Fire Division

The Hong Kong Institution of Engineers

1st Annual Symposium


CCTV © ARUP


HK IFCII

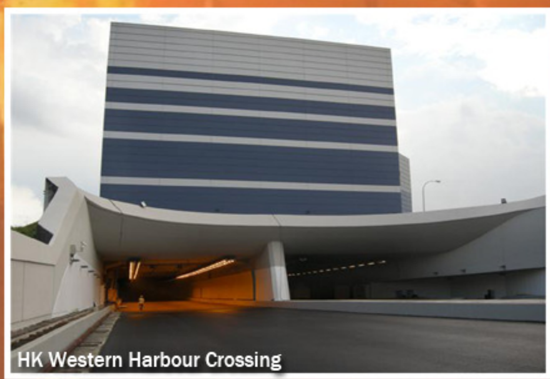
PROCEEDINGS


HK International Airport©ARUP

A NEW ERA OF FIRE ENGINEERING FOR INFRASTRUCTURE AND MEGA BUILDINGS

THURSDAY, 30 APRIL 2009

HONG KONG


HK Western Harbour Crossing


Beijing National Stadium
©ARUP/Ben McMillan


Beijing National Aquatics Centre
©ARUP/Zhao Ruogu Architecture Photography

Symposium Organizing Committee

Chairman
Ir Prof Paul PANG

Members
Ir Paul C Y CHAN
Ir Dr W T CHAN
Ir Charles M C CHU
Ir Elmen CHU
Ir Thomas C C CHUNG
Ir Albert T C HSU
Ir Victor W T LAW
Ir Sally LEUNG
Ir Dr M C LUO
Ir T K TAM
Ir Simon S F TSANG
Ir C K WONG
Ir Dr Dee H K WONG

Editors
Ir Prof Paul PANG
Ir Dr W T CHAN

Published by:
Fire Division, The Hong Kong Institution of Engineers

Printed in Hong Kong

ACKNOWLEDGEMENTS

The Symposium Organizing Committee would like to express sincere thanks to the following sponsors for their generous support to the Symposium:
(in alphabetical order)

Diamond Sponsors
Bun Kee (International) Limited
Mass Transit Railway Corporation Limited
Notifier Far East
Everlight Engineering Company Limited

Platinum Sponsors
Aecom
Gammon Construction Limited

Gold Sponsors
Air Trade Centre Limited
Anway Engineering Company Limited
ATAL Engineering Limited
C M Wong & Associates Consulting Engineers Limited
Meinhardt (C&S) Limited
Ove Arup & Partners (Hong Kong) Limited
Parsons Brinkerhoff (Asia) Limited
Research Engineering Development Façade Consultants Limited
Shinryo (Hong Kong) Limited
Siemens Limited
Siu Yin Wai and Associates Limited
The Hong Kong and China Gas Company Limited
Wong Pak Lam & Associates Consulting Engineers & Architects Ltd

Other
Scott Wilson (Hong Kong) Limited

1-DAY SYMPOSIUM

A NEW ERA OF FIRE ENGINEERING FOR INFRASTRUCTURE AND MEGA BUILDINGS

Organized by
Fire Division, The Hong Kong Institution of Engineers

Supported by
Buildings Department, HKSAR Government
Fire Services Department, HKSAR Government

Date: 30 April 2009 (Thursday)
Time: 8:45 a.m. (registration); 9:00 a.m. to 5:45 p.m.
Venue: Chiang Chen Studio Theatre, The Hong Kong Polytechnic University, Hunghom, Kowloon, Hong Kong.

Program

Time	Program
8:45 am	Registration
9:10 am	Welcome speech by Ir C K WONG, Chairman of the Fire Division, HKIE
	Opening address by Ir C K MAK, Permanent Secretary for Development (Works), HKSAR
	Session 1 : A New Era of Fire Engineering for Infrastructure Construction
9:30am	Paper 1 Train Fire Hazard and Design Fire Size; Conservatism and Credibility – Mr Paul SCOTT (AECOM Asia | Maunsell)
10:00 am	Paper 2 Fire & Life Safety Designs for Road Tunnels in Asia– Ir Dr Dicken WU and Ir Steven LAI (Parsons Brinkerhoff Asia Limited)
10:30 am	Q & A : chaired by Ir Dr Dee WONG
10:45 am	Tea/Coffee Break
11:15 am	Paper 3 Application of Performance-based Fire Engineering approach to the Design of Skypier - Ir Wilson S K TSANG (Hong Kong Airport Authority)
11:45 am	Paper 4 Fire Engineering for HAECO Hangars at Hong Kong International Airport – Mr Victor HO (HAECO) and Ir Dr P LIN (Meinhardt China)
12:15 noon	Q & A : chaired by Ir Anthony CM LAM
12:30 pm	Lunch Break
Time	**Program**
	Session 2 : A New Era of Fire Engineering for Mega Buildings Construction
2:00pm	Paper 5 : 北京奥运工程性能化防火设计与消防安全管理 - 馬建民 (Beijing Fire Bureau, PRC)
2:30 pm	Paper 6 Fire Engineering Design for Innovative Buildings – Ir Dr Mingchun LUO (Ove Arup (HK) Partners Ltd)
3:00 pm	Q & A : chaired by Ir Prof K K CHOY
3:15 pm	Tea/Coffee Break
3:45 pm	Paper 7 Third Party Fire Safety Certification in Singapore – Mr Geok Kwang BOO (Fire Safety and Shelter Department, Singapore Civil Defence Force, Singapore)
4:15 pm	Paper 8 Application of Models for Performance-Based Design – Ir Prof W K CHOW and Ir Dr N K FONG (Hong Kong Polytechnic University)
4:45 pm	Paper 9 Identification of Risk of Interaction among underground utility Infrastructure for Effective Fire Engineering Precautionary Measures - Ir Simon NGO (Hong Kong Town Gas)
5:15 pm	Q & A : chaired by Ir Paul CY CHAN
5:30 pm	Closing remarks by Ir Prof Paul PANG, Assistant Director of Buildings

Page no.

Message from Chairman of the Fire Division, Hong Kong Institution of Engineers

It is my great pleasure and honor to welcome you to the First Annual Symposium of the Fire Division of HKIE.

Fire is essential in all walks of life but may become a major disaster to human lives and properties if not kept under control. There has been a long battle between fire and mankind since the dawn of human history. The challenges has been everlasting and become increasingly complex with the unprecedented global economic development and urbanization in the past decades, which have spurred intensified density of iconic mega building development and extensive infrastructure network. Furthermore, the contemporary architectural concept, new construction technology, post 911 concern for emergency preparedness, environmental concerns for green features, and other public expectations magnify the complexity beyond the limit of traditional prescriptive approach. In response to the growing demand for Fire Engineering Professionals to face the new challenges, the Fire Division was established in June 2008 as the youngest division within the large family of HKIE. Our mission is to serve as a platform to bring together a vast array of knowledge and experience from both the local industry and international fire arenas to serve our communities with the best collective wisdom built on the latest research data, most advanced simulation techniques and also most importantly new ways of thinking.

The Theme of this Symposium is "A New Era of Fire Engineering for Infrastructure and Mega Buildings". Needless to say, efficient infrastructure and iconic mega buildings are indispensable ingredients of all sustainable modern economies. For our region to grow from strength to strength in the future economic cycles, both the China and HKSAR Government have injected enormous investment into the infrastructure which will in turn stimulate strong participation from the private economies in forms of mega building development projects. The core projects for this new era of construction boom, including the world largest Underground Station for Intercity Express Railway, Kai Tak Cruise Terminal Development, Kai Tak District Cooling Network etc, will be unprecedentedly complex and vast to accommodate large numbers of people. It is inevitable that their design and operation will be well beyond the practical limits of the current prescriptive legislation and codes. We have to collectively create a whole new science and legal framework to offer cost effective and reliable fire safety solutions for these important projects. We are honored to invite a number of prestigious fire professionals from Overseas, Mainland and Local Industry to share their thoughts and expertise on these topics. With the valuable inputs from our prestigious speakers, I am sure that as the symposium draws to a close this evening, all participants will bring home new thoughts and fresh insights on the subject.

I would like to express my sincere thanks to Ir Professor Paul Pang, Chairman of the Symposium Organizing Committee and his team members for their outstanding efforts to organize the symposium successfully. Also my heartfelt thanks are given to the Sponsors for their generous sponsorships. Last but not the least, thanks for your participation and hope you all enjoy the symposium and enhance the friendship with all other fire professionals.

Ir C K WONG
Chairman
Fire Division, The Hong Kong Institution of Engineers

Message from Chairman of the Symposium Organizing Committee

On behalf of the Symposium Organizing Committee, I would like to welcome you all to the First Annual Symposium of the Fire Division of the Hong Kong Institution of Engineers.

The theme of the Symposium "A New Era of Fire Engineering for Infrastructure and Mega Buildings" envisages to provide the participants salient projects and methodologies that are recent benchmarks to the realization of the versatile Fire Engineering Approach in the design of infrastructure and mega building projects. Through the application of Fire Engineering Design, we attempt to promulgate the scope of achieving the fire safety requirements for building and civil engineering structures with which the compliance with the contemporary fire codes can be difficult. In this regard, we have invited overseas, Mainland and local experts in the field for exchange and sharing of the topic.

Today, we are honoured to have our Guest of Honour Ir MAK Chai-kwong, the Permanent Secretary for Development (Works), to deliver an opening address. Moreover, we are also very grateful to have the presence of Mr. AU Choi-kai, the Director of Buildings and Mr. LO Chun-hung Gregory, the Director of Fire Services, for rendering their support to this important event.

I would take this opportunity to express my heartfelt thanks to our guests, sponsors for their support to the Symposium. I would also like to express my gratitude to members of the Symposium Organizing Committee for their contributions to the preparation and organization of the Symposium. Lastly, I would like to express my sincere thanks to the editorial board members comprising Ir Dr W T CHAN, Ir Dr M C LUO, Ir Dr Dee H K WONG, Ir Dr Eric CM LEE, Ir T K TAM and Ir Dr N K FONG for their unfailing support in the vetting of the Symposium Papers.

Without your participation and efforts, this event would not be possible and successful. We hope you all enjoy the Symposium.

Ir Prof Paul PANG
Chairman, Organizing Committee of
the 1st Symposium 2009, Fire Division, The Hong Kong Institution of Engineers

TRAIN FIRE HAZARD AND DESIGN FIRE SIZE; CONSERVATISM AND CREDIBILITY

Paul Scott

AECOM Asia | Maunsell

ABSTRACT

The issue of fire peak output for train fires in some projects drives many aspects of the design at significant cost in public funding. The trend, over recent years, has been considering less and less frequent events while producing extremely large events, which many rail and fire professionals consider to be unrealistic.

This paper discusses the issue of peak heat release rate, methods of estimating it, future developments and issues of approval and risk associated with it.

Keywords: Heat release rate, CFD Model, design fire size, equity, utility, train fire hazard, fire retardancy, ignition source, credible fire scenarios, ventilation, flashover

1. INTRODUCTION

It could be assumed that the assessment of the peak output of a train fire is straightforward, given the advancements in the understanding of fire dynamics; the sophisticated tools available for deterministic analysis of fire growth; the long operating experience and statistics available to scientists and engineers.

However, the reality is that there is no consensus on this issue, which is complicated by lack of clear objectives when considering the reasons we focus on peak heat release rate and the responsibility of key stakeholders for this design parameter.

This paper presents several aspects of developments in the assessment of train fire hazard: current methods of assessment; developing new methodologies; and, their implications.

The issues considered are:

- Approvals
- The implications of the increasingly stringent standard of train construction
- Fire development and scenario-based assessment
- Extreme incidents
- Future development in assessment techniques

2. BACKGROUND

The issue of 'design fire size', i.e. the estimated peak output of a fire' has been a fundamental fire design parameter for rail and metro designs in the past twenty years, as designers have attempted to provide a means for people to evacuate in the event of a train stopping in a tunnel with a serious fire on board. If this incident occurs, longitudinal ventilation can create a safe path upstream, away from the smoke, which is pushed downstream: this is the simplest strategy available and generally accepted as good design practice.

Peak heat release rate, therefore, determines the specification of systems and infrastructure to create the safe egress route and remove smoke from the tunnel: ventilation buildings, regularly spaced, are required with significant structures at the surface. Airflow from the non-incident tunnel must be designed to flow though any cross passages into the incident tunnel, and the achievement of critical velocity (Cv), to oppose the buoyancy of the smoke and hold it back from the evacuation route, is required. These facilities can require significant public funding.

3. RAIL TUNNEL RISK PROFILE

Despite the highly publicised accidents of recent years, actual deaths in rail tunnels occur less frequently than in road tunnels, because (see Figure 1) of the inherent safety benefits provided by the strict safety operating systems and the construction of the trains. In fact, when considering major accidents, rail travel including tunnel journeys presents less risk than air travel [1, see Figure 1]

Rather, it appears that political pressure significantly affects the decision making process: statutory authorities are under pressure to ensure that no major incident occurs, as the societal reaction to it can be disproportionate and may take no account of rational and reasonable decisions taken at the time of approval. Therefore, they tend to apply the principle of risk reduction by technology [2]:

Technology: *reflecting the idea that a satisfactory level of risk prevention is attained when state of the art control measures (technological, managerial, and organisational) are employed to control risks whatever are the circumstances:*

However, the process is often focused on provision of systems, not on the management or the organisation. The disadvantage is that this approach on its own neither sufficiently consider the relationship between costs and benefits nor a fundamental principle of design: the creation of simplicity where functions are complex and, by reducing the pressure on operators and emergency services, an increased likelihood of preventing high consequence, low frequency accidents.

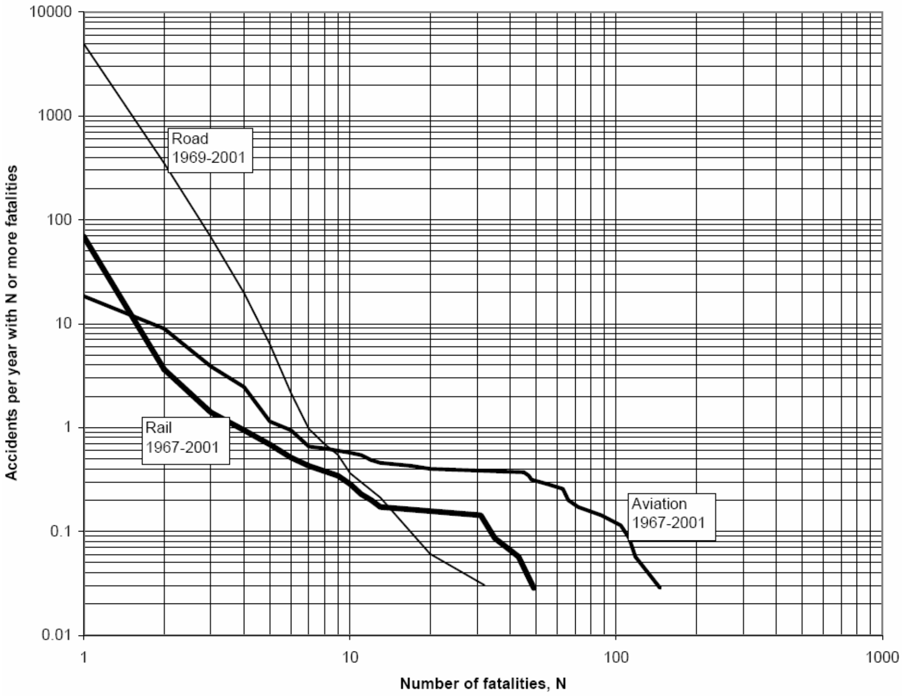


Figure 1: FN-curves for UK Road, Rail and Aviation Transport, 1967-2001

There are, however, two other principles of risk reduction, equity and utility [2, 3], which could be given similar weight in the decision making process:

Equity: *the premise that all individuals have unconditional rights to certain levels of protection and that beyond a certain limit, the level of risk can be deemed to be unacceptable, no matter what the social or economic benefits.* The equity principle works in two ways: firstly, it defines a level of risk which is unacceptable, whatever the benefits are. However, equity also means that if a risk is so small that it is less than that generally experienced by members of society in their everyday lives, the risk may be judged in terms of what is a reasonable and practicable response to it. This then allows the application of utility:

Utility: *applying a comparison between the incremental benefits of the measures to prevent the risk and the cost of these measures; the utility based criterion compares in monetary terms the relevant benefits (e.g. statistical fatalities avoided) with the net cost of introducing the measures.*

Then, by using a combination of equity and utility, a common denominator is derived amongst all relevant parameters to assist decision making.

To put this in the context of a heavy rail system; the RSSB Overview of the Risk Profile Bulletin [4] indicates 1 death per year for every 1,000,000 exposed population for all railway fatality risks in the UK.

RSSB Train fires – Special Topic Report, January 2001 Graph 1 indicates equivalent fire fatalities / year = 0.64, while the total equivalent fatalities / year for all risks is 23.84. The proportion of fire related deaths can therefore be taken as 0.64/23.84 = 0.0268 or 1/ 37.

Broadly, the resultant individual fatality risk is 1 / (1,000,000 x 37) = 2.7×10^{-8} per year, while the general level of individual fatality risk in UK society is 1×10^{-4} per year. The risk of tunnel travel is significantly less than this, which represents the total fire risk on the railway

The general level of risk in tunnels can, therefore, be considered to be acceptable even for those rail tunnels with no or few safety systems; and in addition, tunnels provide significant economic, social and environmental benefits which are taken for granted by society.

These issues are brought sharply into focus when considering train fire hazard, specifically related to tunnels and underground stations, as the cost of the associated systems can be very significant.

4. TRAIN FIRE HAZARDS

There are very few serious fires in recently constructed rolling stock. Most incidents, which may involve undercarriage equipment, are not classified as serious, in that they do not cause exposure of people to hazards and require no significant action to extinguish them.

This development has been accepted as an important factor in the acceptability of railway safety cases, or their equivalent internationally. For example, it is unlikely that older systems could achieve safety certification to modern standards on its existing infrastructure without the fire resisting properties and construction standards of their trains (for example, built to BS 6853 1a [6]). This lack of acknowledgment of train construction standards can be very frustrating for the designer of new systems, when it is implicitly acknowledged for older systems during the approval process.

The few well-publicised incidents that have resulted in major loss of life, have been related to a particular combination of circumstances involving older style rolling stock, infrastructure and the inability or delay in allowing people to evacuate.

However, considering what caused the fatalities and injuries; the mechanism was generally, for those who could have escaped, smoke inhalation. There are two factors; the toxicity of the smoke and its temperature, and related to this, the visibility, which, on its own does not directly kill but causes confusion and poor way-finding, decision making, and hence rendering longer exposure to hazardous conditions. There is no threshold of fire size for any serious fire which determines if people will live or die, as their vulnerability varies significantly.

Putting this point another way:
Any fire size which produces toxic smoke can kill large numbers of people if the circumstances of the incident cause exposure to the hazard, or
The ability of a system to create critical velocity for the spread of a large fire size does not guarantee the safety of persons in an underground fire; it is their ability to move quickly away from the vicinity of the fire that reduces the risk significantly.

The response to this problem has been logical in many ways; very significant improvements in train construction and the fire retardancy of materials. This is one of the factors that allows London Underground, for example, to operate with an accepted safety case (even though much of the infrastructure is over one hundred years old).

The second response is to provide additional safety design features: twin bore single track tunnels; high level evacuation walkways and cross passages or doors into the non-incident tunnel.

However, there are problems with this strategy. Rail operators will not release people from the train until they have established that it is safe to do so, which requires the clearance or stopping of trains in the non-incident and incident tunnels: the cross passages and non-incident tunnel may not be available as a place of safety during the time that people will become exposed to the fire hazard.

Secondly, the high level walkway (generally 850 mm effective width) forms a blockage to evacuation if all doors are opened at the same time and may cause serious problems if there is a developing fire.

Thirdly, the whole question of whether or not to ventilate the tunnel during a fire is unclear [7], as for internal train fires there is a very good chance that up to half the passengers will be exposed to toxic smoke: longitudinal ventilation may destroy efficient smoke layering, so nowhere is safe downstream of the fire.

It can be argued that evacuating passengers are significantly better off at track level and for the majority of fires; that is, more persons would survive (overall evacuation rates would be quicker as faster moving people can by-pass those walking slowly, and they would be further beneath the smoke than on the walkway).

Finally, it is always a very difficult technical decision for operational fire fighters whether or not to ventilate a fire.

This is not to argue against ventilation in tunnels, it is required for comfort and may be useful once an incident has been carefully assessed, but the assumption or requirement to provide systems to cope with very large fire sizes has to be reviewed.

It may be that, in the absence of confidence in the fire retardant construction of trains, statutory authorities focus on fire size to give some positive influence on the safety design; but experience shows that the operation of ventilation systems in real tunnel fires does not necessarily have a prolonged positive effect, for instance, the Channel Tunnel fire in 1997, where the operation of the ventilation system over several hours resulted in significant fire spread and damage to the tunnel [8].

Finally, modern trains are designed to prevent common cause failure; that is, a fire will not cause a fault which will result in the train being unable to proceed to the next station to detrain the passengers.

If key stakeholders seriously consider that trains could have very large internal fires that could develop in a short time, then the improvements in tunnel safety would focus on:

- Wider evacuation walkways with facilities to get down to track level if necessary
- Service tunnels with egress at regularly spaced interval dependent on train length
- Carriages with fire compartmentation between them

However, this is not the case and it appears that in reality, there is an acceptance of the fire retardancy of rolling stock materials of construction.

4.1 Peak heat release rate

What methods do engineers apply to estimate peak heat release rates for modern rolling stock? There are two main approaches:

1. A purely deterministic view of the maximum possible burning rate based on materials of construction, assuming 'perfectly' ventilated, post flashover fires, utilising information on heat release rates from ISO 5660 [9]
2. A scenario based assessment using the same information, but focussing on possible sources of ignition and mechanisms for fire development

Method 1

The method (ISO 5660-1) used in this approach applies a known heat flux against a sample of material and measures the additional heat produced by the sample. A benefit of this method is that it gives a laboratory measure of the rate of heat release per unit area of samples of material. There are, however, also a number of implicit assumptions in the method:

- that there is a fully developed fire
- that the radiant heat fluxes are all achieved throughout the whole space at the same time
- all material surfaces are involved at the same time
- that there is a large ignition source
- flame spread and fire growth occur and are very rapid
- there is no burn-out of materials before others are involved
- there is no local or global ventilation control of the fire
- there is no asymmetry to the development of the fire or the failure of glazing

This is the reason for the prediction of very large peak heat release rates, but there appears to be no firm basis for this method to determine worst credible fires, as full-scale experiments and computer modelling indicate that:

- fire retardants are very effective at resisting ignition and can inhibit fire spread
- fires that develop would develop gradually from the point of ignition
- there needs to be sufficient fuel and ventilation for full development of fire to occur
- fires involving non-fire retardant materials are often asymmetric, developing and breaking the glazing on one side of the vehicle whilst the glazing on the other side remains intact
- fire experiments involving moderately fire retardant materials that do spread and spread gradually around vehicle from the point of ignition, breaking windows

local to the fire leading to a fire that gradually develops around the vehicle and to burn out in the area of ignition before other areas are involved
- full-scale fire experiments with fire retardant materials have not been able to achieve a growing fire or flashover.

Often, during the preliminary design period when the peak fire output is specified, there are some uncertainties relating to the specification and performance of the proposed rolling stock and the materials of construction.

However, it is difficult to conclude that the peak rates of heat release for vehicles built to modern material standards can produce reasonably foreseeable fires in the region of 15 to 35 MW if full-scale experiments and detailed modelling produce no evidence of rapid fire development even with large ignition sources [10].

One of the first studies using this method took place on MTR rolling stock [11], and the method was taken up by others without transferring or publishing caveats that were contained in that report, i.e. that one of the main components of the fire was the floor construction which was very unlikely to burn at any significant rate; and that a flash-over could not take place; but for the purposes of sizing the ventilation system, it was assumed that only one carriage would burn.

The application of this method without the appreciation of what was said in the report has led to increasingly large and extreme events being used as a basic design parameter, without the capability of any realism being applied to the assessment.

There are variations of this method which combine test results and ISO 5660 data, and allow for the fact that materials burn at different rates. A significant benefit of these assessments is that the slow growth of the fire can be identified. However, there appears no account taken of train construction, configuration of materials, enclosure of equipment, the tunnel environment and imperfect ventilation. Additionally, when an estimate of fire growth is produced, which shows a very significant time interval between ignition and peak fire development, well beyond the Required Safe Evacuation Time (RSET) and Available Safe Evacuation Time (ASET), the peak heat release rate still is the focus of statutory authorities.

It could be argued, therefore, that choosing a very large, unrealistic peak heat release rate is not a safety decision, but one of business continuity; just as with building codes, evacuation and fire brigade access are the focus of the code, but business protection is the responsibility of the operator in conjunction with the insurer.

Method 2

Method 2 begins by reviewing statistics on train fires. Operating experience of modern standard railway and metro systems has shown that the occurrence of hazardous fires is an extremely rare event, even when a deliberate arson attack has been attempted. In addition, systems such as Docklands Light Railway (DLR), London Underground Limited (LUL) and Mass Transit Railway Corporation (MTRC) (Hong Kong) and the Mass Rapid Transit Authority (MRTA) (Singapore) apply very high standards in selecting materials of construction’s reaction to fire.

The scenario-based method requires three phases:

- Review of existing studies rolling stock and identification of credible fire scenarios.
- Review of material standards and fire resistance of the construction
- Fire engineering analysis and estimation of the potential fire development and maximum heat output from the identified maximum credible fires.

In support of this and to provide useful information to assess the risk, the threat of extreme events and the likelihood of the credible fires are identified.

4.2 Credible Fire Scenarios

In general, the credible maximum design fire size can be derived assuming an internal train fire within the carriage compartment. This is the fire of interest as it has the greatest safety consequence.

5. INTERNAL TRAIN FIRES – MECHANISM FOR FIRE SPREAD

A typical train cabin can be considered as a set of accommodation sections divided by entrance vestibules. The CFD modelling can be set out to test the possibility of fire spread to remote fuel packages due to downward radiation, or contact with the hot smoke layer; in particular, the potential for a flashover, assumed in previous methods, can be assessed.

