is equal to 1.25 (W_{w2}/W_{h2}) for W_{w2} is smaller than W_{h2}.

(b) Percentage of openings P_{eo2} (%) is:

$$P_{eo2} = \frac{A_o \times 1.25}{1.25\, W_{w2} \cdot W_{h2}} \times 100$$

$$= S\ (\%) \qquad \ldots \text{(G.3)}$$

(c) Attenuation factor

$$F_2 = \frac{I_{i2}}{I_{s2}} \times \frac{100}{P_{eo2}} \qquad \ldots \text{(G.4)}$$

(d) Find the dimensionless conversion factor C_2 from Table B1 of AS 2118.2 by using aspect ratio and attenuation factor. Interpolating C_2 when needed.

(e) Limiting distance

$$D_{l2} = C_2 \times \sqrt{(W_{w2} \cdot W_{h2})} \qquad \ldots \text{(G.5)}$$

If D_{l2} is larger than D_s, then drencher system must be installed.

(f) Area requiring coverage

For a building locating within the range of D_{l2}, in addition to the whole surface of building facing the fire source, an external protection band of width $\sqrt{D_{l2}^2 - (D_s)^2}$ should also be protected.

Case F3: External source

Horizontal sources of radiant heat, such as from roof of a low-level building. Source of radiant heat is assumed to be situated D_{s1} m away from protected zone.

(a) Effective source of radiant heat comes from roof opening of a low-level building. Building with width W_{w3} (in m), height W_{h3} (in m) and area $W_{w3} \cdot W_{h3}$ (in m^2) is given an aspect ratio A_{r3} of (W_{w3}/W_{h3}) if W_{w3} is smaller than W_{h3}.

(b) Percentage of openings is P_{eo3}, which is equal to 100%.

(c) Attenuation factor

$$F_3 = \frac{I_{i3}}{I_{s3}} \times \frac{100}{P_{eo3}} = \frac{I_{i3}}{I_{s3}} \times \frac{100}{100} = \frac{I_{i3}}{I_{s3}} \qquad \text{… (G.6)}$$

(d) Find the dimensionless conversion factor C_3 from Table B1 of AS 2118.2 by using the aspect ratio and attenuation factor. Interpolating C_3 when needed.

(e) Limiting distance

$$D_{l3} = C_3 \times \sqrt{W_{w3} \cdot W_{h3}} \qquad \text{… (G.7)}$$

If D_{l3} is larger than D_{s1}, then drencher system must be installed.

(f) Area requiring coverage

For a building situated within D_3, height of the surface area of building requiring protection is $\sqrt{D_{l3}^2 - (D_{s1})^2}$. This height should be measured from the roof of source building. For example, if height of the source building is 10 m, then height of the surface area requiring protection should be measured starting from 10 m.

Appendix H: Publication Arising from the Thesis

Refereed Journal Papers:

J1. Ng, M.Y. and Chow, W.K. 2001.
General geometrical features of the new airport terminal building and a brief review on its fire safety provisions.
Fire Safety Science, Volume 10, No. 3, pp.178-183.

J2. Ng, M.Y. and Chow, W.K. 2001.
Preliminary review of the Codes on deluge system and the associated key physical aspects.
Journal of Applied Fire Science, Volume 10, No. 4, pp.343-367.

J3. Chow, W.K. and Ng, M.Y. 2002.
Fire risk for a local shopping mall.
International Journal of Risk Assessment and Management, Volume 3, Nos. 2/3/4, pp.152-169.

J4. Chow, W.K.; Ng, M.Y. and Chan, M.K. 2002.
Fire safety aspects for Chinese restaurants in Hong Kong.
Architectural Science Review, Volume 45, No. 1, pp.31-37.

J5. Ng, M.Y. and Chow, W.K. 2002.

Review on the design and scientific aspects for drencher system in different countries.

Architectural Science Review, Volume 45, No. 4, pp.323-335.

J6. Chow, W.K.; Yao, B. and Ng, M.Y. 2002.

Application of water mist fire suppression systems in small retail shops.

Journal of Fire Sciences, Volume 20, No. 6, pp.479-503.

J7. Chow, W.K. and Ng, M.Y. 2003.

Review on Fire Safety Objectives and Application for Airport Terminals.

ASCE - Journal of Architectural Engineering, Volume 9, No. 2, pp.47-54.

J8. Ng, M.Y. 2003.

Fire risk analysis of the airport terminals.

International Journal on Engineering Performance-Based Fire Codes, Volume 5, No. 5, pp.103-107.

J9. Chow, W.K. and Ng, M.Y. 2004.

Fire risk analysis on retailing areas of a new airport terminal.

Journal of System Safety, Volume 40, No. 5, pp.30-37.

J10. Chow, W.K.; Ng, M.Y.; Zou, G.W.; Dong, H. and Gao, Y. 2004.

Full-scale burning tests for retail shop fires: Preliminary studies.

International Journal on Engineering Performance-Based Fire Codes, Volume 6, No. 3, pp.94-121.

J11. Ng, M.Y. 2004.

Fire safety strategy for airport terminals.

International Journal on Engineering Performance-Based Fire Codes, Volume 6, No. 4, pp.210-212.

J12. Ng, M.Y. and Chow, W.K. 2005.

Proposed fire safety strategy on airport terminals.

International Journal of Risk Assessment and Management, Volume 5, No. 1, pp.95-110.

J13. Ng, M.Y. and Chow, W.K. 2006.

A Brief Review on the Time Line Concept in Evacuation.

International Journal on Architectural Science, Volume 7, No. 1, pp.1-13.

J14. Chow, W.K. and Ng, M.Y.2006.

Waiting time in emergency evacuation of crowded public transport terminals.

Safety Science, Accepted to be published.

Refereed Conference Papers:

C1. Ng, M.Y. 2003.

Fire safety strategy for airport terminals.

In: Proceedings of the Education Symposium on Advanced Fire Research, State Key Laboratory of Fire Science, University of Science and Technology of China, Chinese Academy of Sciences, Hefei, Anhui, China. 10-15 January, 2003. pp.32-34.

C2. Ng, M.Y. 2004.

Evacuation Analysis of the airport terminals.

In: Proceedings of the Subgroup 4: Smoke Movement and Toxic Harmful Gases Transfer in Fire of the National 973 Project "Fire Dynamics and Fundamentals of Fire Safety", State Key Laboratory of Fire Science, University of Science and Technology of China, Chinese Academy of Sciences, Hefei, Anhui, China. 26 May, 2004. pp.42-49.

C3. Ng, M.Y. and Chow W.K. 2004.

Numerical Studies on Evacuation Design in the Airport Terminals.

In: Proceedings of the Interflam 2004 – 10th International Conference on Fire Science and Engineering, Edinburgh Conference Centre, Edinburgh, Scotland, UK. 5-7 July, 2004. pp.749-754

C4. Ng, M.Y. and Chow W.K. 2004.

Computer Simulation of Crowd Movement in a Big Airport Terminal for Safety Assessment.

In: Proceedings of the 22nd International System Safety Conference, Providence, Rhode Island, USA. 2-6 August, 2004. pp.423-432

C5. Ng, M.Y. 2004.

Airport Evacuation on Comparing SIMULEX Against buildingEXODUS.

In: Proceedings of the Fire Conference 2004 – Total Fire Safety Concept, Hong Kong. 6-7 December, 2004. No. 2.