5.1 Ignition sources

With the high standard of fire resistance of materials inside modern carriages, the risk of accidental ignition can be considered to be very low [12]. In this example, the materials in the cabin, with few minor exceptions (laser screens, information boards), comply with BS6853 Category 1a or 1b. This standard sets out to ensure that the probability of a transition to flash-over within the vehicle is minimized for the largest credible ignition sources, of the order of 100 kW. It is reasonable to assume, therefore, that this is the minimum ignition source required to start a fire inside the train

It is worth noting that a 100kW ignition source is equivalent to several large newspapers screwed up and ignited. Even then, this would have to be done in such a way that the flames come into direct contact with combustible material on the train. If they were placed on the floor, it could not start a fire unless they were next to a seat or some other fuel load. In fire tests, carbon chunks are covered with flammable liquid and ignited to provide a 100kW ignition source which lasts for approximately 10 minutes

Accidental ignition, therefore, is extremely unlikely: the only credible scenario that will produce this type of ignition source is a deliberate act, involving the ignition of materials brought into the train by the perpetrator.

Although the seat upholstery is fire treated, the seats are considered to be the most likely ignition point. The model, therefore, is based on the seating being the principal source of fuel for fires inside the train as they tend to be the target for attacks, especially attempts at arson.

Two scenarios were categorised by the level of determination required: a random and unplanned attack (say, lighting a newspaper on a seat) which is very unlikely to ignite the train materials; secondly, the addition of a flammable liquid may cause the seat to burn and set the opposite seat alight; spreading flammable materials on two areas of seating which could, if done efficiently, cause two sections to burn.

However, any more determined attack is no longer considered to be arson, as to cover the train in flammable material requires planning, restraint of passengers and train crew and considerable amounts of material brought on to the train. This is the profile of terrorism, and the likelihood of this event is considered below.

5.2 Passenger belongings

Another potential source of fire is passenger luggage, ignited by the following mechanisms:

- Accidental ignition
- Deliberate ignition, for example an incendiary device in a bag, brought on with the specific intention of setting a serious fire in a train

The accidental ignition of luggage is an extremely rare event on railways world-wide and in the UK, the likelihood of this incident as a precursor to a fire is assigned a probability of zero, according to published data from the UK Rail Safety & Standards Board [4]. Therefore, this is not considered to be a credible event.

Deliberate ignition of baggage is considered an unlikely means for a perpetrator to start a serious fire for two reasons: the material inside the bag will not initially be in direct contact with combustible material in the train; and, setting fire to another passenger’s bag in a train is not credible.

The use of a bag to carry an incendiary device is considered terrorism, and this is discussed in below, but it should be noted that incendiary devices are not a favoured mode of attack, due to the size of device, possibility of detection and potential unreliability.

The conclusion is that a luggage-related fire is not a credible incident which should be considered for this fire hazard assessment method. However, the possibility of luggage being ignited remotely by a fire is considered.

6. EXAMPLE OF THE ASSESSMENT APPLICATION

In this section, we provide an example of an analysis of the fire load within BS 6853 1(b) carriage, its configuration and the means by which fire can spread. In addition, we model potential fires in comparison to flashover conditions. i.e.:
‘a transition phase in the development of a contained fire in which surfaces exposed to thermal radiation reach ignition temperature more or less simultaneously and fire spreads rapidly throughout the space[14].

Ventilation is a very significant factor in any contained fire development and the model was subject to a sensitivity analysis to ensure that significant ventilation scenarios were considered, as lack of ventilation can sometimes be critical.

The analysis was not using the CFD model to predict if a flashover occurs, rather to understand why it does not occur in practice: however, we also examine if there is a fire configuration that could lead to a flashover.

The analysis was linked to the potential for fire spread for each of the fire mechanisms. Using this approach, the maximum credible fire was both identified and defined; that is, it is an event which can be reviewed, and amended if further information becomes available, but importantly it contains a significant safety margin in comparison to regularly occurring events.

7. FIRE LOAD

The seats were formed from the following materials:

Material	**Quantity per bench**	**Calorific value**	**Fire load per bench**
Dense fire resisting polyurethane foam	6.10 kg	9.70 MJ/kg	59.2 MJ
Anti-vandal material	1.63 m^2 of material	4.90 MJ/m^2	8.0 MJ
Calico	1.85 m^2 of material	2.70 MJ/m^2	5.0 MJ
Seat covering	2.00 m^2 of material	16.14 MJ/m^2	32.3 MJ
Total fire load for one double seat bench = 104.5 MJ			

7.1 Ignition sources

As discussed in the previous section, the materials in the example cabin, with few minor exceptions, complied with BS6853 Category 1b. This standard sets out to ensure that the probability of a transition to flash-over within the vehicle is minimized for largest ignition sources, of the order of 100 kW, therefore the high standard of fire resistance of materials inside the carriages results in a very low risk of accidental ignition.

Nevertheless, it was assumed that an ignition source this size was present, probably the result of a deliberate fire involving the ignition of materials brought into the train by the perpetrator of an arson attack. The model was based on the assumption that the seating would be the principal source of fuel for fires inside the trains, but the effect on baggage was also analysed.

8. VENTILATION

Fires inside the train would be detected by passengers or the train captain and the train would continue to travel to a suitable point for passengers to evacuate. If the fire began to threaten passengers the train could stop in a tunnel. The train doors would all open to allow passengers to escape. The CFD analyses therefore assumed that the doors would be open once a fire was established. The toughened glass windows would also break due to heat from a fire; windows and wind barriers immediately adjacent to the fire are also broken. However, as ventilation is significant, a sensitivity analysis was completed regarding ventilation conditions

9. MODEL CONDITIONS AND OUTPUT

CFD Models were set up to study the thermal conditions for a fire started at a single point in one of the 8 bench sections of the cabin (Test A); and a larger incident where two fires are started simultaneously (Test B).

Test A – 8 bench fire

Test A modelled a single point of ignition starting at one of the seats with fire spread dictated by simulated thermal conditions in the compartment and an assumed pilot ignition temperature of 270°C.
For the initial fire, it was assumed that one double seat bench was ignited and burned at a defined HRRPUA of 305 kW/m^2. This was based on the following estimate:

- Total fire load for one double seat bench = 104,500 kJ
- Estimated burning time excluding incubation and decay periods = 10 minutes
- Introduced ignition source = 100 kW
- Total area of bench = 0.9 m^2
- Heat release rate for the seat bench = 100 + 104,500 / (10 x 60) = 275 kW
- HHPUA = 275 / 0.9 = 305 kW/m^2

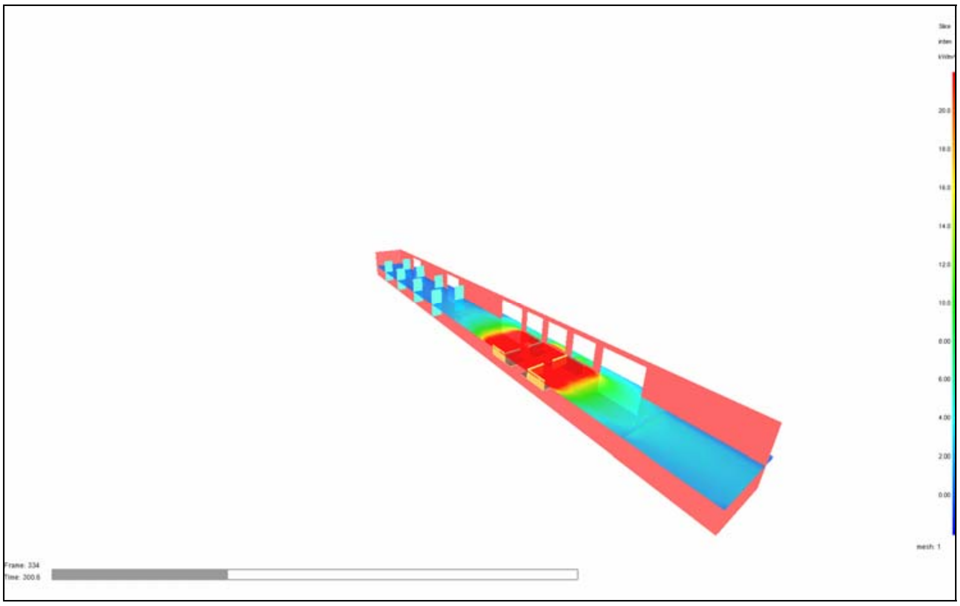


Figure 5: Radiant Flux at 850mm AFL – 300 seconds

<u>Observations</u>
HRR – 1,830kW
$\dot{q}''_{rad}$ - 5.17kW/m^2
At 300 seconds all eight benches are involved and the total HRR reaches 1.8MW. The radiant conditions at seats in the nearest seating outside the 8 bench section are significantly less than 16 kW/m^2 required for piloted ignition of fire resistant polyurethane foam.

The model was set up to record the following output information:

- Radiation slice horizontally at 0.85 m above the cabin floor level to reveal the likely profile of radiation which may affect seating remote from the fire section.
- Radiant flux 'thermocouples' at six locations to record more precise values of radiant flux at the nearest seating outside the fire sections.
- Temperature slice vertically through the centre line of the cabin to establish the likely hot gas layer temperature along the length of the carriage.

Test B – 12 bench fire

Test B assumed a constant defined heat release rate from two seating sections (12 benches) as a result of arson or sabotage. The information on heat release rates in Test A was used to inform the fire size for the Test B fire.

This test assumed a constant defined heat release rate for the seats in two section of the cabin with a value of 275 kW per seat bench (or 305 kW/m^2) based on the results of Test A for a simulated growth 8 bench fire which indicates a peak heat release rate of 1.8MW. When this was increased pro-rata for 12 benches, the resulting peak heat release rate was 12 x 1.8 / 8 = 2.7 MW

The model was set up to record the output information in the same way as test A:

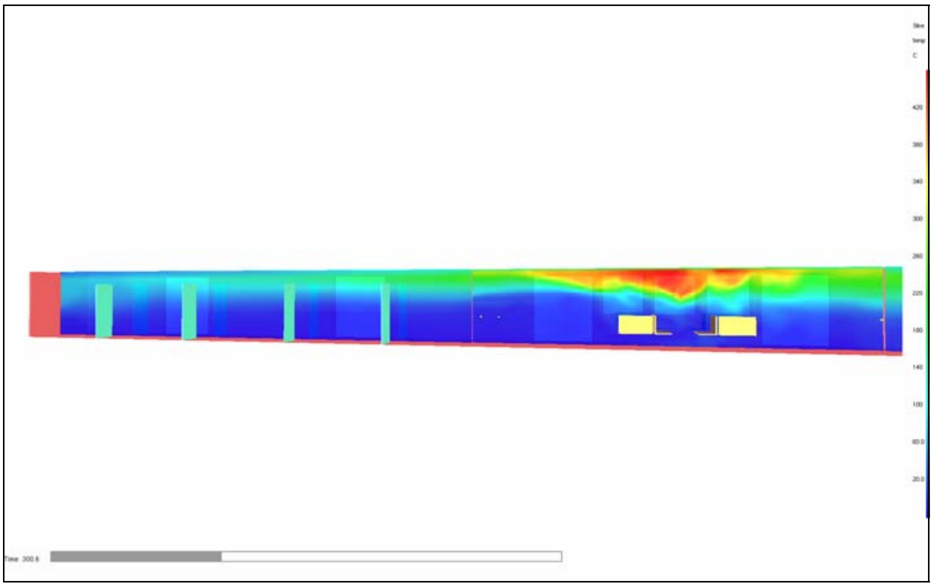


Figure 6: Temperature Slice through Centre of Cabin – 300 seconds

Observations

At 300 seconds, the smoke layer at the top of the cabin is 300 to 350 °C above the nearest seating outside the 8 bench section. This is less than the (non-piloted) ignition temperature of seating foam.

10. INTERPRETATION OF MODEL RESULTS

The heat release rate curves were constructed from a combination of data from the CFD models and assumed fire growth and decay characteristic curves. The 8 bench curve used the data from the simulated fire development model – Test A. The other curves are derived from a combination of CFD modelling data and assumed t^2 fire growth and decay curves as described below:

11. ATTEMPTS TO CREATE FLASHOVER CONDITIONS

The sensitivity analysis included examined ventilation conditions and whether or not there was a credible configuration for the incident train carriage which could result in a flashover. It was found that, with doors open following passenger evacuation, the fire was not sufficiently contained to allow flashover conditions to develop. If there was limited ventilation, then the fire did not develop sufficiently to create the flashover hazard.

The only scenario where radiant heat flux was approaching the threshold to ignite materials below it was partial ventilation, where only 50% of windows directly affected by the fire broke, the carriage doors were shut and all other windows remained intact, even if exposed to gas temperatures sufficient to cause them to break. In this case, the seats in the front section were exposed to radiant heat flux approaching that required for ignition of untreated polyurethane foam after 15 minutes, but the seats in the other half of the train were not.

If more than 50% window breakage was assumed next to the seat of the fire, or any other windows or doors were open or broken, then the RHF was reduced to significantly less than that required for a flashover.

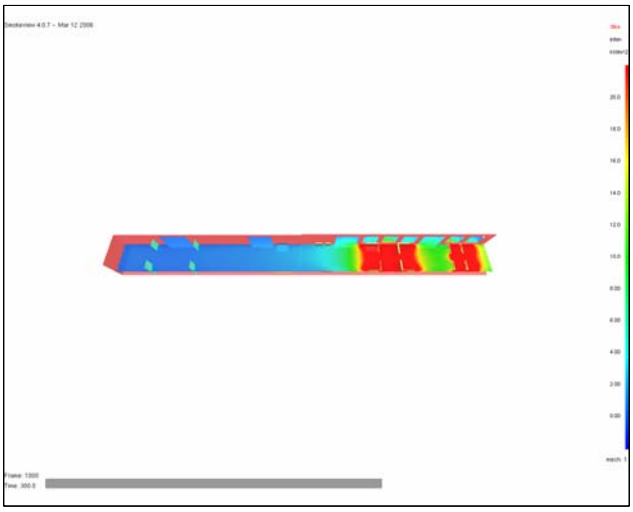


Figure 7: Radiant Flux at 850mm AFL – 300 seconds

Observations

HRR – 2,700 kW

$\dot{q}''_{rad}$ - 6.0kW/m^2

With 12 benches involved in two sections, the total HRR reaches 2.7 MW. The radiant conditions at seats in the central seating section of the cabin are significantly less than 16 kW/m^2 required for piloted ignition of fire resistant polyurethane foam.

.

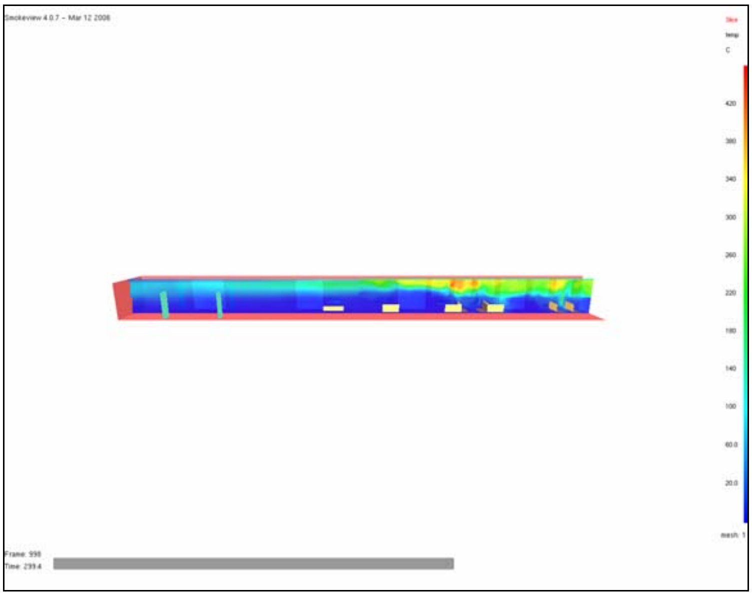
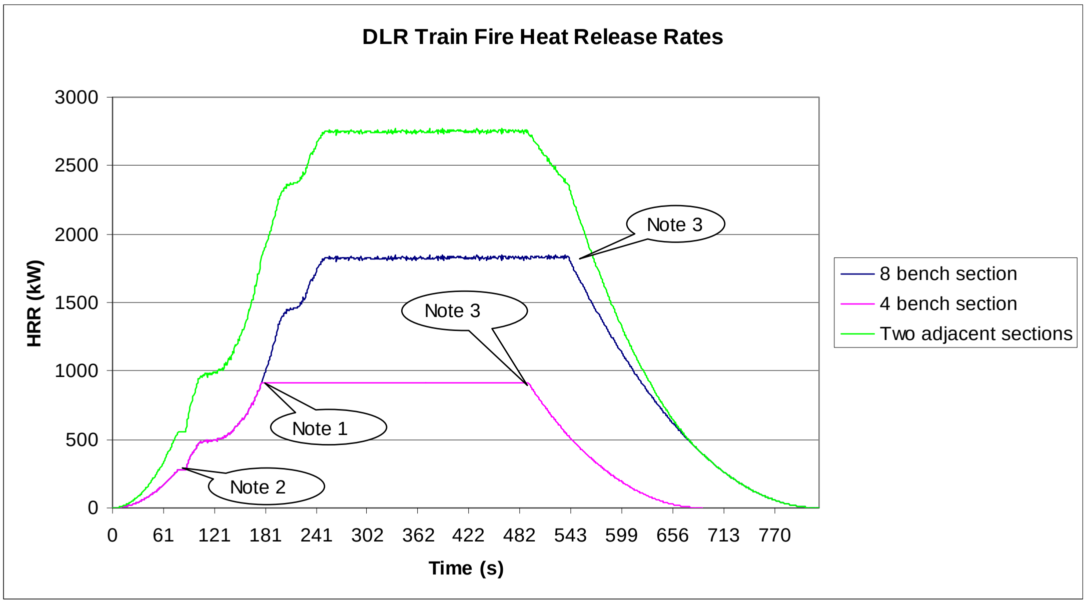


Figure 8: Temperature Slice through Centre of Cabin – 300 seconds

Observations

The smoke layer at the top of the cabin is 300 to 350°C in the central seating section of the cabin. This is less than the (non-piloted) ignition temperature of seating foam.



Note 1

8 bench and 4 bench fire assumed to develop with the same growth rate up to this point. 4 bench HRR reaches 1/2 the 8 bench peak HRR, i.e. 0.9 MW. The 4 bench fire then continues as a constant HRR until the fuel is exhausted.

Note 2
Early growth rate assumed to grow at ultra fast t^2 growth rate Q = 0.0468 x t^2 up to this point
Note 3
At this point, the fire starts to decline due to fuel exhaustion and is assumed to follow a fast t^2 decay. Decay formula: $Q = 0.0234 (t - k)^2$ where $k = \text{peak} (HRR / 0.0234)^{0.5}$
Note 4
For two fires starting at the same time in adjacent train sections, the 8 bench and 4 bench curves are added.

12. SENSITIVITY TO VENTILATION

The maximum temperatures and heat fluxes are usually achieved under a delicate ventilation balance where the heat leaving the carriage is limited whilst sufficient oxygen is provided to the fire so as not to limit growth. Therefore, it is important to test the sensitivity to the ventilation.

Sensitivity of the 8-bench fire spread to ventilation was tested for the train doors (which are designed to open to let the passengers out, but may fail to open), for the quarter-lights at the top of the window (which could be open, perhaps on a hot day, or closed) and for the window breakage. Informal discussion with one manufacturer of toughened glass suggests that it breaks when the temperature differential across the glass is 200 ºC.

The tests showed that the windows would break within a few seconds of the start of the fire (whether specified to break at 300 ºC or 400 ºC). Therefore the results were not sensitive to this parameter. A full fracture was assumed in all tests, except one, where 50% breakage was assumed.

The worst realistic case tested, assuming full breakage, was for closed doors, and with open quarter lights. For this worst realistic case, the heat fluxes at adjacent seating sections towards the end of the carriage reach around 12-13 kW/m^2 and 7-8 kW/m^2 for the adjacent seating in the middle of the train using a coarse grid. This scenario was re-run using the fine grid, giving 9-10 kW/m^2 at the end seating section and 6-7 kW/m^2 in the middle seating section. The heat fluxes in the adjacent seating sections are therefore significantly below the 16 kW/m^2 required to ignite the seats.

In one test, it was assumed that only the upper 50% of the windows broke (at 400ºC), and a fine grid was used to test the model. In this case, five of the six windows broke in the first 10 seconds of the fire. Heat fluxes at the end seating section grew to 11 kW/m^2 in the first 6 minutes of the fire and from 11 to 15 kW/m^2 steadily from 6 minutes to 15 minutes. At the middle seating section, heat fluxes grew to 8 kW/m^2 and then from 8 to 12 kW/m^2 over the same period. Heat fluxes at the end seating section, therefore, are close to the 16 kW/m^2 and thought to be required for fire spread. However, temperatures at the unbroken window halves were in excess of 400 ºC, in this period, despite the upper halves having broken earlier. Therefore, this is not thought to be a realistic scenario, because the lower window halves would be likely to experience further breakage.

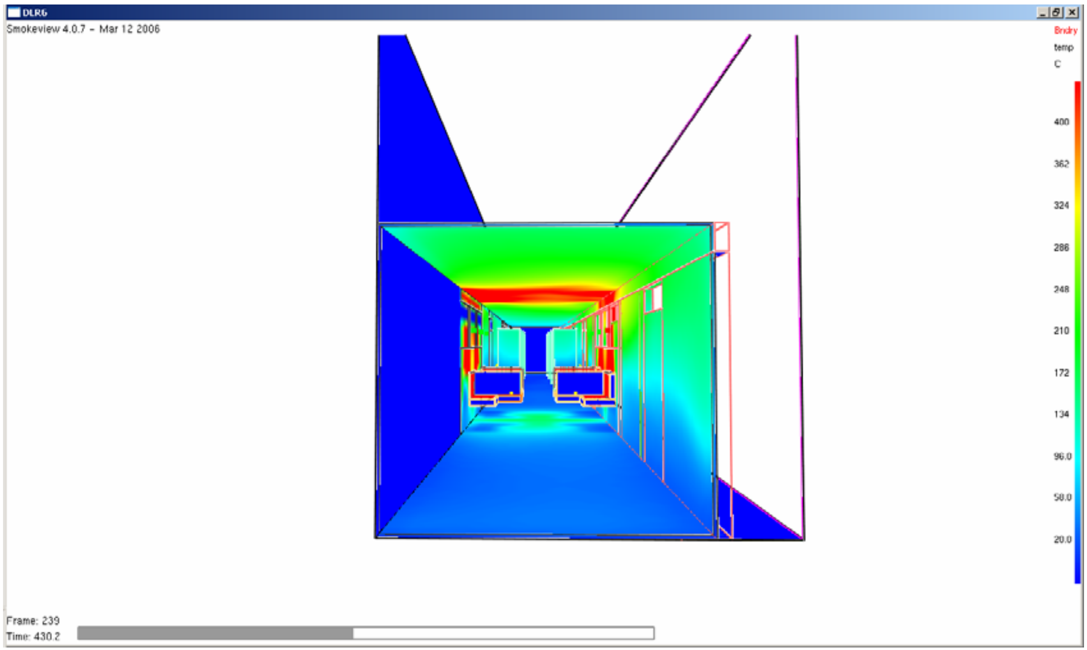


Figure 9: Temperatures on the cabin walls for closed doors and half-broken window scenario– 430 seconds

13. RISK ANALYSIS

Using the scenario based assessment to identify maximum credible events requires an assessment of the likelihood of train fires based upon the identified ignition scenarios. Using data from the rail system and global rail statistics [15], an analysis of ignition events was completed. This included an expert analysis of terrorism attack potential.

The results of the risk analysis, which estimate the likelihood of a major fire from the scenarios analysed, are shown in Figure 5.1 and the fire frequencies are shown below

Fire Size (MW)	Frequency	Fire Return Period (years)	Comment
0.1	2.27E-01	4.40	Most Likely fire, attempted arson which does not ignite seats
0.15	4.00E-02	25	Arson which successfully ignites part of the seat
0.3	1.24E-02	80	One bench alight
0.9	5.71E-04	1750	Two benches alight
1.8	3.43E-03	292	A complete section of benches alight, more likely than the previous scenario, as when two benches are fully alight the model predicts that fire will spread to within that section
2.7	4.24E-04	2357	The result of either a: Determined attack where accelerant is applied to two seating sections A set of very unlikely ventilation conditions where the windows break sufficiently to minimise heat loss and maximise fire ventilation

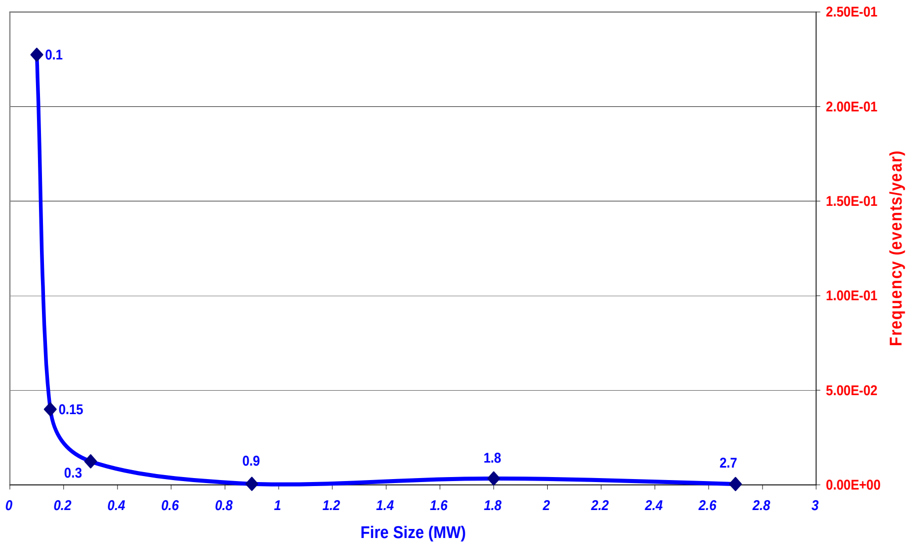
14. DISCUSSION

The objective of rolling stock material fire standards is to reduce risk of a serious fire to a minimum; this is achieved by:

- Limitation of fire load in vulnerable areas
- Use of materials which require significant energy to be ignited
- Specification of materials in the ceiling which do not produce flaming droplets or brands which can cause pilot ignition.

In the case of modern trains the standard of fire resistance has been realised by use of materials and the separation and minimisation of fire loads.

Figure 5.1: Estimated Fire Size & Frequency of DLR Train Fires



Thus, with the results of this method of assessment, a credible train fire indicate that:

- The day to day accidental ignition scenarios do not provide sufficiently energetic sources to ignite the materials of construction within the train
- Vandalism or arson are the only credible sources of a growing fire (centred on the seating)
- It requires a determined attack to create a fire which involves more than one bench
- The separation of seating prevents remote fuel packages from becoming involved, because:
- Radiation is not sufficient to ignite seats outside the initial fire location.
- There is a very small quantity of combustible material at high level: this could fall, but the burning material would not have sufficient heat to ignite combustible materials at low level.
- Greater quantities of non-combustible materials at high level could be heated to the smoke temperature (~300°C) and fall onto combustible materials below, but this would not be hot enough to cause spontaneous ignition.
- Therefore, the only credible mechanism to cause serious fire development is vandalism, which in its most basic unplanned form will cause minor damage to a seat (and a small fire).

With increasing levels of determination (and decreasing levels of likelihood), an attack may cause one section of seating to catch light, or two sections if both are ignited maliciously. Thus, the maximum credible fire is considered to involve two sections of seating and this would result in a fire output of less than three megawatts which would be insufficient to cause flashover.

It is of course possible that a terrorist attack could result in a fire of greater output, but this requires:

- Explosives, flammables and a fire load to be brought on to a train undetected; and,
- Restraint of passengers and train crew, or
- Undetected break-in to DLR premises outside normal working hours and well-informed plan to cause a significant fire.

It is considered that this would be extremely unlikely to occur because the outcome would not be proportionate to the risk of detection and the difficulty of the attack, in rail operations that have modern security systems, revenue barriers and CCTV.
[NB. We are not minimising the risk of attack from terrorist groups, but differentiate between the method employed and that which is required to cause a fire involving a whole carriage.]

15. CONCLUSIONS

The application of modern rolling stock construction standards such as BS 6853 and the general level of construction of trains have reduced the likelihood of serious fires. Furthermore, the maximum fire output, even if the result of a determined arson attack, is significantly reduced from the previous estimates where a ‘post-flashover’ fire is assumed as the starting point of the estimation, and it is entirely reasonable to question the assumption that flashover could occur in credible circumstances.

This is due to:

- The fire resistance of the materials; and
- The separation of fire loads within the vehicles.

Thus, it was found that by adoption of a ‘credible scenario-based’ method, the fire size, while remaining extremely challenging, is more credible and consistent with recent data and analyses elsewhere. An estimation of the likelihood of increasing fire outputs demonstrates that the maximum credible fire is in the region of 1.8 MW, and only a very determined arson attack or very unlikely ventilation conditions could result in a larger fire, and we estimate the upper bound for this fire to be 2.7 MW for vehicles built to modern rolling stock standards.

The assumption by statutory authorities that the choice of a large fire size enhances the safety of the system may not be correct, as the typical tunnel fire strategy is at best a compromise between conflicting safety requirements.

However, by understanding the pressures that statutory authorities are under to prevent societal accidents, and using a combination of technology, equity and utility for risk based decisions, a more holistic approach to design may be taken. This recognises that fire size is not a fundamental safety parameter in tunnel strategies and that in fact, modern vehicle construction standards can allow a reduction in fire size. Thus, key stakeholders can, with confidence, allow a realistic appraisal of fire size to be included in fire safety design strategies.

REFERENCES

[1] Transport Fatal Accidents and FN-curves, 1967-2001, Research Report 073, prepared by Andrew Evans of University College London on behalf of HSE. HSE Books, 2003.
[2] Reducing Risks, Protecting People, HSE's Decision Making Process. HSE Books, 2001.
[3] UK Health & Safety Executive: Quantified Risk Assessment – Its input into decision Making HMSO, 1989 ISBN 0 11 885499 2.
[4] UK Rail Safety & Standards Board Safety Performance Report and Risk Analysis 2008; HSE Publications 2009.
[5] Assessment of Safety of Tunnels, European Technology Assessment Group Assessment of the Safety of Tunnels part of the project "Assessment of the Safety of Tunnels" European Technology Assessment Group (ETAG) Wednesday, 16 May 2000.
[6] BS6853: 1999: Code of Practice for Fire Precautions in the Design and Construction of Passenger Carrying Trains.
[7] Charters, D., Scott P.D. To Blow or not to Blow, When to use Ventilation to Protect Tunnel Users: Safety in Road and Rail Tunnels, International Technical Conferences, Marseille 2003.
[8] Channel Tunnel Safety Authority, Inquiry into the fire on Heavy Goods Vehicle Shuttle 7539 on 18 November 1996, May 1997, ISBN 0115519319.
[9] Reaction-to-fire tests -- Heat release, smoke production and mass loss rate, HMSO Books, 2003 edition.
[10] Sanchez, J. Greg: Predicting Fire Growth and Smoke Conditions in Tunnels and Metros – an Advanced Fire Model, 4th International Conference Tunnel Safety and Ventilation 2008.
[11] LAL & AEL Rolling Stock: Power Output on Flashover: Predictions and Experimental Assessment, September 1993.
[12] Docklands Light Railway Assessment of Fire Design Size, DLR May 2007.
[13] UK Rail Safety & Standards Board Safety Performance Report and Risk Analysis 2008; HSE Publications 2009.
[14] Kennedy, P. & Kennedy, K.: Flashover and Fire Analysis, Investigations Institute 2003.
[15] Union International de Chemin de Fer: International Railway Statistics 2009.

FIRE AND LIFE SAFETY DESIGNS FOR ROAD TUNNELS IN ASIA

Dicken Wu [1], Steven Lai [1] and Dee Wong[2]

[1]Parsons Brinckerhoff (Asia) Limited
[2]Advanced Safety & Fire Engineering (ASFE)

ABSTRACT

Safety is the crucial design factor for successful road and transit tunnel projects. Nevertheless, there are no universal standards that could be applied for different countries. For instance, fire suppression is mandated in some countries or governmental jurisdictions but not required in others.

In this paper, the authors will try to delve into the fire and life safety design considerations in transit and road tunnel projects in Mainland China, Australia, Singapore and Hong Kong in the past decade. Further details on recent road tunnel projects will be discussed and benchmarked against with the normal design provisions adopted in Hong Kong.

This paper will present some ad hoc study cases in the context of some universally recognized performance-based fire engineering approaches and state-of-the-art computerized technologies, in the combined context of quantitative fire hazard and risk analyses. Throughout this set of analyses, this paper may shed some insightful light on the optimal yet time-cost effective and efficient designs on this crucial fire and life safety issue.

1. INTRODUCTION

Tunnels are major parts of many infrastructure projects in built-up areas, across rivers, harbours, and terrain areas. Among different design options, tunnels are generally more expensive than bridges and at-grade structures. Safety is the most crucial design factor for successful transit and road tunnel projects. Nevertheless, there are no universal standards that could be applied for different countries. This paper will discuss the fire and life safety design considerations in transit and road tunnel projects. Then, references will be made to the design considerations for projects in Mainland China, Australia, Singapore and Hong Kong, etc. and shed some insightful light on the optimal yet time-cost effective and efficient designs on this crucial fire and life safety issue.

2. DESIGN CONSIDERATIONS

In the design of a transit tunnel or a road tunnel, it is important to identify the operations and safety requirements for a given project [1]. The operations and safety requirements under normal, abnormal and fire emergency conditions shall be established at the inchoate stage of a project. Each project has its own characteristics; and therefore, the above requirements and the associated design do vary from project to project. Based on the operational requirements and the site constraints, the finally selected alignments and the configurations of the tunnel network can be cogently established.

For a transit tunnel project, based on the operational requirements and the site constraints, the tunnel gradients, the number of tracks per tunnel, the number and locations of crossovers and portals, and their attributes, will be determined. Based on the structural gauge requirements, likewise, the mechanical and electrical (M&E) system requirements; e.g. tunnel ventilation system (TVS), traction supply system, signalling and communication system, the evacuation requirements, the tunnel construction methods, the tunnel cross-sections, the crossovers, the cross-passage arrangements, and likewise, can be optimally determined. 2007 NFPA 130 [9], which addresses the fire and life safety requirement for transit tunnel, has been universally adopted for projects in North America, Southeast Asia, and perhaps the rest of the world.

For road tunnels, the tunnel gradients, the number of lanes per tunnel, the number and the locations of slip road, and the likewise, will also be similarly determined. Based on the structural gauge requirements, the M&E system requirements; e.g. tunnel ventilation system (TVS), tunnel lighting system, traffic control, monitoring system, and likewise, the evacuation requirements and the tunnel construction methods, the tunnel cross sections and the cross passage arrangements can be resultantly finalized. 2008 NFPA 502 [10], which addresses the fire and life safety requirements for road tunnels, has also been universally adopted in the above regions of the world.

In the event of a fire in either a road or railway tunnel, the TVS shall be operated to provide a tenable environment for passenger evacuation. The tenable environment requirements for transit (railway) tunnels and road tunnels are generically and similarly summarized in Table 2.1 [9, 10]. These, in essence, the so-called universal performance-based fire and life safety design criteria.

Table 2.1: Tenable Environment [9, 10]

	Transit Tunnel (Based on NFPA 130)	Road Tunnel (Based on NFPA 502)
Heat effects (thermal burns)	60°C (140°F)	60°C (140°F)
Heat effects (radiant heat)	2.5 $kW{\cdot}m^{-2}$	2.5 $kW{\cdot}m^{-2}$
Air CO content	(1) Maximum of 2000ppm for a few seconds (2) Averaging 1150ppm or less for the first 6 minutes of the exposure	(1) Maximum of 2000ppm for a few seconds (2) Averaging 1150ppm or less for the first 6 minutes of the exposure

	(3) Averaging 450ppm or less for the first 15 minutes of the exposure (4) Averaging 225ppm or less for the first 30 minutes of the exposure (5) Averaging 50ppm or less for the remainder of the exposure These values should be adjusted for altitudes above 1000m (3000ft).	(3) Averaging 450ppm or less for the first 15 minutes of the exposure (4) Averaging 225ppm or less for the first 30 minutes of the exposure (5) Averaging 50ppm or less for the remainder of the exposure These values should be adjusted for altitudes above 984m (3000ft).
Smoke obscuration levels	Continuously maintained below the point at which a sign internally illuminated at 18 lx (7.5 ft-candles) is discernible at 30m (100ft) and doors and walls are discernible at 10m (33ft)	Continuously maintained below the point at which a sign internally illuminated at 18 lx (7.5 fc) is discernible at 30m (100ft) and doors and walls are discernible at 10m (33ft)
Air velocities*	$0.75m/s \leq V \leq 11m/s$	$0.75m/s \leq V \leq 11m/s$
Noise levels	A maximum of 115dB(A) for a few second and a maximum of 92dB(A) for the remainder of the exposure.	A maximum of 115dB(A) for a few second and a maximum of 92dB(A) for the remainder of the exposure.

* Critical velocity is the minimum longitudinal velocity at the fire location, such that the smoke can be desirably directed to one direction, which is the short length of the train in relation to the location of the fire on the train.

Table 2.2 indicates some of the design considerations for road tunnel used in various locations.

Table 2.2: Road Tunnel Design Considerations

	Hong Kong	Mainland China	Singapore	Australia
Tunnel Name	Western Harbour Crossing Tunnel	Chong Ming Road Tunnel	Kallang-Paya Lebar Expressway Road Tunnel	Lane Cove Tunnel
Design Fire Heat Release Rate	50~100MW (50MW fanned to 100MW)	50MW	100MW	50MW
Cross Passages for Passengers	Yes	Yes	Yes	Yes
Cross Passages for Vehicles	No	Yes	Yes	No
Water Based Suppression System	No	Yes	No	Yes

3. DESIGNS FOR ROAD TUNNELS

To achieve an effective-efficient fire and life safety design for a road tunnel, performance-based fire engineering approaches and state-of-the-art computerized technologies are used in the design processes. In particular, the following designs are discussed.

3.1 Eastern Distribution Tunnel, Sydney, Australia [7, 11]

For a densely populated urban area, it is sometimes neither trivial nor feasible to construct tunnels. Case in point, the desired tunnel is to be built on a soft ground; and the tunnel is within the proximity of grade level. Under such a circumstance, a stacked tunnel may resolve the land issues.

The Eastern Distributor in Australia is a 6-km long route in Sydney. It includes a new 1.7-km main tunnel, and the 600-m Decay Todman Underpass. The main tunnel is a double-deck, dual, three-lane tunnel with two portals and a few exit ramps. The tunnel has a widest point of 24.5-m and it is probably the widest stacked tunnel in the world. With a 14-m ceiling in height, the tunnel is also notably tall. A concrete ledge in the middle has been added after the original construction phase having been separated the northern roadway from the southern roadways. The northbound traffic uses the three top lanes, whereas the southbound traffic uses three lanes below. Since the tunnel is located in a densely populated urban area, the requirement for three lanes in each traffic direction for the existing roadway corridor infers that a piggyback tunnel perhaps is the only viable design option. The skepticism of the piggyback construction style is that the tunnel is one of the only three of its kind in the world.

Due to a very stringent environmental requirement at the tunnel portals; i.e., quasi-zero pollutant emission, a ventilation building must be located at each portal to extract the polluted air from the tunnel. The polluted air will then be exhausted vertically to the atmosphere at a high velocity to achieve the outdoor air quality requirement.

Since the thermo-aerodynamic effects in a tunnel, especially at the portal interfaces, are quite phenomenally complex (especially when the design anticipates case numerous slip roads or bi-directional traffic, or both), advanced computerized modeling and simulations is the only cogent resort. Subway Environment Simulation (SES) computer program, which is designed to analyze such complex phenomena, has been widely used. Figure 3.1b simulates the fire growth and smoke propagation for Eastern Distributor Tunnel.

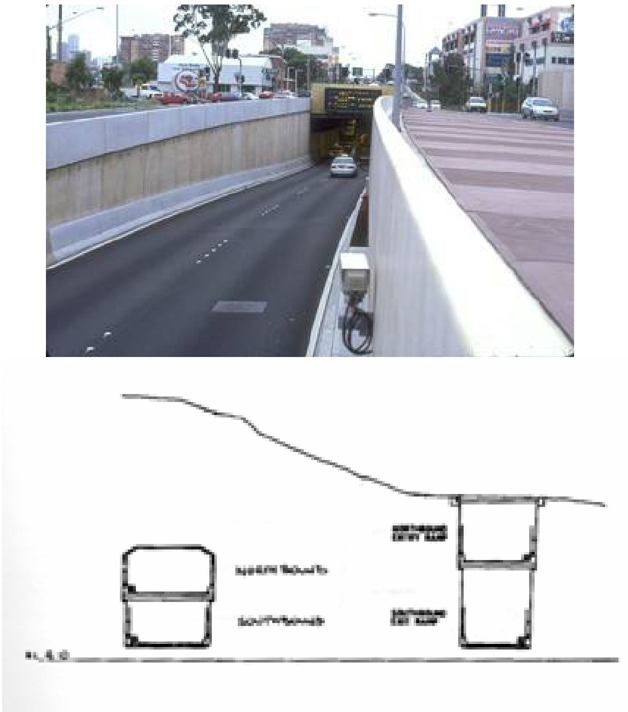


Figure 3.1a: Eastern Distributor Tunnel

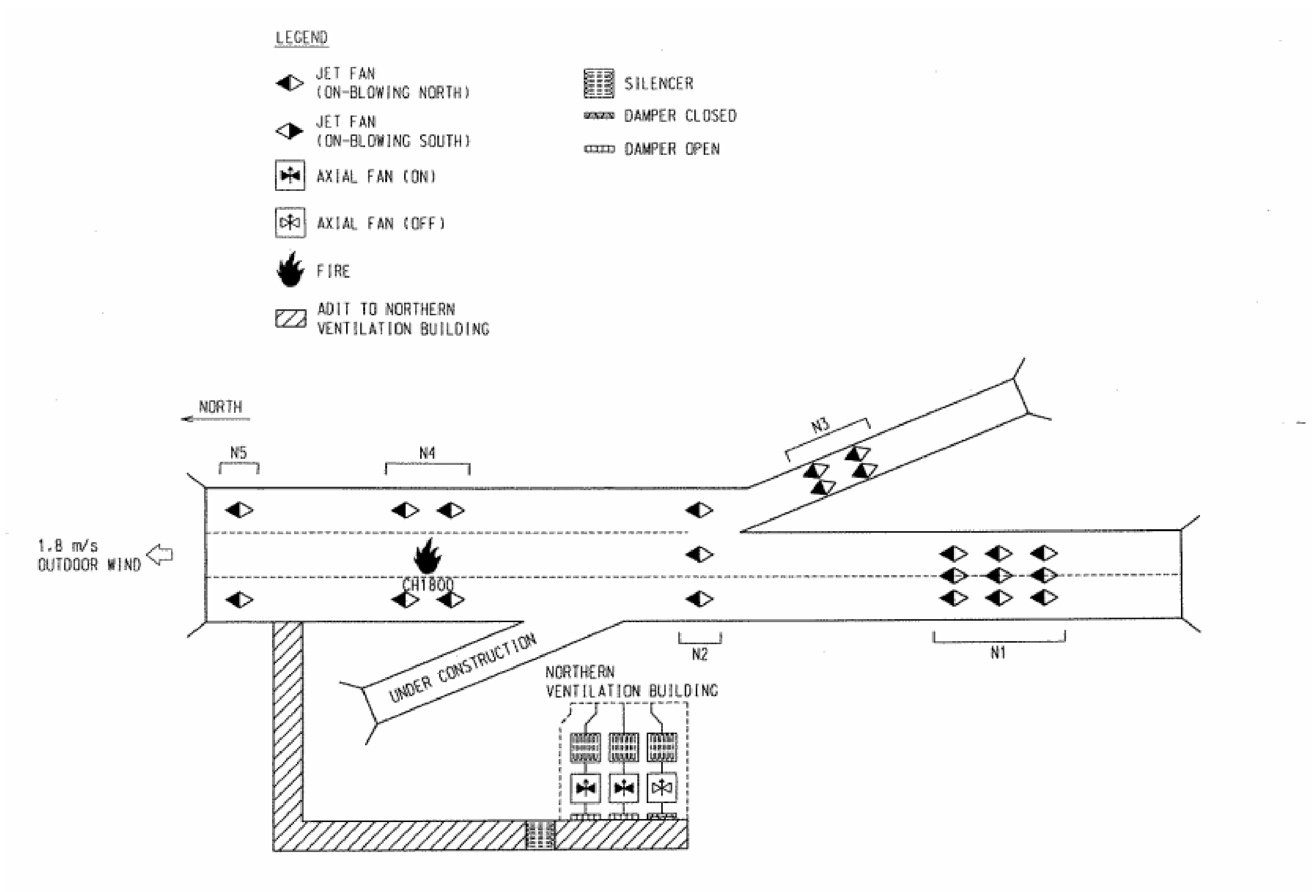


Figure 3.1b: SES Analysis (Sample)

3.2 Western Harbour Crossing, Hong Kong, China [7, 12]

The construction of an immersed tube tunnel is difficult and costly. In general, semi-transverse ventilation system, instead of full transverse ventilation system or longitudinal ventilation system, is preferred. Such an optimized design approach can significantly pare down the air duct spaces, and hence, the submerged volume of the immersed tube tunnel.

Western Harbour Crossing (WHC) in Hong Kong comprises a 1.36-km long immersed tube tunnel and a 0.64-km long cut-and-cover tunnel. Inside the immerse tube, there are equivalent 12 units, each measuring 113.5m(L) x 33.4m(W) x 8.57m(H) and weighing 35,000 tons. WHC is indeed one of ten Airport Core Programme (ACP) Projects in Hong Kong. In addition, it is the first dual 3-lane immersed tube in South East Asia; and the only Build-Operate-Transfer (BOT) project in the ACP [2, 5, 6]. Commissioned on 30 April 1997, WHC was approximately three months ahead of its target date.

The design fire heat release rate is based on an oil tanker fire of 50 MW. With the consideration of the use of longitudinal ventilation system during uni-directional traffic condition, the design fire is conservatively assumed 100MW; i.e., 50 MW yet fanned to 100 MW.

In this project, the tunnel ventilation system and the tunnel services are optimized to reduce the volume of the air duct and the services duct inside the immersed tube tunnel. As a consequence, the width and the height of the tunnel have been significantly reduced. Such an optimized design helps reduce the civil construction cost, thereby drastically shortening the construction period.

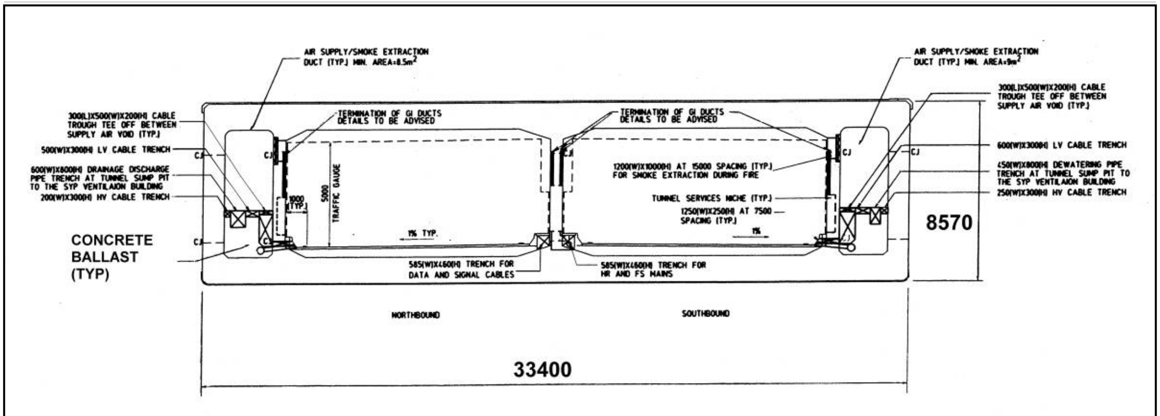


Figure 3.2a: Western Harbour Crossing

3.3 Kallang-Paya Lebar Expressway (KPE) Road Tunnel, Singapore [14]

Kallang-Paya Lebar Expressway (KPE) is the main line connecting the south of, with the north, in Singapore. The expressway is 12-km long and it connects the East Coast Parkway in the southern region to the Tampines Expressway in northeast region, which shares 9.6 km of the total tunnel length.

KPE tunnel is twin bored, carrying three lanes per tube, spanning 8 main intersections, 11 entrance branches and 12 exit branches. The tunnel is the longest double-tube, three-lane road tunnel in Southeast Asia.

SES is a one-dimensional model. For tunnel with huge tunnel cross section, three-dimensional CFD fire-smoke modeling and simulations have been applied to analyze the phenomena within the fire plume vicinity. Figure 3.3b shows a fire emergency simulation for KPE Tunnel.

For long tunnel or a complicated tunnel network, it is common to use jet fans or Saccardo Nozzles to direct the tunnel airflow to the _only_ ventilation direction, which congruently aligns with the direction of traffic. In order to design an effective-efficient nozzle and ensure the air velocity along the evacuation path can meet the design criteria as set forth in Table 2.1, CFD analyses, in conjunction with a validated evacuation model, have been performed. Figure 3.3c shows a numerical result of an airflow simulation for a Saccardo Nozzle used in the project. In this aspect of fire engineering approach, the so-called Available Safety Egress Time (ASET) can be established. Otherwise, the other tenability criteria, such as hot smoke layer temperature, radiative flux, and toxicity, can be applied if either evacuees or fire fighters would have to cope with the smoke interface below 2.0 m.

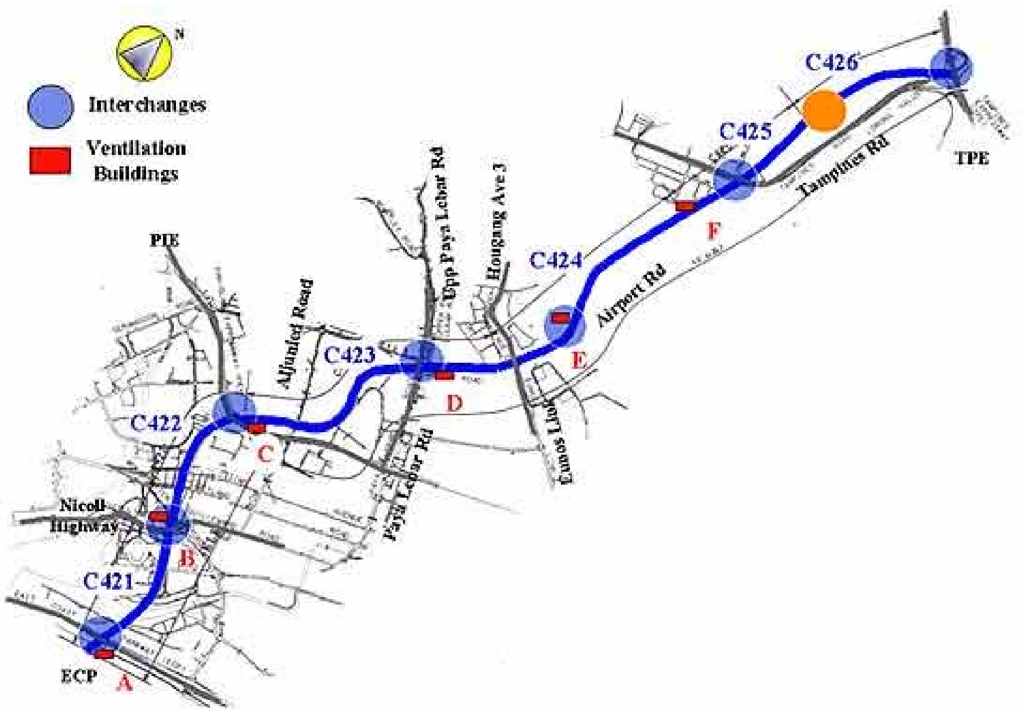


Figure 3.3a: Kallang-Paya Lebar Expressway (KPE) Road Tunnel

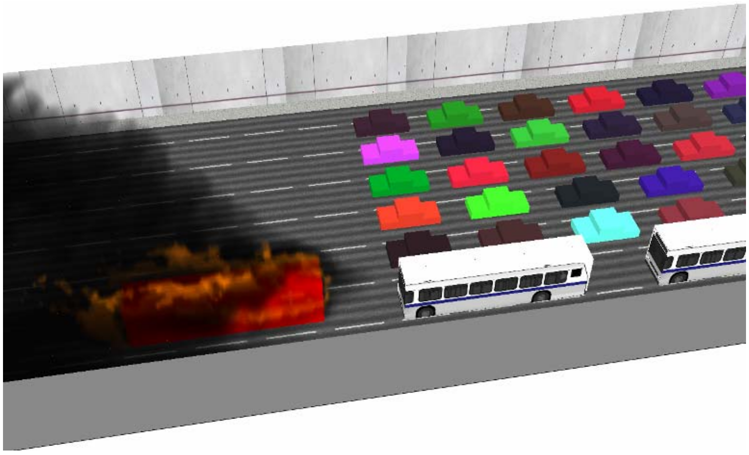


Figure 3.3b: CFD simulation on a Fire Scenario (Sample)

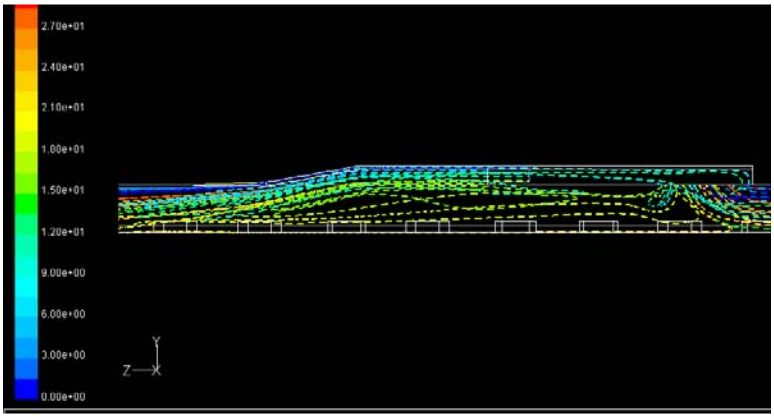
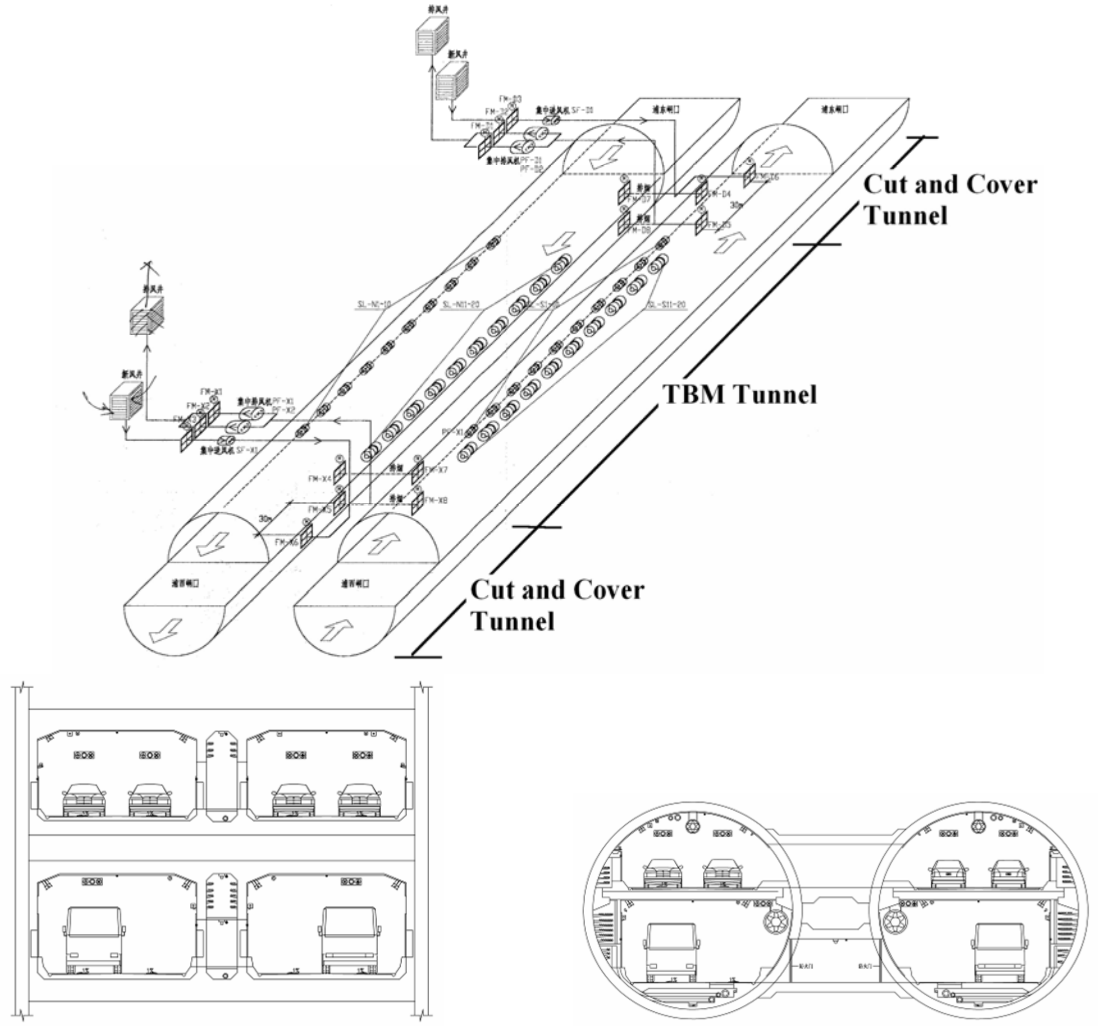


Figure 3.3c: CFD Simulation on Re-circulation Effect near Saccardo Nozzle (Sample)

3.4 Fuxing East Road Tunnel, Shanghai, China [8, 13]

Shanghai Fuxing East Road Tunnel, the first double-deck road tunnel in China, has been greatly improved of its cross-river vehicular traffic between Pudong and the Shanghai city center.

The 2.3-km long tunnel is also twin bored, each tube with a double deck and providing three-lane traffic in one direction. In each bore, there are two lanes on the upper deck and one lane on the lower deck. The upper deck is designed for the use of private cars, whereas the lower deck is for all types of vehicles including buses. This double-deck tunnel provides a cost-effective solution, as it has only a marginal increase in construction cost in comparison to a conventional 2-lane tunnel, thereby increasing traffic handling capacity by almost 33%.



Cut and Cover (C&C)
Tunnel Section

Tunnel Boring Machine (TBM)
Tunnel Section

Figure 3.4a: Fuxing East Road Tunnel

Two value engineered options, with a number of cross-passages within the TBM tunnel sections, are considered. SIMULEX, or some of its similar engineering software packages such as STEPS, EXODUS and FDS+EVAC, which is an evacuation computer model, has been used to determine the evacuation times, or in terms of fire engineering, Required Safety Egress Times (RSETs), for both options.

A set of credibly worst scenarios, based on the traffic mix and the fire location, has been considered as shown in Table 3.4.

Table 3.4: RSETs for Different Cross-passage Arrangements

Tunnel	Evacuation Time	
	Option 1	Option 2
Upper Deck Tunnel	4min 49sec (4 cross-passages in TBM tunnel section)	6min 58sec (3 cross-passages in TBM tunnel section)
Lower Deck Tunnel	6min 57sec (2 cross-passages in TBM tunnel section)	12min 43sec (1 cross-passage in TBM tunnel section)

Note: The width of each cross-passage door is 1.3m.

It is noted that by reducing four (4) cross-passages to three (3) in the upper deck, RSET will be increased by 2 minutes. By reducing two (2) cross-passages to one (1) in the lower deck tunnel, RSET will be increased by 6 minutes. The explanation is that more tunnel users are anticipated in the evacuation process. Otherwise, they would have to walk for a longer distance in case of a fire occurring in the lower deck.

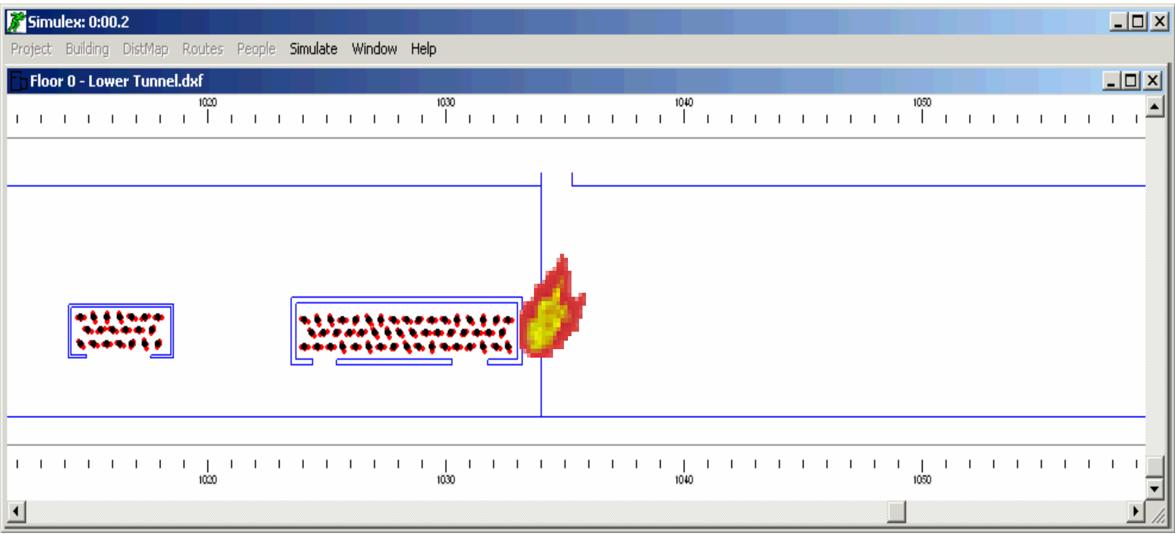


Figure 3.4b: Evacuation Simulation Analysis (Sample)

3.5 Lane Cove Tunnel, Sydney, Australia [3]

Connecting the Gore Hill Freeway with the M2, the 3.6-km Lane Cove Tunnel is the final link in Sydney's orbital motorway network, and allows quicker commuting times between the city and Sydney's north-west. Twin, 3.6-km, two-lane tunnels are constructed, with three lanes provided in long sections to improve safety and traffic flow.

The eastbound tunnel begins with two lanes. In approximately 1.1-km distance into the tunnel, a third lane is added to carry traffic to a Pacific Highway exit into a new transit lane on the Gore Hill Freeway. To avoid forced merging of traffic in the tunnel, the westbound tunnel has three lanes for most of its length. The tunnel will begin with two lanes from its entrance on the Gore Hill Freeway, with a continuous third lane added to accommodate the Pacific Highway entry-ramp traffic.

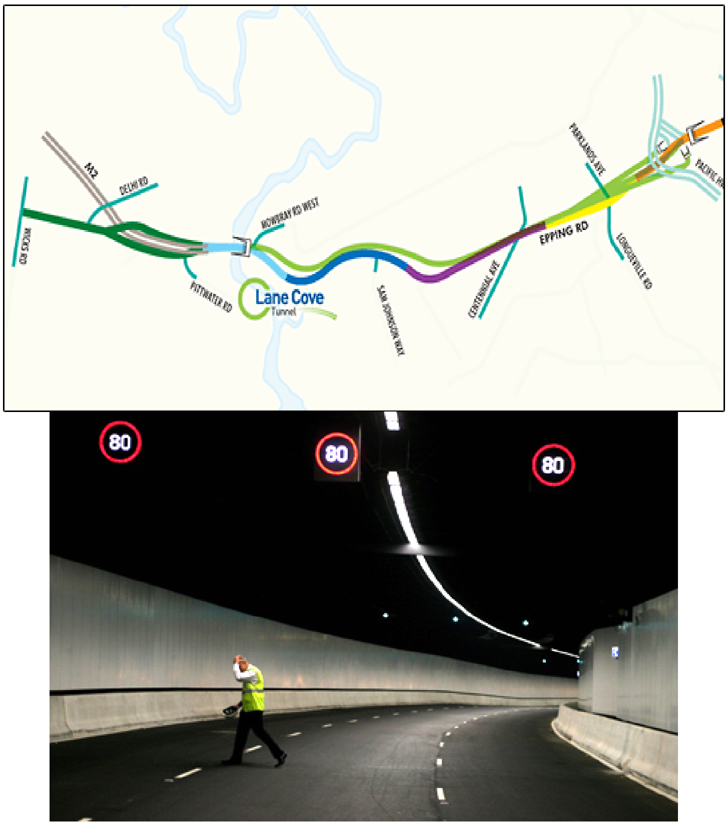


Figure 3.5a: Lane Cove Tunnel

This project is complicated by the fact it is both likely and credible that a fire occurs during a traffic jam inside the tunnel. Hence, a performance-based fire engineering approach augmented by state-of-the-art computerized technologies has been employed. A timeline analysis has been conducted with the appropriate evacuation software packages. Fig. 3.5 b schematically illustrates the numerical timeline (RSET) from the evacuation models, which is much less than the ASET of 17 minutes. It should be pointed out that both RSET and ASET are within the context of relatively places of safety in lieu of ultimate places of safety, which are the open air or portals at grade. Generically, the non-incident tube, whether pressurized or non-pressurized, would be the designated relative place of safety.

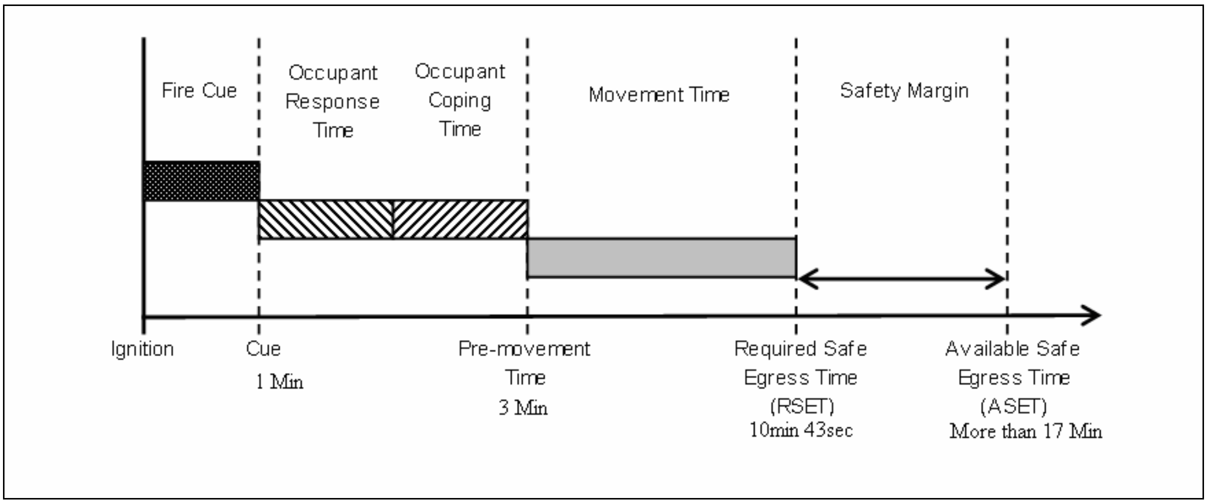


Figure 3.5b: Timeline Analysis for Lane Cove Tunnel (Sample)

3.6 Chongming Road Tunnel, Shanghai, China

Chongming Island, located at the outlet of Yangtze River, is the third largest island in China. The Chongming Island tunnel is one of key projects for the completion of artery road network. The project is indispensable for Shanghai not only to promote the economic development in Yangtze delta but also to meet the peak transportation demands in the south and north of the Yangtze River.

The tunnel is about 7.5 km long, connecting Shanghai Pudong with Changxing Island in the south. Then the Yangtze River Bridge connects the Changxing Island with Chongming Island. Chongming tunnel are the longest, three-lane and double-lane, single bore, river road tunnel with the largest diameter in the world

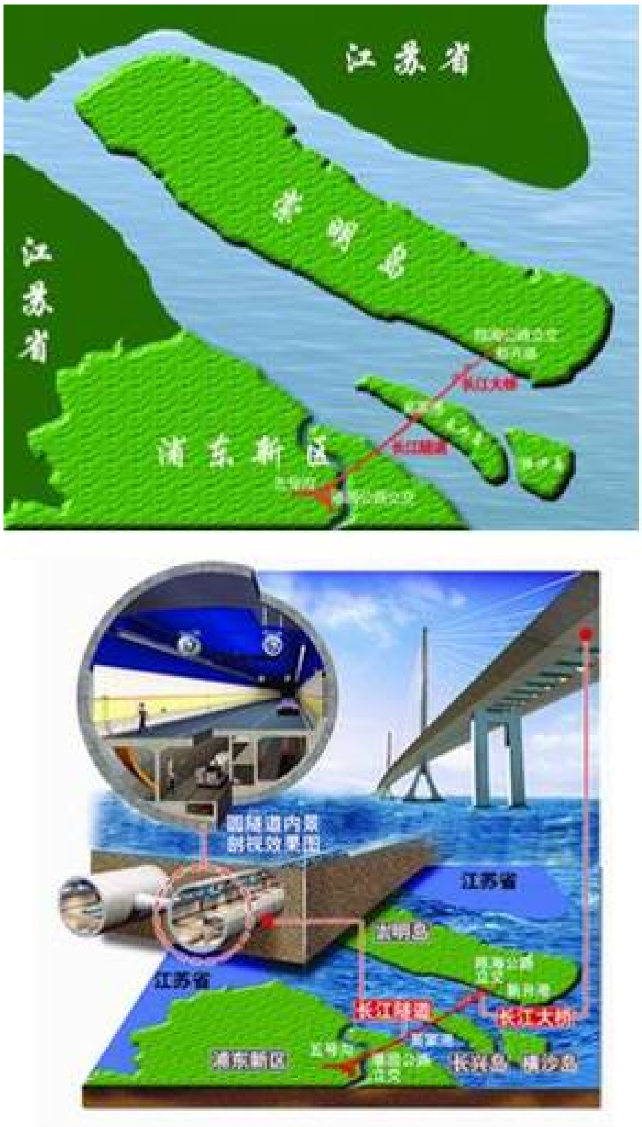


Figure 3.6a: Chong Ming Road Tunnel

In case of a fire in the road tunnel section, passengers can resort to a special feature called the evacuation corridor in the lower level as shown in Figure 3.6a. This evacuation method has been adopted in Japan. Further, cross passages are provided along the tunnel as shown in Figure 3.6a and 3.6b to enhance the evacuation.

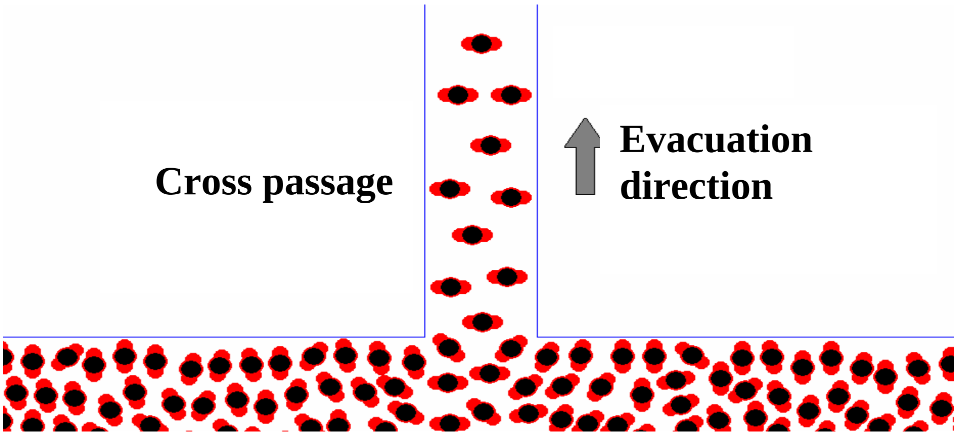


Figure 3.4b: Result of Evacuation Simulation Analysis (Sample)

4. CONCLUSIONS

Emerging approximately two decades ago, performance-based or fire engineering approaches have been prevalently applied to not only built environments but also heavy infrastructure including transportation ports and terminals.

Benchmarked against a few prescriptive codes, especially NFPA 130 and 502, a selection of some generic yet representing design transit tunnel and road tunnel designs have been demonstrated in this paper. In a nutshell, the designs crucially depend upon the operational requirements, its physical locations and construction methods, availability of ventilation buildings, safety issues, maintenance requirements, initial costs and construction cost, not to mention the political-economical elements of land resumptions and geological constraints. Cost-effective designs are the keys to achieve a sustainable environment for tunnel operations, while striking the delicate balances among the above attributes in view of acceptable yet viable safety levels. As illustrated by projects discussed herein, it is imperative to coordinate the desirable or mandated fire and life safety provisions with other engineering disciplines so as to achieve the most cost-time effective and efficient designs.

While it is recognized that prescriptive codes can be a good rule of thumb, and perhaps over-conservative (over-designed), it is most advantageous to invoke the emerging performance-based or fire engineering approaches to optimally analyze the extents and magnitudes of quantitative fire-smoke hazards and perhaps risks. Otherwise, the design projects may not materialize or result in exorbitant costs which pass beyond the asymptotic cost yielding no additional benefits or levels of fire and life safety. For example, a 244-m cross passage interval and a 5-minute evacuation time may not be realistic, and even impossible to achieve in practice, in which fire engineering approaches can be adopted to justify the reasonable levels of safety.

Although performance-based design criteria and the concepts of ASET and RSET are still controversial, and fire engineering is still an evolving discipline, interested researchers, modelers, analysts and designers can always apply innovative methodologies and approaches stemming from the current advances of applied fire safety science to optimally design time-cost effective and efficient, complex and challenging infrastructure and transportation projects.

ACKNOWLEDGMENT

The authors would like to acknowledge Parsons Brinckerhoff (Asia) Limited for the permission to use materials in this paper. Finally, the authors would like to thank the organizers for the opportunity to present this topic at this conference.

REFERENCES

[1] Chiu, T. S.W., Lai, S.K.H. and Wong, C.W., A Comparison of the Tunnel Ventilation systems for Railway Tunnels and Road Tunnels, 11th International Symposium on Aerodynamics and Ventilation of Vehicle Tunnels, Luzern, Switzerland, 7-9 July 2003.

[2] Leung, A.W.H. and Cheung, E.K.Y., Design of the Tunnel Ventilation System for the Western Harbour Crossing, 10th International Symposium on Aerodynamics and Ventilation of Vehicle Tunnels, 2000.

[3] Connector Motorway. (http://www.lanecovetunnel.com.au/)

[4] Chiu, T.S.W., Lai, S.K.H. and Wu, D.K.H., The Tunnel Ventilation System and the Evacuation Strategy for a Long Railway Tunnel with Busy Traffic, Long Road and Rail Tunnels, Second International Conference, Hong Kong, 9-11 May 2002.

[5] 15 Most Outstanding Projects in Hong Kong. Published Jointly by the Editorial Teams of Building journal and Construction & Contract News (http://www.cityu.edu.hk/CIVCAL/book/misc_book.html).

[6] http://www.info.gov.hk/archive/napco/p-coren.html

[7] Chan, Alex S.K. and Lai, Steven K.H., Cost-Effective Designs for Tunnels, IES/IEM/PII Tripartite Conference on Major Building and Infrastructural Construction Projects, Singapore, 25 & 26 March 2004.

[8] Shen, X.F., Lao, H.S., Lai, Steven and Wong, C.W., Tunnel Ventilation System for the Shanghai Fuxing East Road Tunnel, 11th International Symposium on Aerodynamics and Ventilation of Vehicle Tunnels, Luzern, Switzerland, 7-9 July 2003.

[9] NFPA 130 Standard for Fixed Guideway Transit and Passenger Rail Systems, 2007 Edition.

[10] NFPA 502 Standard for Road Tunnels, Bridges, and Other Limited Access Highways, 2008 Edition.

[11] http://www.easterndistributor.com

[12] http://www.westernharbourtunnel.com

[13] http://www.allaboutsh.com/Transportation/Tunnels/FXRTunnel.html

[14] http://en.wikipedia.org/wiki/Kallang-Paya_Lebar_Expressway

APPLICATION OF PERFORMANCE-BASED FIRE ENGINEERING APPROACH TO THE DESIGN OF SKYPIER

Wilson S.K. Tsang

Airport Authority Hong Kong, Chek Lap Kok, Hong Kong (SAR), P.R. China

ABSTRACT

To cater for the increasing traffic demand between Hong Kong International Airport (HKIA) and the Pearl River Delta (PRD) region, HKIA has invested to build a permanent cross-boundary ferry terminal - SkyPier to provide convenient, accessible and comfortable services to passengers. An Automated People Mover (APM) system links the ferry terminal with the passenger terminal buildings, T1 and T2. The facility currently serves six ports in the PRD region - Shenzhen Shekou, Shenzhen Fuyong, Macau, Zhongshan and Humen in Dongguan and ZhuHai

The four-storey SkyPier is provided with four ferry berths (with capacity for expansion to eight berths) and has a total floor area of 16,000m2 or 8 times the size of the existing temporary ferry terminal. SkyPier will also provide passenger check-in and baggage handling facilities and will provide a larger handling capacity and more advanced facilities to support the development of new ferry routes.

Due to the nature of the building, compartment volumes are over 28,000 cu.m and the travel distance exceeds the prescriptive codes. A Fire Safety Strategy was therefore developed to meet the safety requirements by using a fire engineering approach.

This paper will summarize the salient points of the fire safety strategy, namely, phased evacuation, restricting the fire growth and development, separation of large volume spaces by fire shutters and fire curtains, maintaining smoke layer above clear zone by a dynamic smoke extraction system and a fire services installation to facilitate firefighting and rescue operation.

Keywords: Compartment volume, Fire resistance, Timeline approach, Skypier

1. INTRODUCTION

1.1 Project Background

The SkyPier development is a new building that forms part of the SkyCity complex and comprises four main elements:

(1) APM (Automatic People Mover) facilities at Level 1 including the station and void connected above;
(2) Baggage handling area at Level 2;
(3) Public areas including the Arrivals and Departure Levels, check-in hall, and security screenings; (Levels 3 and Level 4); and
(4) The SkyPier roof (The space above the SkyPier roof is available for future hotel expansion).

2. PROPOSED FIRE SAFETY STRATEGY

2.1 General

The salient points of the proposed fire safety strategy that apply generally to the entire SkyPier development are summarized as follows:

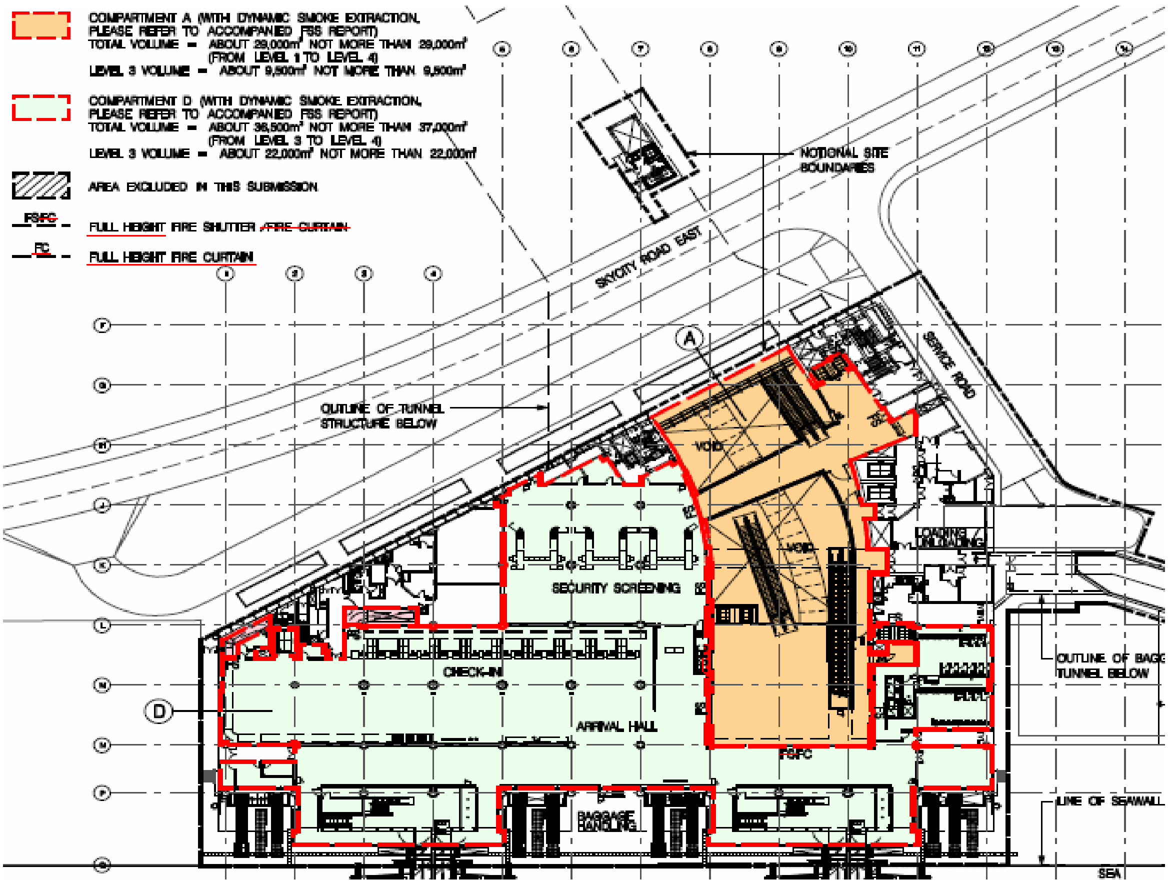
1 Phased evacuation of the building divided into the following evacuation zones. Evacuation will be initiated in the zone where fire is detected.
   1.1 APM Station (Level 1)
   1.2 Baggage Basement (Level 2)
   1.3 Arrival and Departure Levels (Level 3 and 4)
2 Restrict fire growth and development.
3 Separation of large volume spaces by approved fire shutters in most areas and in some locations by fire curtains.
4 Maintain the smoke layer interface above head height.
5 Facilitate firefighting and rescue operations by HKFSD.

2.2 General fire compartmentation of SkyPier

The SkyPier building is sub-divided into the following fire compartments

1 Compartment A: APM Station and Void
2 Compartments B and C: Baggage Basement
3 Compartment D: Arrival and Departure Levels
4 Plant rooms – 2 and 4 hour FRP construction for above ground and under ground areas respectively.

Compartment A and Compartment D are illustrated in the following diagram



The reason for combining APM Station plus void above (Compartment A), and Arrival plus Departure Levels (Compartment D) to form a single fire compartment is because the operational requirements of the spaces render the separation into fire compartments as per the FRC Code requirements impractical.

To deal with the effect of the oversized fire compartment, the Arrival and Departure Levels (Compartment D) are divided into smoke zones by smoke barriers and smoke curtains, with each smoke zone not exceeding 2,000m². A smoke extraction system is provided in Arrival and Departure Levels (Compartment D) and APM Station (Compartment A) to maintain a smoke free zone for occupants in the occupied spaces.

A smoke detection system and the relevant sprinkler flow switches are used to actuate the smoke extraction system.

The non-provision of sprinklers in the APM Station is consistent with the existing APM Station in the East Hall and the West Hall, and in T2. Adequate means of egress is provided in conjunction with exit signage and emergency warning message announcement through a Public Address (PA) system in public areas to facilitate occupants to complete their evacuation prior to the onset of untenable conditions with a significant safety margin.

The performance of the proposed alternative fire safety measures with respect to life safety of occupants has been evaluated by using a "time line approach (BS7974, 2001)", which compares the available safe egress time (ASET), i.e. the time of onset of untenable conditions, and the required safe egress time (RSET), i.e. the time required for occupants in the areas to complete their evacuation into escape stairs or protected passages. When ASET > RSET with a significant safety margin, the design is considered to be acceptable.

2.3 Emergency Warning Messages and Directives

A PA system is provided throughout the SkyPier development to broadcast emergency warning messages and directives to occupants in public areas. The PA system will also be used for delivering background music to the spaces on a daily basis.

2.4 General Means of Access and EVA for SkyPier

Emergency Vehicular Access is provided on the west side of the SkyPier building at ground level (Level 3). Access staircases are provided within 18m from the EVA.

2.5 Emergency Power Supply

Two generators are provided to serve various services essential for the operation of SkyPier, including the fire service installations, i.e. fire pumps, smoke management systems, and fireman's lifts. Other FSI's including emergency lighting, exit signs and fire alarm panels will also be powered by these generators.

2.6 Level 2 Baggage Basement

2.6.1 Usage of the Area

The baggage basement is used for loading and unloading the passengers’ baggage to and from the electric vehicles traveling between the T2 and SkyPier. Only authorized and trained staff are allowed in the Baggage Basement.

2.6.2 Fire Compartmentation

The Baggage Basement is separated from adjacent areas by 4 hour fire rated barriers (FRC,1997) comprising concrete roof and walls and fire shutters. Fire shutters are installed to divide the baggage basement into fire compartments of less than 7000m3 (FRC, 1997) each.

2.6.3 Means of Egress and Evacuation Strategy

In the event of a fire in the Baggage Basement, staff will evacuate away from the fire and towards the escape stairs or protected corridors to escape stairs within 30m from any point. Only authorized and trained staff will be allowed in this basement, who will be alerted and familiar with emergency procedures and exit routes.

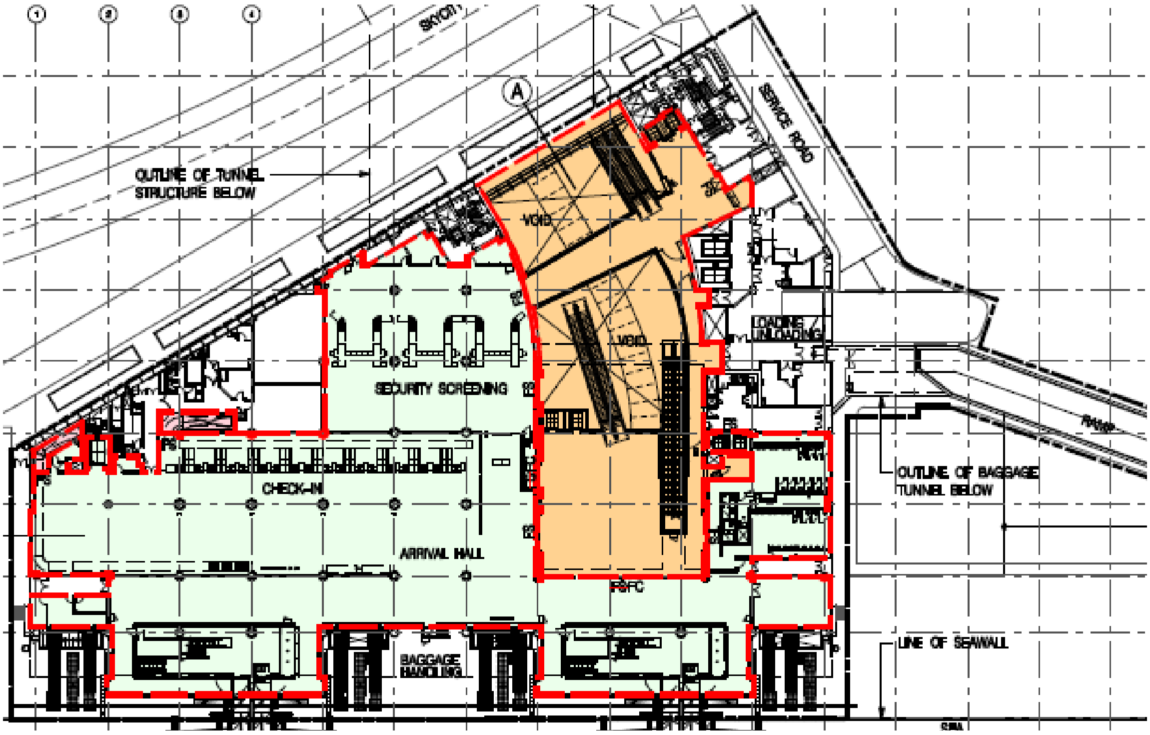
2.6.5 Fire Service Installations

The Baggage Basement is provided with the following FSI's as per the FSI Code (2003) requirements:

- automatic fire sprinkler system employing fast response sprinklers
- audio advisory system (in the form of alarm bell)
- automatic actuating devices
- emergency lighting
- exit signs
- fire alarm system
- fire detection system
- fire hydrants/hose reel system

No smoke extraction system is provided because the volumes of fire compartments are less than 7,000m3. Pressurization for the stairs that leads to the baggage basement is not required as per FSI Code (2003) requirement since the baggage basement is less than three levels from ground level.

2.7 Level 3 Arrival (as sketch below) and Level 4 Departure



2.7.1 Usage of the Area

The Arrival Level of SkyPier is located at ground level. The Arrival Level consists of check-in facilities and security screening areas which allow passengers to enter the airside of airport facilities directly after disembarking from the ferries. Escalators are provided to connect Arrival Level to the Sea to Land and Sea to Air Platforms of the APM Station underneath.

The Departure Level of SkyPier is located one floor above street level. The Departure Level consists of a seating area for the passengers to wait for the ferries and retail shops.

2.7.2 Fire Compartmentation

Due to the operational requirement to provide an unobstructed space to facilitate passenger movement, the separation of the space into fire compartments as per the FRC Code requirement is impractical.

The Arrival and Departure Levels are treated as one single fire compartment and separated from the void by 2 hour FRP construction as per FRC Code requirement. The fire compartment size is about 37,000m3, with L3 about 22,000m3 and L4 about 15,000m3.

The Arrival and Departure Levels are divided into smoke zones by fixed type smoke barriers above the ceiling and smoke curtains, with each smoke zone not exceeding 2,000m². Smoke zones are separated by full height 2 hour FRP construction from areas without smoke extraction system and 1 hour FRP smoke barriers and smoke curtains are provided to separate between smoke zones.

Smoke barriers above the ceiling and smoke curtains are also located around the openings or escalator voids that connect to upper levels to create a smoke reservoir and minimize smoke spilling to upper levels.

2.7.3 Means of Egress and Evacuation Strategy

The two short sides on the Arrival Level and the west side of the building along SkyCity Road East are connected to the exits which are the place of ultimate safety in terms of fire escape.

An announcement will be made via the PA system in public areas to advise occupants of the movement direction and they will also be assisted by Airport Authority Hong Kong (AAHK) staff on site. The occupants will be directed by AAHK staff members to proceed to the dedicated assembly areas.

2.7.4 Means of Access for Firefighting and Rescue

According to the Mean of Access (MOA, 2004) section 6, means of escape can be used as access for firefighting and rescue. The exits on the sides of the building and escape stairs are to be used for firefighting access to the Arrival and Departure Levels.

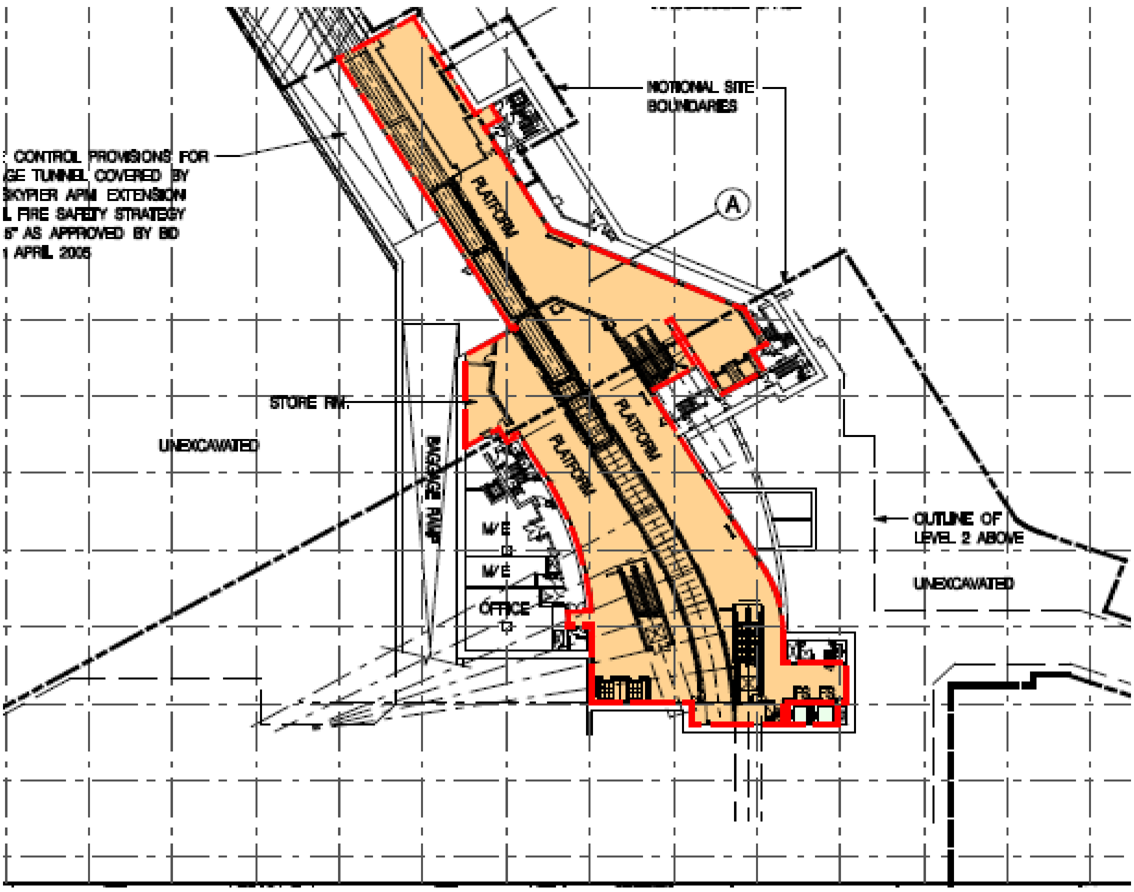
2.7.5 Fire Service Installations

The Arrival and Departure Levels are provided with the following FSI's as per the FSI Code (2003) requirements:

- automatic fire sprinkler system employing fast response sprinklers
- dynamic smoke extraction system that is activated by a cross-circuit smoke detection system and sprinkler flow switches in the smoke zone of fire origin.
- audio advisory system (in the form of alarm bell)

- automatic actuating devices
- emergency lighting
- exit signs
- fire alarm system
- fire detection system
- fire hydrants/hose reel system
- portable fire extinguisher – as required by occupancy
- automatic HVAC system shut down in event of fire

2.8 Level 1 APM Station and Void



2.8.1 Usage of the Area

The APM Station is at the end of the Airport APM Tunnel extension connected to T2 and T1.

2.8.2 Fire Compartmentation

The APM station and the void above are fire separated from the Arrival and Departure Levels by fire shutters in most areas and some locations by fire curtains which form different fire compartments. The fire compartment size is slightly more than 28,000m3, about 29,000m3. The maximum height of compartment will be about 21m.

The void on top of the APM Station platforms is treated as a smoke reservoir. Smoke from the APM Station Platforms will spill to the void above. The area of the Sea to Air Platform that is not opened directly to the void is divided into separate smoke zones by fixed type smoke barriers at high level above the ceiling to create a smoke reservoir and minimize smoke spilling to the void.

2.8.3 Means of Egress and Evacuation Strategy

Independent escape stairs are provided on the APM Station platforms leading to open air at street level as the place of ultimate safety in terms of fire escape. The maximum travel distance does not exceed 30m, with a maximum dead end distance of 20m.

In the event of a fire on the APM platform, occupants on the platform will approach the protected corridors connected to the escape staircases leading to street level and finally to open air.

An announcement will be made via the PA system in public areas to advise occupants of the movement direction assisted by AAHK staff on site. The occupants will be directed by AAHK staff members to proceed to the dedicated assembly areas.

2.8.4 Means of Access for Firefighting and Rescue

According to the Mean of Access (MOA, 2004) section 6, means of escape can be used as access for firefighting and rescue. Escape stairs are to be used for firefighting access to the APM Station.

2.8.5 Fire Service Installations

The platform and the void above are not provided with fire sprinklers as these are not appropriate for high voltage applications.

A dynamic smoke extraction system that is to be activated by a smoke detection system is provided in the APM station and void above. The capacity of the smoke extraction system had been sized by using fundamental fire safety engineering principles to deal with the smoke production rate of the design fire on the void and Sea to Air Platform. The calculated smoke extraction rate in the void is at least 65m3/s, based on a design smoke clear height of 15m. The calculated smoke extraction rate on Sea to Air Platform is at least 8m3/s, based on a design smoke clear height of 3.0m. The smoke clear height was lowered from the original 3.7m ceiling level to 3.0m to cater for the plugholing effect of the dynamic smoke extraction system.

The FSI's for the APM Station and void above are provided as per the FSI Code (2003) requirements including:

- audio/visual advisory system (in the form of a PA system broadcasting pre-recorded messages and flashing directional signs in public areas)
- automatic actuating devices
- emergency lighting
- exit signs
- fire alarm system
- fire detection system

• fire hydrants/hose reel system
• portable fire extinguisher
• automatic HVAC system shut down in event of fire
• smoke extraction system

Static smoke vents for the APM Station were not recommended since the large void above ground level connected to the APM Station can form the reservoir for smoke discharge.

2.9 APM Tunnel

APM Tunnel:
• Fire compartment size over 28,000m3
• No fire separation between tunnel and station
• Dynamic push-pull smoke extraction system activated by smoke detectors
• No sprinkler provision
• Fire hydrant at 60m intervals along the tunnel
• Traction power cutoff capability
• Maximum escape distance > 30m
• Distance between exits > 48m
• Fireman's lift coverage > 60m

3. CONCLUSION

Due to the unique operation mode of the building with compartment volume over 28,000 cu.m and the escape distance exceeding 30m, it is not possible for the building to be designed to follow prescriptive code requirements.

In order to enhance the fire safety, fast response type sprinklers are provided for the SkyPier building to restrict fire growth and development. The oversized fire compartment is divided into smoke zones by smoke barriers and smoke curtains and a smoke extraction system is provided to maintain a smoke free zone for occupants in the occupied spaces.

Based on the fire engineering calculations that untenable conditions are unlikely to occur and that the time required for occupants to complete their evacuation away from the building has a significant safety margin, it is thus concluded that the life safety of occupants in the SkyPier Building are not affected by the oversized fire compartment and extended travel distance and the FSI as provided can provide an equivalent standard of fire safety not less than the prescriptive codes.

REFERENCES

[1] Fire Safety Strategy for SkyPier, Hong Kong Airport Authority.

[2] BS7974 (2001) Application of fire safety engineering principles to the design of buildings - Code of practice, London, British Standards Institution.

[3] FRC (1996) Code of practice for fire resisting construction, Building Authority, Buildings Department, Government of Hong Kong Special Administrative Region, Hong Kong.

[4] MOA (2001) Code of practice for means of access for firefighting and rescue, Buildings Department, Government of Hong Kong Special Administrative Region, Hong Kong.

[5] FSI (2005) Code of practice for minimum fire services installations and equipment, Fire Services Department, Government of Hong Kong Special Administrative Region, Hong Kong.

FIRE ENGINEERING FOR HAECO HANGARS AT HONG KONG INTERNATIONAL AIRPORT

Victor Ho[1], P. Lin[2] and C.K. Wong[2]

[1]Hong Kong Aircraft Engineering Co. Ltd, 80 South Perimeter Road, Hong Kong International Airport, Lantau, Hong Kong.
[2]Meinhardt China, 4/F Wah Ming Centre, 421 Queen's Road West, Hong Kong

ABSTRACT

As the most important aviation regional hub, the Hong Kong International Airport and its core facilities have been offering enormous business opportunities for the local aviation related industry. Hong Kong Aircraft Engineering Company Limited (HAECO) has been operating world class quality aircraft maintenance facilities for serving Hong Kong and the Region. After the successful operation of two existing hangars since the opening of the Hong Kong International Airport at Chek Lap Kok, HAECO is embarking on a third Aircraft to cope with its expanding business. The HANGAR 3 development contains two phases. Phase one (H3A) is an area of 175m x 98m while phase two (H3B) is an area of 109m x 98m.

Aircraft hangar is a special industrial undertaking and poses a great challenge to fire protection due to the nature of its contents, i.e. high value aircrafts with potential risk of aviation fuel fire. As Hong Kong has no specialized code to cope with such occupancy, after extensive research and discussion with the statutory authorities, National Fire Protection Association (NFPA) Standard 409, Standard on Aircraft Hangars (2004) is accepted as reference guideline. An overhead foam-water deluge system with supplementary foam-water under-wing protection is provided to discharge a blanket of foam over a large floor area to extinguish any fuel fire on the aircraft or floor and prevent the fuel fire from spreading to adjacent aircraft.

With the limitation of the local prescriptive codes to encompass the functional requirements of all types of buildings, the voluminous Hangars also inevitably cannot fully comply with the code limit with respect to the compartment volume. Therefore, in addition to the fire protection features provided in compliance with NFPA 409, holistic performance-based fire engineering is conducted to demonstrate that the proposed project provides an equivalent or superior level of safety for the building's occupants compared with direct compliance with the Hong Kong Codes of Practice.

Keywords : Hangar, Spillage fire, Fire protection, NFPA

1. INTRODUCTION

Located in the Hong Kong International Airport, the Hong Kong Aircraft Engineering Company Limited (HAECO) has grown from a small aircraft maintenance company to a global aircraft engineering enterprise since 1950. The HAECO Group operates aircraft maintenance business in China (Xiamen, Shandong, Sichuan, Jinjiang), Singapore and Bahrain, offering all round engineering services for major aircraft types for over 130 worldwide customers from 27 countries. The Hong Kong base has more than 5,000 employees and over 13,000 for the group including some joint ventures.

HAECO is operating 2 heavy maintenance hangars in Hong Kong and 5 in the Xiamen subsidiary, these facilities are amongst the most technologically advanced in Asia. These facilities adopted same design concepts for similar operation procedures catering frequent staff training and exchange. The first hangar in Chek Lap Kok started operation in 1998, is 220m wide by 70m deep for three wide-body aircrafts. Due to the rising business, the second hangar completed in 2006 is 170m wide by 85m deep, which provides two wide-bodied plus one Boeing 767 sized aircraft maintenance positions. The first phase of the third hangar is targeted to start operation in 2009 third quarter, it is a 175m wide by 98m deep 2-bay hangar; the second phase will add 109m width that can cater Airbus A380.

Figure 1: The Location of HAECO at International Airport at Chek Lap Kok

2. FIRE RISK ANALYSIS

Other than providing world class aircraft engineering services to customers, it is also essential to protect the clients' aircrafts, the staff and properties. A reliable fire services system is serving this purpose. On the operation side, HAECO employs a security and fire team operating the fire services system together with a duty maintenance contractor keeping the system in good condition.

Even though operational procedures during maintenance and testing of an aircraft are extremely strict due to fire risk of a fueled aircraft and the high value of aircraft, a malfunction or damage to the aircraft still may cause a fuel, or hydraulic fluid leak, which can be ignited by hot surfaces or electric sparks.

NFPA (cited from Meinhardt Ltd report, 1995) had studied major fires occurred in aircraft hangars in the USA since 1974. The common factor among these fires was the absence of any fire protection systems other than portable extinguishers. For those hangars had been properly equipped with fixed fire protection systems, no catastrophic fire was reported.

In the past, the gasoline grade fuel (JP4) was wildly used in aviation industry. This kind of fuel has a flash point of about -20^{0}C, and the modern aircraft has replaced the gasoline type fuel by kerosene grade fuel(JP8), a more efficient and safety fuel with a flash point of 40^{0}C (Joseph et al,2000). US air force research laboratory had done a serious comprehensive fuel ignition test to determine the differences and similarities of JP-4 and JP-8 fuel spills when exposed to ignition sources that are common in everyday life (Gottuk ,2000) and results show that chance of being ignited of JP8 is much reduced at ambient temperature.

Furthermore, the flame spread rate of Kerosene Grade is one tenth of the gasoline grade fuel, thus kerosene grade fuel allows a longer time for personnel, a suppression system, or firefighters to respond to control at its incipient stage (Hill, 1999, Buigoyne, 1968).

In conclusion, the fire risk of hanger is much reduced in nature with the replacement of gasoline by kerosene grade fuel.

3. MEANS OF FIRE PROTECTION

National Fire Protection Association (NFPA) Standard 409, Standard on Aircraft Hangars (2004) is accepted as reference guideline for HAECO hangars fire protection. In this paper, HANGAR 3 at the Hong Kong international airport is taken as an example to illustrate the adoption of fire engineering principle in this kind of premises.

In accordance with NFPA 409 2004, hangars with door height greater than 28 feet (8.5 m) or single fire area larger than 40,000 ft^2 (3,716 m^2) are classified as Group I. The floor area of HANGAR 3 is about 284m x 98m, and it is Group I Hangar in the classification and all fire protection provisions for this group will be adopted.

For Group I fueled aircraft hangar, NFPA 409 recommends the following means of fire protection:

(1) A foam-water deluge system as the primary fire suppression system and supplementary under-wing low-expansion foam system, or
(2) A combination of automatic sprinkler protection and an automatic low-level low-expansion foam system, or
(3) A combination of automatic sprinkler protection and an automatic low-level high-expansion foam system.

Which options are adopted depends on a variety of factors, e.g., site conditions, type of aircraft, operation requirements, costs and maintenance, etc. For HANGAR 3, option 1 is recommended to the client in consideration the limitations of storage of water and foam as well as operational requirements. 25 set of AFFF foam systems, each system covering an area of not exceeding 1394m^2, are installed to provide throughout fire prevention to this premise. The overhead system that corresponds with the first set of detectors to activate will discharge together with the next three systems on either side, up to a maximum total of any 7 systems operating at one time. This is consistent with the 30m rule in NFPA 409.The system can be actuated automatically through fire detection system or manually.

The foam cannons are provided as supplementary protection in the event that foam from the overhead deluge system cannot reach the floor because of the aircraft wing. The two front aircraft parking positions are designed for wide bodied aircraft which have wing areas exceeding 279m^2. Therefore, these areas will be protected by under-wing oscillating type foam cannons. All foam cannons in the base maintenance and line maintenance slots will be activated automatically or manually on an individual basis. The foam cannons for the line maintenance slot(s) will be fed by an underground piping system. These cannons will be made removable to allow for the aircraft to be moved in and out of the hangar. Once the aircraft has been moved, the foam cannons will be re-fitted. The owner, HAECO, will ensure that procedures are enforced to ensure foam monitors are refitted as soon as the aircraft has been moved to/ from a line maintenance slot.

Trench drains are required to prevent build up of flammable liquids over the floor so as to reduce fire and explosion hazard. The floor drain will be a grating covered channel, sized to remove fuel spills as quickly as possible from the hangar. The floor will be sloped toward the drains and away from the aircraft. The drains will be sized to allow quick run-off of any fuel spill to the retention tank located outside the hangar. Flame traps will be provided at the channel discharge connections, to prevent the fire from passing to the retention tank.

4. PERFORMANCE-BASED STUDY

In addition to the fire protection features provided and compliance with NFPA 409, holistic performance-based fire engineering is conducted to demonstrate that the proposed project provides an equivalent or superior level of safety for the building's occupants compared with direct compliance with the Hong Kong Codes of Practice.

The effectiveness of AFFF on pool fires associated with aviation hazards is well known [8, 18], and the purpose of this analysis is to ensure the safe egress of all occupants from the aircraft hangar. A time-line analysis is adopted to see whether the time required for evacuation (RSET) is greater than the time available for safe evacuation (ASET) and a sufficient safe margin is maintained.
The tenability criteria for occupant’s safe evacuation are specified by NFPA 92B as Table 1.

Table 1: The Tenability Criteria for Occupant’s Safe Evacuation

LIFE SAFETY CRITERIA	LIMIT
Visible distance	15m
Carbon monoxide concentration	1,200 ppm
Temperature	60°C
Carbon Monoxide (ppm)	< 1200

4.1 Smoke Movement Analysis

As discussion in section 2, the most lethal fire risk for hangar is the spillage of aviation fuel. HANGAR 3 is protected by foam-water deluge system in tandem with lower level supplementary foam-water under-wing protection and most of fires incident can be extinguished effectively and efficiently within few seconds. For a conservative assumption, we assume that the fire is only controlled, not extinguished, at the time when the maximal area of spilled oil is ignited.

Pool fires are defined as flames established over horizontal fuel surfaces (as opposed to wall fires which involve vertical fuel surfaces). The heat release rate (HRR) of a pool fire may be estimated by multiplying the heat of combustion and area of the pool. Generally, pool fires discussed are, essentially, “tray fires” or “pan fires”, that is, they are fires of liquid fuel contained within a vessel with walls of significant height, allowing the fuel to exist as a layer of sufficient depth. In this circumstance, the spillage of fuel flows on a relatively flat concrete surface and seeks an equilibrium depth in the range 0.7 to 4 mm (Anthony and Putorti, 2001, Babrauskas,V.,1983, Thomas,2007) The fire will consume its available fuel supply and burn out much faster than a pool fire. So, the intensity of fuel fire on concrete surface is much less than that of a pool fire.

The floor of the hangar will be sloped according to NFPA 409 and drainage trenches have been designed to collect a fuel spill from the largest fuel tank along with the discharge from the foam-water deluge system. Based on the geometry of the floor and the use of a smooth concrete floor finish, a maximal fuel spill area can be estimated. In this way, the fire size for HANGAR 3 is estimated to be 50MW as the worst scenario.

Fire Dynamics Simulator (FDS) (McGratta, 2004) was used to calculate smoke movement in the hangar during a fire condition. CFD fire models can calculate the expected temperature, carbon monoxide concentration, visibility and radiation during a fire condition. These factors are used in conjunction with the results of the egress calculations to determine the conditions that the occupants are exposed to during a severe fire condition. The build-up of modelling is shown in Fig.2. Different fire scenarios are simulated using the CFD fire model.

The simulation shows that the tenability criteria can be maintained for more than 10 minutes at 3m AFFL. Thus the available safe evacuation time (ASET) is about 10 minutes. Please note that the in this analysis, the fire size is determined by the ignition of maximal area of spilled fuel and the fire burns at its peak HRR for the simulated period,i.e.,10 minutes. In fact, the foam-deluge system will extinguish the fire within 2-3 minutes. Therefore, a considerable safety factor is included in the ASET analysis.

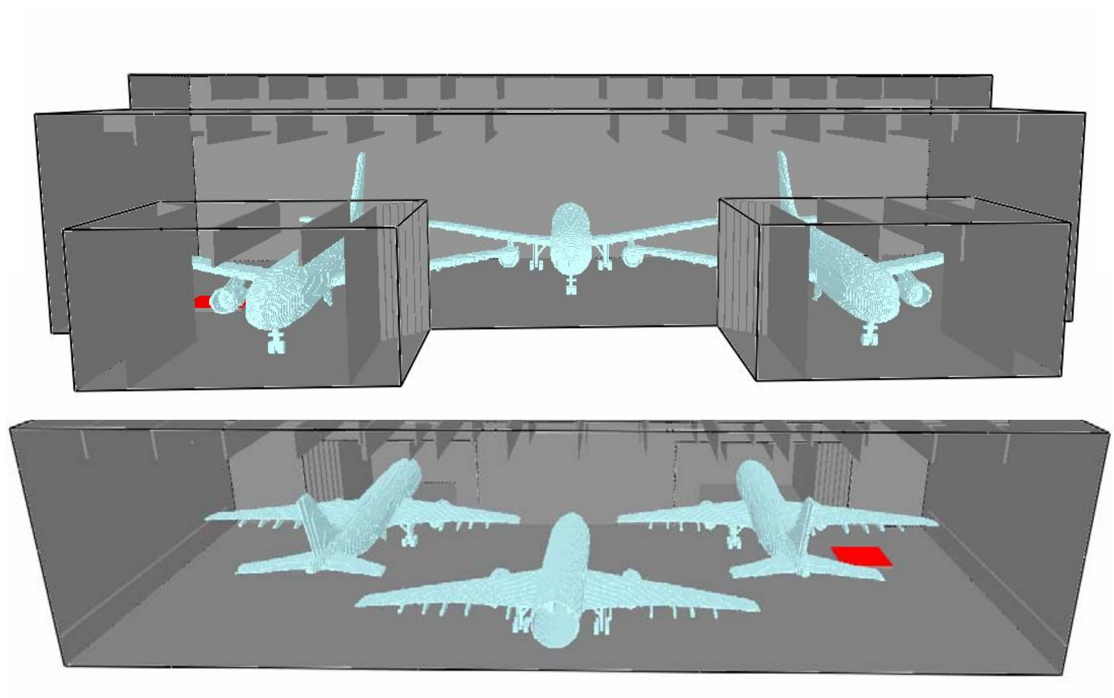


Figure 2: The FDS Modelling for HANGAR 3A

Table 2: The Summary of the FDS Simulation

Items	At 600 seconds	Tenability Criteria	Satisfy the Criteria?
Temperature (^{0}C)	< 60	< 60	Yes
The Visibility 3m AFFL	> 15	> 15	Yes
Carbon Monoxide (ppm)	< 1200	< 1200	Yes

4.2 Evacuation Time Analysis

"STEPS" (Simulation of Transient Evacuation and Pedestrian movements), which predicts the movement time of people under emergency conditions, is used to estimate the evacuation time. "STEPS" employs a modern entity-based approach which predicts the movement of discrete individuals (virtual people) through 3-dimensional space. The purpose of the simulation is to predict the evacuation time in the worst-case scenario when the HANGAR 3 is fully occupied. A total population load of 332 people is assumed in accordance with the operational requirement of this premise.

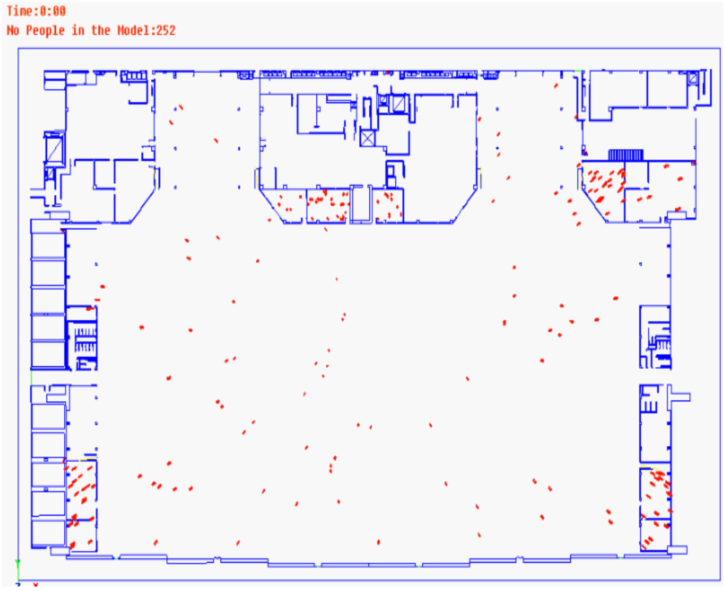


Figure 3: The STEPS Simulation for HANGAR 3A

According to the CIBSE Guide E, other than the physical travel time, the Required Safe Escape Time (RSET) includes the two other periods of time, i.e., the time of detection of a fire from the point of ignition (i.e. detectors) and the pre-movement (response) time for an occupant to become aware of a fire, perceive a fire threat and make their decision to evacuate.

Optical fire detectors (IR 3), approved by FM, will be provided throughout the HANGAR 3. With reference to the FM test reports, the average response time of IR 3 is from 1s to 9.2s and it also provide better immunity to false alarm than that of UV/IR detection(Gottuk,2000). For a conservative assumption, a detection time of 60 seconds is taken as the detection time when a fire is initiated.

As for the pre-movement time, Staff in HAECO is all well-trained and quite informed. Fire wardens, who have been trained for fire-fighting, should be on the presence on a 24/7 basis and they shall also be responsible for the evacuation of all staff members. It is believed that the pre-movement time is quite short, i.e., few second. For a conservative purpose, the time required to confirm the fire incident and to start the evacuation is about 30 seconds. By considering the above components, the total pre-movement time is about 90 seconds for a fire incident.

Based on the simulations (as shown in Figure 3), the total evacuation time for people to leave the HANGAR 3A is summarized as table 3.

Table 3: The Summary of the Evacuation Analysis

Detection Time (s)	Pre-movement Time (s)	Movement time(STEPS)(s)	Total Evacuation Time (s)
60	30	84	174

The total required safe evacuation time (RSET) is about 174 second, approximate 3 minutes.

4.3 A Comparison of ASET and RSET

As discussion in section 4.1 and section 4.2, the available safe evacuation time is more than 10 minutes whilst the time required for evacuation is about 3 minutes. About 7 minutes of safe margin is maintained.

The results of the performance analysis demonstrate that even under the worst fire scenario, occupants of the hangar have enough time to escape

5. TESTING, COMMISSIONING AND FIRE SAFETY MANAGEMENT

The whole fire protection system should be tested and commissioned thoroughly to make sure that system will work as intended during a fire emergency. The test includes commissioning tests and periodic in-service testing.

Commissioning testing includes the test of the complete system to demonstrate its correct operation and performance prior to acceptance plus all component checks, adjustments, preliminary tests, etc necessary prior to the final test and the test should be carried out with foam, and with the maximum number of monitors or sprinkler zones that would be required to operate simultaneously. The test is supervised on-site by local fire department officers.

Periodic in-service testing, jointed with Hong Kong Fire Services Department, is organized once a year, to ensure all system will be in a good state at all times. All staff members are required to participate in the fire drills. Each department or section appoints fire wardens who help to ensure full evacuation and assembly at the designated point outside the building. In addition to the above, HAECO’s insurance provider carries out annual audit making valuable improvement suggestions base on their experience.

Furthermore, a comprehensive fire and safety management system will be proposed and implemented. The system should include the strictly operational requirements to hold back the occurrence of fire incident in the first place and detailed roles and responsibilities of each staff when a fire emergency does happen.

6. CONCLUSIONS

At present, there isn’t a specialized fire protection code for hangar in Hong Kong.

As hangar is a specialized industrial-undertaking and the provision of a safe fire protection system is crucial to the successful operation as well as the occupant safety. NFPA 409 is adopted to provide a satisfied level in fire protection.

In addition, a holistic performance analysis is conducted. It accounts for real fire behavior within the complex, as developed through fire engineering, fire simulation and modeling approaches.

In conclusion, justifications are made to illustrate that the proposed hangar provides an equivalent level of safety for the building's occupants compared with direct compliance with the Hong Kong Codes of Practice.

REFERENCES

[1] NFPA 409, Standard on Aircraft Hangars, 2004.

[2] Meinhardt (M&E) Ltd., HAECO, Aircraft Maintenance Hangar No. 2, Hong Kong International Airport, Fire Safety Strategy Report, 2005.

[3] Scheffey, Joseph L., Gott, Joseph E. and Wakelin, Allison J., Aircraft Hangar Fire Suppression System Design Study, Naval Research Laboratory, 2000.

[4] Gottuk, D.T., Scheffey, J.L.,Williams, F.W., et al., Optical Fire Detection (OFD) for Military Aircraft Hangars-Final Report on OFD Performance to Fuel Spill Fires and Optical Stresses, Naval Research Laboratory, 2000.

[5] Thomas, S., Stephen W., Richard C. and Torero, Jose L., Large-Scale Pool Fires, BRE Centre for Fire Safety Engineering, The University of Edinburgh, 2007.

[6] Gottuk, D.T. and White, D.A., Liquid Fuel Fires, SFPE Handbook on Fire Protection Engineering, 3rd ed., Quincy, MA, Vol. 297, No. 316, 1995.

[7] Torero, J.L., Olenick, S.M., Garo, J.P. and Vantelon, J.P., Determination of the Burning Characteristics of a Slick of Oil on Water, Spill Science and Technology Bulletin, Vol. 8, No. 4, pp. 379-390, 2003.

[8] Hill, S. A. Scheffey, J.L., Walker F. and Williams, F.W., Tests of Alternative Fire Protection Method for USAF Hangars, Naval Research Laboratory, 1999.

[9] White, D., Beyler, C.L., Fulper, C., Leonard, J., Flame Spread on Aviation Fuels, Fire Safety Journal, Vol. 28, No. 1, pp. 1-31, 1997.

[10] Anthony, D. and Putorti, Jr., Flammable and Combustible Liquid Spill/Burn Patterns, NIJ Report ,U.S. Department of Justice, 2001.

[11] Babrauskas, V., Estimating Large Pool Fire Burning Rates. Fire Technology, Vol. 19, pp. 251-261, 1983.

[12] Ross, H.D., Ignition of and Flame Spread Over Laboratory-Scale Pools of Pure Liquid Fuels, Prog. Energy Combust. Sci., Vol. 20, No. 1, pp. 17-63, 1994.

[13] Mckinven, R., Hensel, J.G. and Glassman, I., Influence of Laboratory Parameters on Flame Spread over Liquid Surfaces.Combustion Science and Technology, Vol. 1, pp. 293-306, 1970.

[14] Buigoyne, J.H., Roberts, A.F. and Quinton, P.G., The Spread of Flame across A Liquid Surface.Part 1, Proceedings of the Royal Society. London. Vol. 308, pp. 39-54, 1968.

[15] McGratta, K. and Forney, G., Fire Dynamics Simulator (Version 4) – User's Guide. NIST Special Publication 1019, National Institute of Standards and Technology, Gaithersburg, MD, 2004.

[16] McGrattan, K., Fire Dynamics Simulator (Version 4) – Technical Reference Guide. National Institute of Standards and Technology, Gaithersburg, MD, 2004.

[17] Wang, H.Y., Coutin, M. and Most, J.M., Large-eddy-simulation of Buoyancy-driven Fire Propagation Behind a Pyrolysis Zone Along a Vertical Wall, Fire Safety Journal, Vol. 37, pp. 59-285, 2001.

[18] Scheffey, J.L., Darwin, R.L. and Leonard, J.T., Evaluation of Firefighting Foams for Aviation Fire Protection. Fire Technology, Third Quarter, Vol. 31, No. 3, pp. 224-243, 1995.

北京奥运工程性能化防火设计
与消防安全管理

馬建民

北京市公安局消防局高級工程師、奧運辦主任

一、 北京奥运工程简介

2002 年 7 月 13 日，申奥成功一周年之际，北京市人民政府、北京奥组委发布了《北京奥运行动规划》，包括总体战略构想、奥运比赛场馆及相关设施建设、生态环境和城市基础设施建设、社会环境建设、战略保障措施等五个部分，作为指导性文件对未来七年北京市如何筹办奥运会进行了规划。其中，定义北京奥运工程建设，是指奥运会各项比赛场馆以及与奥运会息息相关的一切相关（基础）设施建设，包括竞赛、非竞赛、训练、相关配套设施等，其中：

1、 竞赛场馆：31
2、 非竞赛场馆：15
3、 相关设施：若干
4、 独立训练场馆：45

内容：分布、名称等，呈“一个主中心加三个区域”的分布格局。一个主中心是指奥林匹克公园中心区，三个区域是西部社区、大学区和北部风景旅游区。

二、 北京奥运工程建筑设计特点及特殊要求

1、建筑体量大：

国家体育场，占地面积 20.42 公顷，总建筑面积（含看台面积的一半以及立面楼梯）257,989m^2。南北长 333 米、东西宽 298 米，双曲面马鞍型钢结构屋盖最高 69 米，赛时容纳 91,000 人。

国家会议中心，用地面积 81,400 ㎡，总建筑面积 271,900 ㎡，东西长 148 米，南北长 398.2 米，地上建筑面积 154,690 ㎡，地下建筑面积 117,210 ㎡，建筑高度 27 米，局部 43 米。赛时作为国际广播中心使用。

国家会议中心配套项目，用地面积 40738 ㎡，总建筑面积 263,818 ㎡，东西长 85.5 米，南北长 398.2 米，。建筑分为 A、B、C、D 段，地上建筑面积 201,798 ㎡，地下建筑面积 62,020 ㎡，建筑高度 60 米，赛时作为主新闻中心使用。

2、建筑结构形式特殊：

国家体育场，主体建筑呈空间马鞍椭圆形，为钢结构＋框架剪力墙结构。外壳由钢结构有序编织成“鸟巢”，钢结构外壳里面的看台及附属用房采用框架剪力墙结构，部分框架柱子为斜柱，十二个核心筒为剪力墙结构。钢结构总用钢量为 4.2 万吨，混凝土看台分为上、中、下三层。屋顶钢结构上覆盖了双层膜结构，即固定于钢结构上弦之间的透明的上层 ETFE 膜和固定于钢结构下弦之下及内环侧壁的半透明的下层 PTFE 膜。

国家游泳中心，又称“水立方”， 是一座梦幻般的水蓝色建筑，为多面体空间刚架结构，由上部的空间网架钢结构和下部的钢筋混凝土结构组成，外墙体及屋面为新型钢膜结构体系，看台及室内为全钢筋混凝土结构。

国家体育馆，主体结构为框架—抗震墙结构与型钢混凝土框架—钢支撑相结合的混合型结构体系，屋面采用集防水、保温、装饰为一体的金属板材，外围护结构采用玻璃幕墙与金属幕墙相结合方式。钢屋架南北长 144 米，东西宽 114 米，整个体育馆钢屋架工程由 14 榀桁架组成，总用钢量达 2,800 吨，钢屋架形状呈扇形波浪曲线，是目前国内空间跨度最大的双向张弦钢屋架结构体系。

3、建筑使用功能复杂：

国家体育场，包括比赛场地、看台、贵宾休息区、餐饮区、包间区、电视转播区、热身场地、兴奋剂检测以及赛事功能用房、场馆运行管理用房、车库、高、低压配电室，通信、净水、监控、垃圾处理、空调、冷冻机房等。

国家会议中心，包括国际广播中心和国家会议中心击剑馆。其中，国家会议中心击剑馆位于国家会议中心南侧赛后的会议区部分，共分击剑训练馆、赛事管理用房、击剑热身场地和正式比赛大厅四部分，可容纳观众数量约 4,500 人；国际广播中心（简称 IBC）位于国家会议中心北侧赛后的展览、商业和办公用房部分，是奥运会和残奥会期间集中进行奥林匹克广播和电视转播的场所，包括北京奥林匹克转播有限公司（BOB）运营区、转播权持有者（RHB）运营区、北京奥组委（BOCOG）运营区、餐饮区、仓储区、设备区以及技术、管理服务、设备用房等，赛时将为近 15,000 名记者提供 24 小时服务。

4、室内空间高大：国家游泳中心主比赛大厅以及嬉水大厅均为单层大空间，高度为 28.8 米；国家体育馆比赛场地上空为单层高大空间，最小最大净空（结构下皮）分别为 26.3 米、33.1 米，热身场地同样为空为单层高大空间，最小最大净空（结构下皮）分别为 19.2 米、24.7 米；五棵松篮球馆比赛场地净高 26 米；国家会议中心展览厅、宴会厅、大会堂等均为开放的大空间，天花高度在 12 米-19.65 米之间。

5、三位一体需求满足：在《北京奥运行动规划》中，要求奥运比赛场馆及相关设施建设需遵循国际奥委会和各国际单项体育协会的技术要求，符合国家有关法律法规以及残疾人奥运会的特殊使用要求。

6、工期时限要求：2008 年 8 月 8 日确定为奥运会开幕式，是确定无疑的，工程建设要以此进行倒排工期。

7、赛时使用和赛后利用相结合，两者在使用功能方面相距较大。既要保证赛时节俭，还要保证赛时安全，以利赛后改造成本减少。国家游泳中心南北临时看台赛后全部拆除改建为独立小楼，增加网球场；国家会议中心内的击剑馆恢复为大会堂、宴会厅，国际广播中心全部恢复为展览、商业和办公用房；国家会议中心配套内的主新闻中心将恢复商业、餐饮、停车、服务等功能。

8、坚持勤俭节约原则。

三、 消防设计难题

1、 高大空间火灾探测与灭火保护方式：
2、 人员疏散：
3、 防排烟问题：
4、 钢结构防火保护：
5、 防火分区：

四、 北京奥运工程消防设计解决方案

1、性能化防火设计，其特点，北京市开展情况，奥运特殊性
2、新产品新材料新技术推广应用
3、强化灭火科学规划，研制数字化灭火救援课题和发大空间灭火课题指导工作
4、实验验证

五、 国家体育场及奥林匹克公园中心区地下商业性能化防火设计简介

六、 北京奥运场馆运行消防安全管理，推动奥运场馆性能化解决方法的有效实施

七、 今后展望

1、建立相关的法规体系。
2、规范审批程序，审慎对待性能化防火设计需求
3、促进火灾科学的研究

FIRE ENGINEERING DESIGN FOR INNOVATIVE BUILDINGS

Mingchun Luo, Young Wong and Anny Ip

Arup Fire, Ove Arup and Partners Hong Kong Limited

ABSTRACT

In the past decades, the economy in Asia has experienced fast growth. The infrastructure and building projects are becoming larger, more complicated and with plenty of innovative design.

In Hong Kong, during the last 20 years, innovative approach of many significant developments, such as Hong Kong International Airport, railway terminal / stations, super high-rise buildings, and very large space atria gave great challenges to designers on fire safety perspective. The existing prescriptive codes in Hong Kong cannot provide sufficient support to meet the functional requirements of these large, complicated and innovative projects. Fire engineering approach was introduced to these projects and solutions were developed on the basis of the first principle of engineering, which was well supported by the approving authorities.

In China, the international architects compete to work on projects related to the 2008 Beijing Olympics and the Shanghai Expo 2010, as well as mega infrastructure constructions and super high-rise towers in all major cities. The architects brought new ideas and creative designs to challenge the existing fire safety regulation systems. The fire authorities in China realised that the existing prescriptive codes could not meet the functional requirements of these large and complicated projects, and a performance-based fire engineering approach for significant infrastructure and commercial development is essential.

This paper is to discuss the fire engineering design for the innovative buildings in the past decade and to summarize the major items using the new approach in the successful cases.

Keywords: Fire engineering design, high-rise buildings

1. INTRODUCTION

In recent years, it is a trend that the architectural design of the modern buildings becomes very innovative. There may be a few reasons that the architects worked very hard to bring new ideas to building design, and create innovative architectural features.

- For crowded cities, such as in Hong Kong, Beijing and Shanghai, the building height increases significantly. The heights of some super high rise buildings are over 500m in order to make use of the land more effectively.
- For some very special buildings, the architectural design may be in pursuit of a strong visional impact. The shape of the China Central Television Headquarters may be one of the best cases to illustrate this point.
- For mixed use developments, the functionality of the building is vey complicated. Multi occupancies exist in the same complex. The architectural design has to be innovative in order to meet the requirements of the function and usage.

The innovative design for these buildings provide significant challenges to all engineering disciplines, including fire engineering design. This paper will address the major issues of the fire engineering design for innovative buildings using case studies, and will cover the flowing elements:

- Means of escape and evacuation of super high rise buildings
- Fire protection of the very tall atrium space
- Innovative design of the spandrel and facade system
- Fire separation of large space terminal buildings

2. MEANS OF ESCAPE AND EVACUATION OF SUPER HIGH RISE BUILDINGS

The definition of “high-rise building” changes as construction technology improves. The US NFPA 101 Life Safety Code [1] defines high rise building as buildings with heights more than 23m. This is the maximum elevation resulted from the less favorable rescue and fire fighting operations with the use of extendable ladders. Since high rise buildings are unique with regard to their elevated height from conventional lower buildings, different design considerations including additional features are required for fire safety. Prescriptive codes in a number of countries [2, 3] have separate sections to cater for high rise building fire safety design. The additional enhancements in the prescriptive codes include suppression system, detection and alarm, but do not always include the egress component.

The current high-rise building evacuation strategies include the total building evacuation, phased evacuation and stay-in-place approach. These strategies are regarded as sufficient to handle most of the traditional fire scenarios in high-rise buildings. Following the terrorist attack on 11 September 2001 to the prominent super high rise building World Trade Center in New York, many questions have been asked about the resilience of high rise buildings to withstand extreme events. There is a trend to investigate the actual performance of buildings and determine what enhancements can be considered when a building is subjected to the extreme events, especially for the prestigious new super high rise buildings close to 500m or more in elevation. Evacuation component, such as how to simultaneously evacuate the building occupants efficiently, is a hot topic for discussions.

2.1 Means of Escape for ICC Hong Kong and WFC Shanghai

Due to the height of high-rise buildings, it is expected that occupants would take longer to travel from their original location to ground level. In addition to the horizontal travel time from their initial position to the staircase lobby on the floor, the occupants are required to travel an extended vertical distance, which can be up to 500m in super high-rise buildings. Occupants may have to walk down hundreds of flights or thousands of steps. Whilst there is the inevitable consequence of exhaustion amongst the occupants, another negative consequence is the slow discharge time that is the result of extensive queuing at the entrance of the stairwells. In some places [4, 5], additional provisions like refuge floors are provided to improve the egress conditions in high-rise buildings.

The increase in the occupant load of high-rise buildings due to stacking of floors can reach up to 100 times for super high-rise buildings, thus making the egress situation even worse. When compared with the density of occupants per building footprint and per staircase, the density in the high-rise buildings is significantly higher than in the shorter buildings. In addition, modern super high-rise buildings serve multi purposes, such as observation facilities on the building top, hotel or service apartment on the higher levels, office floors on the lower levels, and retail or exhibition facilities in the podium. In these types of super high rise buildings, different usages and occupancies exist. The differences in occupancies extend itself to the different familiarities with the building, which further complicates the evacuation process.

Total Building Evacuation

The traditional design of building evacuations in case of emergencies is based on the principle of a single staged total evacuation. The evacuation provisions of the building, i.e. escape staircase, are designed to allow all floors to be evacuated simultaneously. In the current Hong Kong Code Means of Escape [4], discharge value tables for staircases are used to prescribe the minimum stair requirements in the design of new buildings. These discharge value tables are formulated on the basis of a strategy of a total evacuation. Using the total building evacuation principle, evacuation provisions are sufficient for all occupants to enter the staircases simultaneously and leave the building. The total building evacuation is the simplest strategy to implement. Once the alarm signal is sounded, all building occupants are expected to evacuate to the staircases leading to the ground floor. In high rise buildings, where there are a large number of occupants on an extensive number of floors, a total building evacuation of all occupants results in extensive queuing before discharge into the staircases.

The International Commercial Centre (ICC) on the top of the Kowloon Station is a 108 storeys, 441m tall super high-rise building. The design of the means of escape for the ICC mostly complies with the Hong Kong prescriptive codes of practice but the travel and direct distances on typical office floors exceed the code requirement. The evacuation time of each floor is within one or two minutes. However, the total building evacuation time is nearly 120 minutes.

Lifts for Evacuation

Over the last 15 years or so research has been carried out into the potential for using lifts for evacuation, particularly for super high rise buildings. Evacuation by lift is already an established strategy in a few special structures. The NFPA 101 Code has allowed lifts to become the means of evacuation for airport control towers since 1997.

The final report on the Collapse of the World Trade Center Towers by the National Institute of Standards and Technology (NIST) in the US [6]] recommended that tall buildings should be designed to accommodate timely full building evacuation of occupants. Building size, population, function, iconic status, plus the counter flow due to the emergency personal should be taken into consideration in designing egress provisions. Without huge investments in additional evacuation provisions like constructing more and wider staircases, lift evacuation has been put in the agenda as one of the means to facilitate the high-rise building evacuation. The development of using protected/hardened lifts has already been recommended by the NIST as the next generation of evacuation technology to be evaluated for future use. The fire engineering guide in UK [7] has also listed the use of lifts for evacuation as one of the fire safety issues subject to evaluation as an enhancement during extreme events.

Proposed Lift Evacuation Strategy for Shanghai World Finance Centre (WFC)

The Shanghai WFC is currently the tallest mixed use building in China with 101 storeys and 492m in height. A refined lift evacuation strategy which consists of combining stair evacuation from a group of occupied floors to a refuge floor followed by lift evacuation from the refuge floor to street level is proposed. The proposed lift evacuation strategy can prevent major problems in traditional lifts including the spread of smoke into lift shafts, water spillage and fire hazards to occupants in the lobbies [8, 9, 10, 11]. For the proposed lift evacuation strategy, occupants on each floor will evacuate through the stairs to the refuge floors first, where the occupants can choose to travel down to street level by using shuttle lifts or stairs. It is recommended that both stairs and lifts are allowed to evacuate occupants from the refuge floors, and lifts would be the primary means in evacuation. The comparison of the proposed lift evacuation strategy with the traditional method has been discussed in detail in the literature [12].

Refuge floors are provided in this strategy as a temporary place of safety for occupants to have a rest and wait for the lifts during an emergency evacuation. The refuge floor is a safe place for a short rest before people continue to escape downwards or change to another set of stairs when occupants encounter smoke, fire or obstructions in the original staircase. The general requirements of refuge floors include an adequate height, lighting, ventilation, signage, free from obstruction, and completion with fire rated constructions that separate the refuge floors from the rest of the building. Refuge floors are important components in this lift evacuation strategy. The requirements of the refuge floor in this strategy will be the same, except that shuttle lifts must be able to pick up occupants on the refuge floors. Since refuge floors are originally designed to be a temporary place of safety for the staging of building occupants during the phased evacuation, it is safe for occupants to take rest and stay there to wait for the evacuation lifts. The risk of fire and smoke affecting the occupants waiting in the normal lift lobbies can thus be eliminated.

In the lift evacuation strategy, shuttle lifts are used. Local lifts within each zone will not be used to pick up occupants between floors. The use of shuttle lifts can eliminate the complicated control and management required to pick up occupants on different levels. These shuttle lifts only travel between the refuge floor and the street level. The shuttle lift shafts are blind shafts where there is no opening on typical floors; therefore, the provisions of a practically complicated lift shaft pressurization system and lift lobby water entry protection can be eliminated from these shafts completely.

Nevertheless in the Shanghai WFC building, it was recommended each shuttle lift used for evacuation during an emergency is provided with at least one or two trained staff for lift and crowd control. Human behaviour during an emergency is not currently a well researched subject. It is a general public perception to not use lift for evacuation during a fire, and there may be confusion in the crowd and affect the orderly manner of the lift evacuation process. In order to have a better crowd control and reduce the level of panic, the trained staff will provide clear instruction and order to control the situation. Until lift evacuation become a common feature in super-high rise building, such control by staff is thought to be essential.

Efficiency of Lift Evacuation

With the advancement of computational capacity and software technology, evacuation simulation that can handle individual human behavior for a massive number of occupants becomes feasible. The use of computerized evacuation simulations to estimate the efficiency of a lift evacuation has been discussed in the literature [13]. By acknowledging each individual's walking speed, escape route finding, familiarity of exits, decision making in choosing the exits, merging between flows in the staircase, queuing behavior, etc., a realistic and comprehensive analysing tool can estimate the total evacuation time of entire building. The specification of the model input parameters consists of describing people types, body dimensions and their associated walking speeds.

The total building evacuation for ICC and WFC has been simulated in a way that all the occupants start evacuating at the same time. This is the worst scenario as far as stair usage is concerned. For the Shanghai WFC tower, two scenarios, traditional evacuation using stairs only, and the proposed lift evacuation strategy of using lifts and stairs together, have been simulated. The numbers of occupants in the building have been plotted against time in Figure 1.

When comparing the total building evacuation times, it can be seen that using lifts and stairs in this evacuation strategy can reduce evacuation time by 36%. In the case of human factors such as occupants hesitating and refusing to take the evacuation lifts and insisting to use stairs for evacuation, the simulated evacuation times will be bound by the two cumulative percentage curves.

For the Hong Kong ICC tower, lifts are not proposed for evacuation. The height, the number of storeys and the total occupant numbers of the ICC tower are similar with the Shanghai WFC tower. The total evacuation time of the ICC tower is very close to that of the Shanghai WFC tower without using the shuttle lifts.

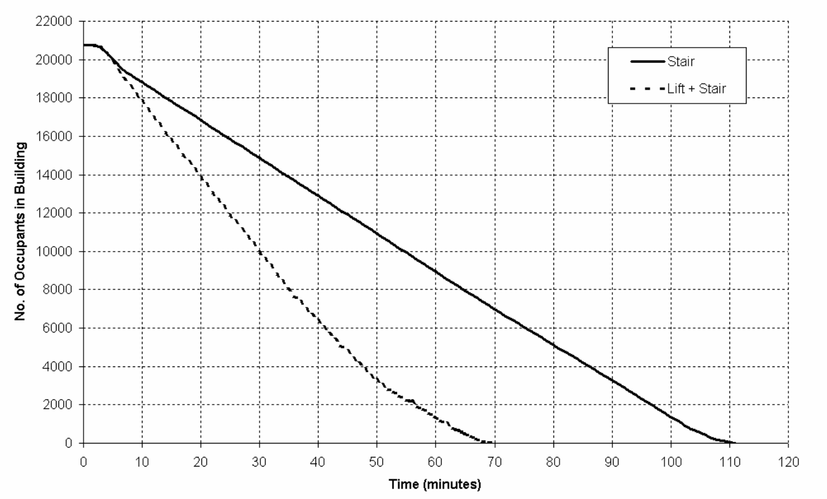


Figure 1: Comparison of Evacuation Times

2.2 Means of Escape for the China Central Television (CCTV)

The CCTV Headquarter buildings are located in the Central Business District of Beijing with a total site area of 196,960m². There are two main buildings and a series of secondary and underground facilities with total construction area of 599,700 m². These two main buildings are the China Central Television (CCTV) Headquarters for administration, news, broadcasting, program production and services in a single structure and the Television Cultural Centre (TVCC) building housing a five-star hotel, a 1500-seat theatre and large exhibition facilities.

Figure 2: CCTV Main Building

The CCTV Tower is 234m tall at its highest point and has approximately 400,000 m² of floor area including basement and podium structures. There are 51 stories above grade and 3 stories below grade. It consists of two leaning towers with 6 degree lean in each direction. The two leaning structures rise from a common platform, the plinth, which is partly underground space. They join at 37th floor to create a penthouse for the management, which are linked together via a 14-storey cantilever link element.

The CCTV tower is unique in its architectural design, and has various functional spaces, which are different from ordinary civilian buildings. Many aspects of the design cannot comply with the requirements of China codes.

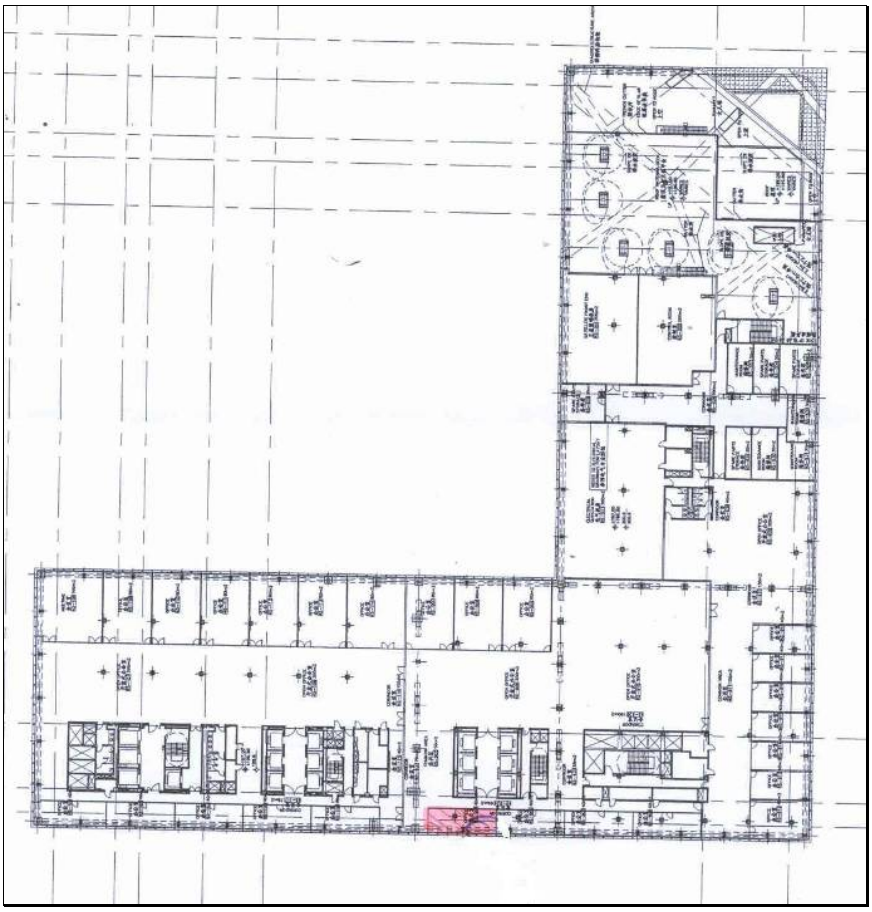


Figure 3: CCTV Main Building: Layout of Floor 45

Each of the two leaning towers has about 2,000 m^2 office area per floor. Each floor of the individual towers forms its own fire compartment. The two towers have their own stairs for evacuation. The total width is 6.8 m, which meets the requirements of the China codes for the evacuation in emergency and the distance for evacuation. Refuge areas are located on Floors 17, 37 and on the roof.

In the overhang from Floor 37 to Floor 51, there is an L shape section sitting on the top of these two towers. The largest floor area of the overhang is 8,500 m^2. There are 7 stairs for evacuation of the occupants in the overhang section. The occupants from F37 and above will use these 7 stairs and discharge to the refuge areas on Floor 37 first, and then through the protected corridors transferring to the stairs in the two leaning tower for further evacuation.

There are two refuge areas on Floor 37 as two baffle zones for transferring the occupant during emergency evacuation. These two refuge areas are connected via protected corridors. The refuge areas are totally separated from other occupancies with 3 hr FRP walls and doors with lobbies.

<u>Total Evacuation</u>

The CCTV towers are different from any ordinary civilian building in its architectural design, particularly there are 14 floors with over 4,000 m^2 area hanging in air without escape stairs directly discharge to street level. It is essential to carry out analysis of the whole building evacuation and justify the level of safety of the building design.

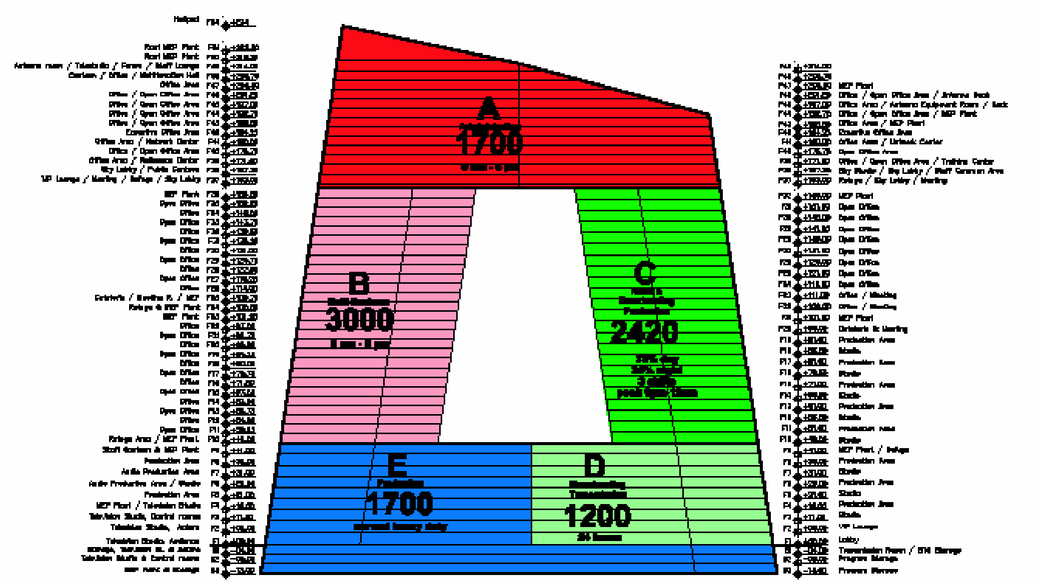


Figure 4: Estimated Maximum Population in CCTV Tower by Clien

The number of occupants in a building is a critical factor for evacuation analysis. Based on the function of the building, the client estimates that not more than 8,000 staff will work in the CCTV tower, and the number of people in the building will not exceed 10,000 including the visitors (see Figure 4). However, in the process of performance based design, the maximum population has been further estimated for the areas that require a fire engineering analysis by the designer. The population in each of the locations in the building is given in Table 1. The total population is significantly higher than that given by the client.

Table 1: Population of the CCTV Towers

Function Division	Designer	Client
A	7,022	1,700
B	3,005	3,000
C	2,429	2,420
D	1,462	1,200
E	10,618	1,700
Total Population	**24,533**	**10,020**

For the purpose of analysing the performance of the whole building, a comparison is also made with another similar and code compliant building illustrated in Figure 5. The code compliant building is assumed with an extension of floors to makeup the loss of the overhang. The topmost floor of the building is therefore 57 floors instead of 51 floors. Such a design satisfies the functional requirement and also complies with the code.

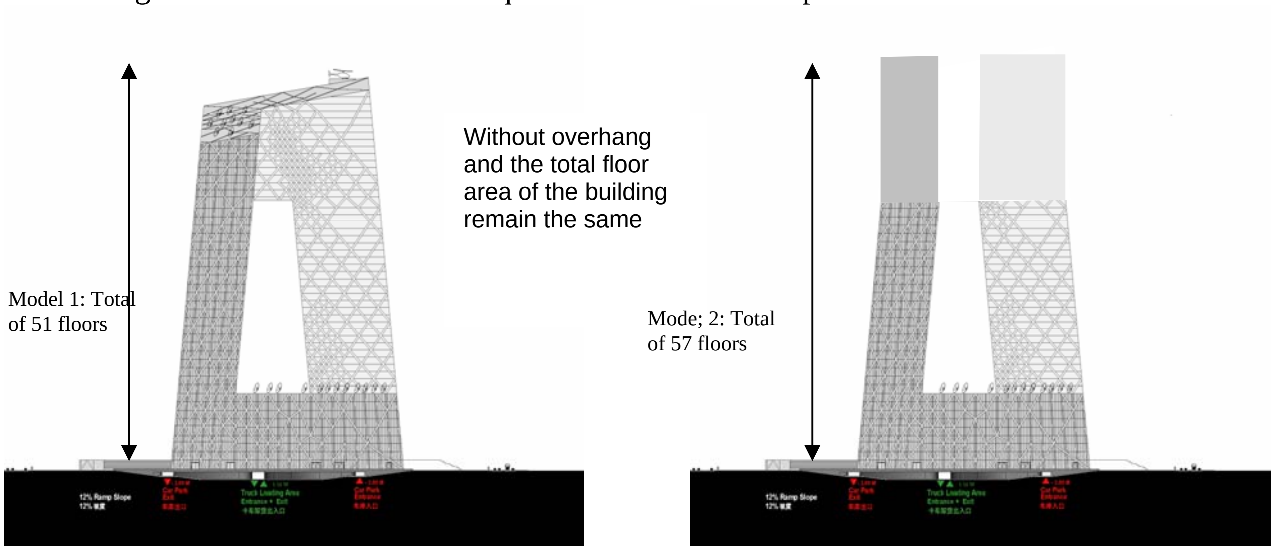


Figure 5: Models for Evacuation Analysis

The building with no overhang but adding the floor area to the towers takes 60 seconds longer than the overhang design to complete the total building evacuation. It is concluded that the design of means of escape for the CCTV towers is acceptable from the point view of both the code compliance and performance based approach.

Table 2: Comparison of the Evacuation Time

Current Design (min: sec)	Two Towers instead of Overhang (min: sec)
48:58	49:58

3. FIRE PROTECTION OF VERY TALL ATRIUM SPACE

Langham Place in Mongkok, Hong Kong is well known of its very high ceiling atrium of large volumetric space. The Grand Atrium with the saddle bag has an approximate volume of 105,000m³ and the Mini-Atrium has an approximate volume of 32,000m³. The combined volume of the two atria is in the order of 137,000m³ approximately. Such novel, aesthetic architectural feature leads to challenges in full compliance of the prescriptive Hong Kong code specifications, particularly size of fire compartment. Fire engineering principles were applied extensively to address various fire safety matters of such big and high ceiling space including smoke control, fire detection, atrium based fire suppression, oversized fire compartment, and fire resisting rating of construction elements.

Figure 6: Langham Place

3.1 Smoke Control

Dynamic smoke extraction systems are proposed for the Grand Atrium and the Mini-Atrium. These smoke extraction systems are designed on the basis of a fire engineering approach. It is assumed that the smoke control system in both the Grand and Mini Atria together with the sprinkler (Mini Atrium only) creates a steady state environment. Smoke clear height is maintained. Occupants at Level 4 in the Grand Atrium and Level 10 to 12 in the Mini Atrium will be able to escape to adjacent compartments under the smoke layer. The occupants present in the circulation areas open to the Grand Atrium on the upper levels will be able to escape into the adjacent compartment on the arcade levels separated by fire shutters. It is proposed that shops opening onto the atrium be provided with fire shutters to separate them from the Grand Atrium.

3.2 Hot Smoke Test

The Grand Atrium is a unique space that is equipped with the dynamic smoke extraction system. Smoke extraction grilles located at ceiling level of the atrium remove smoke from the space and discharge to outside at roof level. Automatically opening air vents located at lower level (above kiosks) allow make up air into the atrium.

Due to the height of the atrium space, a Hot Smoke Test (HST) has been requested by the Hong Kong Fire Services Department (FSD) in order to comply with the Circular Letter No. 2/2002 [14]. The objective of the Hot Smoke Test is to demonstrate that the installed systems are operational and work effectively in a realistic fire condition.

Figure 7: Hot Smoke Test in the Grand Atrium

In accordance with AS 4391, the test fire fuel is Denatured Industrial Grade Methylated Spirit (Grade 95). The quantities of fuel used follow the recommendations In AS 4391 and are sufficient for a steady state burn time of about 10 minutes. Approximately 100 litres of fuel has been used for a 2MW fire. The results of the hot smoke test conclude that the installed systems are operational and work effectively in a realistic fire condition.

3.3 Long Throw Sprinkler System

With collaboration of the building services engineers and the Hong Kong Polytechnic University, the Loss Prevention Council (LPC) endorsed design arrangement of the long-throw sprinklers was modified to suit the aesthetical and functional needs of the unobstructed atrium base that the sprinkler heads can be mounted at 0.5m centers in radial form with either 30^o or 45^o apart. Water collection tests were carried out on site to verify the performance of the modified arrangement can meet the LPC minimum design density 5mm/min for Ordinary Hazard (see Figure 8).

Figure 8: Field Test of Long Throw Sprinkler with 30° and 45° inclined

The results of the field tests conclude that water distribution by the proposed radial arrangement of sprinklers with their axes inclined at 30^o and 45° satisfy the LPC requirements [15] over the protected segment areas of 8m long and 6.5m long respectively.

4. INNOVATIVE DESIGN OF SPANDREL AND FACADE SYSTEM

A new office tower of 67 storeys located at the Hong Kong Island East has recently been completed and is currently in use. The building was intended to be at the forefront of international tall building design. The client has a strong desire to adopt innovative design and features for the office tower. Spandrel areas have been normally perceived as solid and heavy visual elements of a building facade due to their 900mm depth and transparency. The proposed architectural design of this new office tower includes a slim, light-weight appearance from the exterior with floor-to-floor external glazing. Therefore a thin spandrel is essential to express the lightness of the building structure and to achieve a more glassy and transparent building that is comparable to world-class office buildings worldwide. The building facade has employed glass construction and it was aimed to minimize the visible structure from external view. It is also an important design approach to enhance the natural lighting quality with the increase in vision panel area as a result of the reduced spandrel depth. Therefore a unique design of spandrel has been developed specifically for this office building to achieve the desired performance

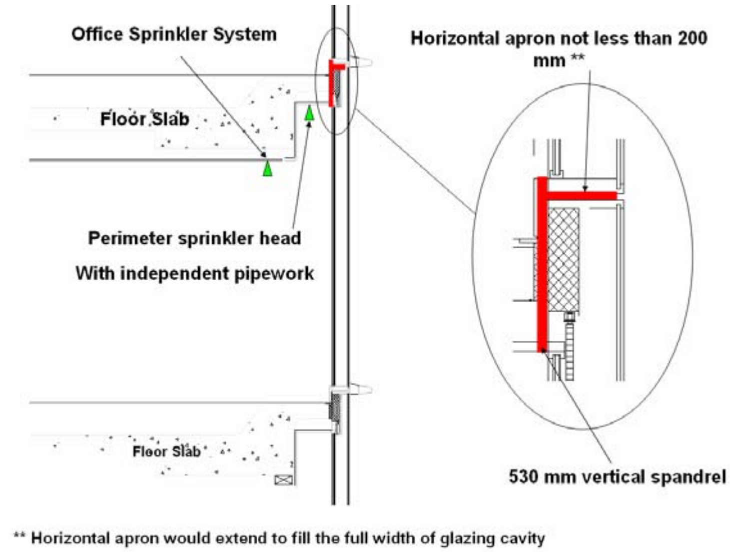


Figure 9: Cross Section through the Building Facade Showing the Location of Spandrel and the Sprinkler Head Along Building Perimeter

Under the guidance of the Code of Practice for Fire Resisting Construction (FRC Code) [16], the external wall of a building at any floor is required to contain a non-combustible 900mm spandrel in order to reduce the risk of vertical fire spread between floors. An extensive investigation of spandrel design, including international practices [17], has been conducted in order to arrive at an alternative design proposal whilst satisfying the performance requirement under the FRC Code. The alternative proposal comprises 4 enhancements: (a) 530mm vertical spandrel; (b) horizontal apron of not less than 200mm; (c) horizontal apron that extends to the full width of glazing cavity; and (d) a more robust perimeter sprinkler protection with sprinkler heads located at 600mm or less from the facade at each floor. Figure 9 shows the alternative spandrel arrangement.

The perimeter sprinklers are linked with water pipes branched off from the riser that controlled by a separate subsidiary valve. Additional sprinkler heads are provided to protect the general office areas that comply with the prescriptive requirements of maximum spacing (1.5m) from the internal pane of the facade, resulting in duplicated sprinkler coverage for the perimeter zone of the building. The vertical spandrel and horizontal apron have a Fire Resistance Period (FRP) of not less than 1 hour in terms of integrity as per the FRC Code.

A fire engineering analysis has been undertaken to assess the fire safety performance of the alternative proposal. The analysis has shown the following:

- The behavior of sprinklered fire has been investigated by looking into research conducted internationally. It is found that sprinklers could control the fire effectively and prevent vertical fire spread to upper floors.
- A study on conventional sprinkler reliability has been carried out. It indicates that sprinklers are highly reliable in operation and fire control/suppression. The reliability of a sprinkler system is around 98% and will be higher if it is installed and maintained to the standard requirements. The sprinkler system within the office tower will be inspected and maintained at regular intervals built in as part of the management handbook. In addition, the enhanced feature, i.e. duplicated sprinkler coverage and independent water supply pipe for the perimeter sprinklers, will further improve the reliability.
- Further study of the fire behavior within an office floor has been conducted to reflect effects of the particular façade details. A fire near the perimeter of the building is identified as the worst credible fire scenario for vertical fire spread. With sprinkler protection, it is likely 1 or 2 glazing panels at most will be broken due to thermal effects.
- The maximum heat release rate of the fire is assessed as 1.4MW by sprinkler protection. The flame height is calculated as 1.73m, which will not cause direct flame spread from the fire floor to the floor above.
- The smoke and heat effects are further investigated using Computation Fluid Dynamics program named Fire Dynamics Simulator (FDS). The results of FDS indicate that the smoke plume that is exposed to the upper floor facade glazing is less than 250^{o}C. It is not likely to cause failure of the glazing. Therefore fire spread to the upper floors via the external wall is unlikely.
- It was found that the proposed arrangement is efficient in preventing vertical fire spread. The horizontal apron helps to divert the hot gases outwards as shown in Figure 10 of the FDS simulations. It is an effective measure to minimize the risk of fire spread.

The proposed arrangement of vertical spandrel, horizontal apron and enhanced sprinkler protection is specifically designed for this office tower and will perform adequately in minimizing and even in preventing fire spread from floor to floor as per the FRC Code. Such design was submitted and subsequently approved by the Hong Kong Buildings Department.

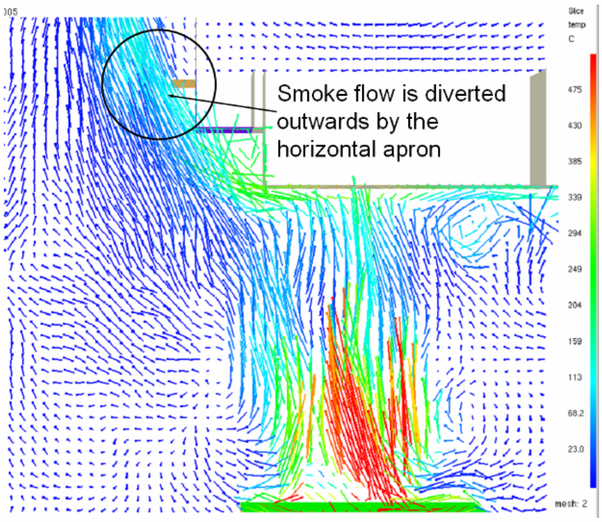


Figure 10: Velocity Profile of Hot Gases on the Facade at 10 Minutes

5. FIRE SEPARATION OF LARGE SPACE TERMINAL BUILDINGS

The functionality and operation for transportation terminals, i.e., airport passenger terminals and rail station, require large open spaces. It is difficult to meet the requirements of the building regulations for compartmentation and at the same to meet the operational requirements. In the past 20 years, fire engineers developed innovative solutions to solve these problems.

5.1 Cabin Concept

The cabin concept is an important example of a fire engineering approach to fire safety protection of large spaces. It was developed in late 80's of last century [18, 19]. The concept has been tested with a series of experiments [20] and used for fire safety design in a number of significant developments around the world, including the International Airport and MTRC stations in Hong Kong.

The principle of the cabin concept is to provide protection to the areas of high fire load, whilst permitting flexibility in use of the large space without physical compartment walls. The essential elements in a "cabin" include:

- Smoke reservoir at the area of high fire load
- Fire detectors in the reservoir and alarm
- Combined smoke extraction and ventilation systems
- Sprinkler system

Figure 11 illustrates the cabin concept. A smoke bulkhead forms a smoke reservoir over the protected area. A smoke extraction system is applied to the protected area and the extraction rate of the system is based on the design fire, which represents the worst case. Smoke will not spread to the adjacent zones with low fire load. A sprinkler system is designed to protect the areas of high fire load.

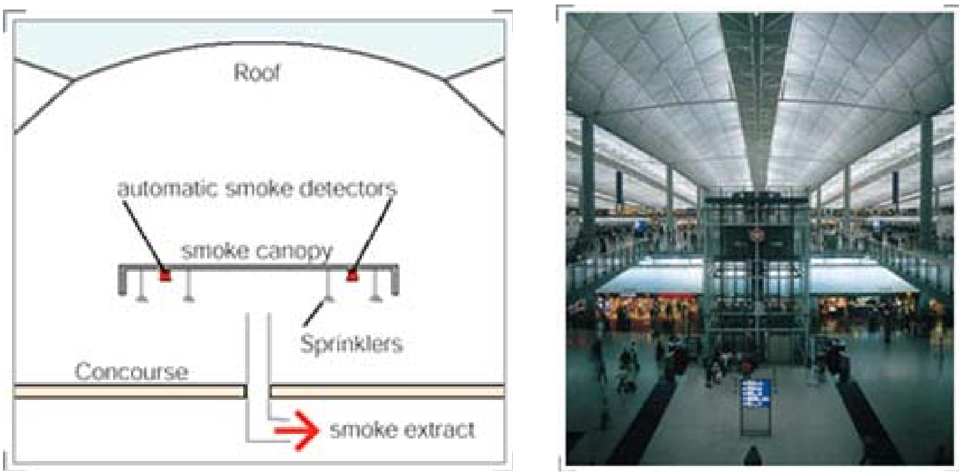


Figure 11 Sketch of Cabin Concept Design

5.2 Island Concept

In large open space, there may be movable or fixed kiosks. These kiosks cannot be protected by cabin concept. Island concept has been used to protect these areas, i.e. to limit the total combustible material in each of the kiosks and separate the kiosk to avoid fire spread from island to another.

When a fire occurs in a large open space, around two thirds of the heat generated from the fire is convective heat, which will be carried by the smoke plume and raise to the ceiling. The rest is radiant heat and emitted to the environment. If the surrounding combustibles are close to the fire, these combustibles would be ignited by radiant heat. The effective radius to ignite the materials during a fire can be estimated from the following equation:

$$R = \left(\frac{Q}{12\pi q''} \right)^{1/2}$$

Where：

- Q is total heat release rate, kW;
- R is radius from the centre of the fire, m；
- q'' is the minimum radiant heat flux to ignite the combustible materials, kW/m^2.

To prevent fire spread from one island to another, the distance between the islands (combustibles) has to be controlled.

5.3 Smoke Clearance System

In the island concept, the commercial kiosks are exposed in a very large and tall space. If a smoke control system is designed to comply with the air-change rate as required under the Hong Kong prescriptive code, the extraction rate of the system will be unrealistically huge due to the large volume of the space.

For a large transportation terminal, in the event that a kiosk fire is to occur in the circulation area, a smoke clearance system is provided at the terminal roof or at the lower zone. The system is designed for clearing diluted cool smoke and is of much reduced capacity compared with the prescriptive requirement. The smoke clearance system is for business continuity purpose.

6. CONCLUSION REMARKS

In recent years, architectural design for infrastructure facilities, super high rise buildings and mega size shopping malls has created various innovative buildings. The aesthetic architectural features lead to challenges in full compliance of the prescriptive code specifications for fire compartmentation, means of escape, smoke extraction, and fire suppression systems etc.

Fire engineers have worked closely with the architects and authorities to develop tailored solutions for each unique building. These solutions were developed on the basis of the first principles of engineering and illustrated the excellent examples of fire engineering approach.

This paper summaries the major items of these innovative solutions produced in recent years, which covers the means of escape and evacuation of super high rise buildings, fire protection of the very tall atrium space, innovative design of the spandrel and facade system, and fire separation of large space terminal buildings.

With the ever growing demand in innovative and complex design for buildings and infrastructures, fire engineering design forms an extremely important part of the building engineering process. The advancement of technology and fire engineering technique also enable designers to improve the fire safety design on a project by project basis. Different objectives such as life safety, property and environmental protection can be considered as necessary. The approach enables better, safer and more cost effective solutions to be produced.

REFFERENCES

[1] Cote, R. ed., NFPA 101 Life Safety Code, 8th ed., National Fire Protection Association, Quincy, 2000.

[2] Code for Fire Protection Design of Tall Buildings, GB 50045-95, 2005 ed., National Standard of The People’s Republic of China, Beijing, 2005.

[3] NFPA 5000, Building Construction and Safety Code, 2006 ed., National Fire Protection Association, Quincy, 2006.

[4] Code of Practice for the Provisions of Means of Escape in Case of Fire, Building Authority Hong Kong, 1996.

[5] Regulamento de Segurança contra Incêndios, 1995 ed., Imprensa Oficial de Macau, Macau, 1995.

[6] Federal Building and Fire Safety Investigation of the World Trade Center Disaster: Final Report on the Collapses of the World Trade Center Towers, NIST NCSTAR 1, National Institute of Standards and Technology, Gaithersburg, MD, 2005.

[7] CIBSE Guide E, Fire Engineering, Chartered Institution of Building Services Engineers, London, 2003.

[8] Klote, J.H., Elevator Piston Effect and the Smoke Problem, Fire Safety Journal, Vol. 11, No. 2, pp. 227-233, 1986.

[9] Klote, J.H., Analysis of the Lift Safety Consequences of Smoke Migration Through Elevator Shafts, Atlanta Workshop On the Use of Elevator in Fires and Other Emergencies, American Society of Mechanical Engineer, 2004.

[10] Klote, J.H., Elevators as a Means of Fire Escape, National Institute of Standards and Technology Report NBSIR 82-2507, Gaithersburg, MD, 1982.
[11] Klote, J.H., Deal, S.P., Donoghue, E.A., Levin, B.M., and Groner, N.E., Fire Evacuation by Elevators, Elevator World, Vol. 41, No. 6, pp. 66-70, 72-75, 1993.
[12] Wong H.L.K., Hui M.C., Guo D.G., and Luo M.C., A Refined Concept on Emergency Evacuation by Lift, Proceeding of 8th International Symposium on Fire Safety Science, China, 2005.
[13] Wong H.L.K., and Luo M.C., The Application of New Technology in Quantifying the Effectiveness of Lift Evacuation, Proceeding of Fire Australia 2005, Australia, 2005.
[14] FSD Circular Letter No. 2/2002; Hot Smoke Tests on Smoke Extraction System, Hong Kong Fire Services Department, November 2002.
[15] LPS 1039: Issue 5 Requirements and testing methods for automatic sprinkler, 2002.
[16] Buildings Department, Code of Practice for Fire Resisting Construction, 1996, Hong Kong.
[17] Department of Building and Housing, Compliance Document for New Zealand Building Code, Clauses C1, C2, C3, C4, Fire Safety, 2005, New Zealand.
[18] Beever, P., Cabins and Islands: A Fire Protection Strategy for an International Airport Terminal Building. Fire Safety Science Proceedings of the 3rd International Symposium, Edited by Cox, G. and Langford. B., Elsevier, London, pp. 709-718, 1991.
[19] Waters, R. A., Stansted Terminal Building and Early Atrium Studies, Journal of Fire Protection Engineering, Vol. 1, No. 2, pp. 63-76, 1989.
[20] Bressington, P., Railway link to Chek Lap Kok, Fire East ’95, Conference & Exhibition, 7th November 1995.

THIRD PARTY FIRE SAFETY CERTIFICATION IN SINGAPORE

Geok Kwang Boo

Director of Fire Safety and Shelter Department, Singapore Civil Defence Force

1. INTRODUCTION

Singapore Civil Defence Force (SCDF) regulates fire safety in buildings to attain a fire-safe built environment in Singapore. Its mission is to protect and save lives and property for a safe and secure Singapore. We formulate and implement fire safety policies and regulate fire safety standards in buildings and these are governed by the Fire Safety Act, its Regulations and a set of codes of practice related to fire safety systems. The Act was first enacted in 1993 and was made effective on the 8th April 1994, with several amendments made in subsequent years. We achieve our fire safety goals through an effective fire safety regulatory system that calls for active participation by and partnership with the professionals, developers and building owners in the building industry.

SCDF regulates the design of safety measures in buildings from the inception to the completion stages and the upkeep of the buildings. Under the Fire Safety Act, all fire safety works require approval from SCDF. Qualified Persons (QP) who are either professional architects or engineers with valid practicing certificates issued pursuant to the Architects Act or Professional Engineers Act to practice in Singapore must prepare all fire safety plans based on the fire regulations and submit them to SCDF for approval. The QP is responsible for the supervision of construction works and installation of fire safety systems. Upon completion of work, the owner shall engage Registered Inspectors (RIs), who is empowered by law, to inspect completed building for compliance of fire safety standard. After RIs certify the works, QP can then apply for a Fire Safety Certificate (FSC), which allows the building for occupation. A Temporary Fire Permit will be granted to any building where there are minor requirements that are still outstanding. Otherwise, for full compliance, a Fire Safety Certificate will be issued.

In 2004, we launched the performance-based regulatory system that specifies the desired fire safety objectives but leaves it to the industry to propose their own appropriate fire-safety engineering solutions to meet those objectives. Only QPs who are fire safety engineers (FSEs) are allowed to undertake performance-based design and as such only RIs, who are QPs with more than 10 years of experience and a registered FSE, can inspect completed fire safety works under the performance-based regulatory system. SCDF may take enforcement action when failure to comply with fire safety requirements is detected.

2. PARTNERING THE INDUSTRY

While SCDF is the regulatory body on fire safety matters, it also recognizes the importance of fostering close ties with the building industry so that fire safety standards can be effectively administered and enhanced. In this respect, SCDF maintains constant link with the professional bodies, including developers and owners through avenues such as regular dialogue sessions and seminars. This allows SCDF to keep the industry informed of the latest developments in fire safety and to understand the changing needs of the building industry.

Another useful forum is the FSSD Standing Committee which convenes bi-monthly to reach out to the professionals in the building industry to clarify and seek feedback and consensus on proposed changes to fire safety legislation, policies, procedures and requirements prior to implementation. The Committee is chaired by the Commissioner SCDF and comprises representatives from 13 professional organizations and government agencies such as the Singapore Institute of Architects (SIA), Institution of Engineers Singapore (IES), Building & Construction Authority (BCA), Jurong Town Corporation (JTC), Housing & Development Board (HDB), etc. The Committee has indeed been a useful platform for frank and rigorous discussion and also served as an effective feedback channel for fire safety issues facing the building industry.

The joint collaborative effort between SCDF and the building industry to review the Fire Code is also another example to reflect the close working relationship between the regulatory body and the industry. The Fire Code is periodically reviewed by a Fire Code Review Committee, chaired by the SCDF and comprises representatives from government agencies and professional and tertiary institutions. The review is intended to keep the Fire Code relevant in today’s fast changing business environment where new construction techniques and materials are constantly evolving. Over the years, SCDF had received suggestions for improvements from the building professionals via channels such as FSSD Dialogue Sessions, FSSD Standing Committee Meetings, consultations and feedback. These suggestions led to the revision of some clauses in the Fire Code which are then conveyed to the building industry through circulars and regular fire safety seminars prior to implementation. These changes are subsequently consolidated and published in the Fire Code’s revised edition.

The purpose of the Fire Safety Act is to bring about a higher standard of fire safety throughout the lifetime of buildings in our country. Buildings were not only required to be designed to the standards of the latest fire safety codes but were also required to have proper fire safety management to ensure that fire safety systems are properly maintained and fire emergency procedures prepared and practiced regularly. This required the efforts on the part of owners/management of buildings and the fire safety professionals to co-operate with SCDF. SCDF has since successfully introduced fire safety schemes to oversee fire safety management in buildings. In this regard, two schemes were introduced, the Fire Safety Manager (FSM) Scheme and the Fire Certificate (FC) Scheme.

The FSM scheme aims to assist the building owner in ensuring that the building is fire safe at all times, and that in the event of a fire emergency, evacuation of building occupants can be carried out expeditiously. Under this scheme, the building owner is required to appoint a FSM to assist him in managing fire safety in the building. The scheme applies to any commercial and industrial building with gross floor area exceeding 5000m^2 or an occupant load of more than 1000 persons, and high risks premises such as hospitals or buildings with activities involving hazardous materials. An FSM is a trained personnel designed to help the building owner manage the fire safety of the building. The duties of the FSM include: ensuring that addition and alteration works are carried out only with the necessary approvals; fire emergency plans are drawn up, carried out and updated as required; annual fire safety report is prepared and acted upon; and fire hazards such as locked exit doors, obstructed escape passageways, poor housekeeping, etc do not exist in the premises. Trained FSMs must be certified by the SCDF before they are recognized as the FSM for any premises. Through the FSM fire safety activities and fire prevention measures are implemented to promote fire safety awareness among the building occupants

In the Fire Certificate (FC) scheme, buildings that come under the FSM scheme and any public building with occupant load exceeding 200 persons are also required to obtain an FC from the SCDF. The owner has to engage a QP in the appropriate discipline to check and test the fire protection system before making an application for an FC. The FC is a certification that all the building fire safety measures have been properly maintained and are in good working order. Examples of fire safety measures include sprinkler system, fire alarm system, dry and wet risers, engineered smoke control system, emergency power supply, etc. This certificate has to be renewed annually. Such a scheme provides the assurance that the fire safety provisions that are designed and incorporated into the building are regularly checked for operational readiness.

3. SELF-REGULATION SYSTEM

Fire safety plans are approved based on the self-regulation system which was introduced in September 1998. Prior to its introduction, each and every plan that was submitted to SCDF was checked by our plan processing officers for compliance. Written directions were issued to the QP, who would re-submit the plans upon compliance. SCDF then repeats the checking process. Such process could go on iteratively, taking several months before the plans were finally approved.

However, in the self-regulation system, the approval of plans takes only two working days after some preliminary checks. To serve as a checking mechanism, about 10% of the approved plans are randomly picked for audit. The audits involved thorough scrutiny of the plans selected and correspondence with the QPs for any non-compliances spotted.

The key thrust of the system therefore lies with bestowing full trust on the Qualified Person (QP) to comply with the fire safety requirements in making his plan submission. On the other hand, it is also essential that SCDF plays its part in enabling QPs to fulfil their responsibilities. How do we do this?

Firstly, it is important that the Fire Code is clear and easily understood by the QPs so that they can adhere to the requirements. Towards this end, SCDF has categorized the Fire Code into 8 volumes based on the building classification so as to make it more user friendly, e.g. residential buildings, institutional buildings, offices, factories, etc. A QP who is involved in a residential project would refer to the Fire Code relating to such building type. This would greatly facilitate his design of fire safety measures, and not to miss out on the important requirements.

Secondly, to aid in the QPs' comprehension of the Fire Code, SCDF has also produced a set of diagrammatic handbooks to illustrate and explain the rationale of the fire safety requirements. This would better enable QPs to appreciate the need for these requirements. In addition to these handbooks, SCDF also conducts fire safety courses, seminars and dialogue sessions for the industry. All these serve to level up the knowledge of fire safety in the industry and help QPs fulfil their responsibilities.

Thirdly, as a transitional measure to prepare the QPs to be more self-reliant prior to the full implementation of the self-regulation system, a "self-declaration" system was introduced. In this "self-declaration" system, all the plans are audited but only with regards to the essential aspects of fire safety. As such, the self-declaration system has given rise to greater fire safety awareness and the need to submit good quality plans. Any non-compliance detected on the plans during audit by SCDF may render the QP to disciplinary action. It is thus not in the interest of the QP to submit a poorly prepared plan.

In addition, QPs are encouraged to come forward for consultation and make clarification on any doubts in their process of designing to comply with the Fire Code. The consultation process is open to all QPs and developer/building owners. Thus, the efforts involved in conducting checks on every plan submitted by QPs have been transformed into consultation services at the onset before the QPs make their plan submission.

The outcome of the Self-Regulation System is encouraging, as the level of compliance has vastly improved compared to the old system. Statistics show that less than 2% of those audited cases have non-compliances, as compared to about 75% in the old system.

4. REGISTERED INSPECTOR SCHEME

While the project QP is overall responsible for technical compliance of fire safety requirements, the Registered Inspector (RI) is responsible for inspecting the fire safety works on site to see that the QP has not missed out anything. The Registered Inspectors (RI) Scheme was implemented to support the self-regulation system. The scheme allowed for professionals from the private sector who are highly competent in fire safety requirements to inspect and certify for the issuance of the Fire Safety Certificate (FSC).

The RI is required to verify that fire safety works are consistent with the fire code. They also carry out tests on the active fire fighting systems. The RI shall notify the Commissioner SCDF of any deviation or non-compliance with the Fire Code. Under the Fire Safety Act, it is mandatory for the building owner to engage Registered Inspectors to carry out the inspection of fire safety works upon completion of a project. After the RI has inspected and certified the fire safety works, the QP can then apply to SCDF for the FSC for the purpose of occupying the building. This new system enables SCDF to issue FSC within 3 days upon receipt of the application and thus benefiting building owners.

The RI scheme serves as a good safety net to the Self-regulation system of plan approval. As not all plans are subjected to thorough checks by our processing officers, there may be some QPs whose work may have escaped the audit system. However, with the RI checking every case upon completion of work, there is better assurance that things are well in place.

SCDF has in place a system to countercheck RI work, by carrying out random checks and instituting disciplinary actions against the offending RIs. Similar to the audit system of plans, SCDF conducts site inspection for 10% of the applications received. These audit inspections not only serve as a check on the fire safety compliance of the projects but also on the quality of work by the RIs.

RIs are registered with SCDF under the Fire Safety Act and the selection criteria are very stringent. To qualify as an RI, the person must be a QP with at least 10 years of experience in designing and inspecting fire safety works. The candidate has to undergo a selection process. His fire safety competency and past experience are assessed by our officers who have been dealing with the QPs. In addition, he is put through an interview panel. When selected, he has to undergo a familiarization course before he is conferred the status as an RI. To-date there is a total of 218 RIs.

To support the RI scheme, the RI Continuing Education Programme has been introduced to keep RIs updated on the latest fire safety requirements. The RI Code of Conduct governs the conduct as RIs and there is also an RI Inquiry System to investigate complaints against RIs for their poor performance of inspection duties and to recommend appropriate penalties. One important requirement an RI must strictly observe is that he must not have any financial or professional interest in the project that he undertakes. This is to maintain independency of the RI so that he can act impartially and exercise his judgment professionally.

5. FIRE SAFETY ENGINEER AND PEER REVIEWER

Generally, our buildings are designed based on fire safety requirements prescribed in the Fire Code. However, the prescriptive approach to fire safety design has its limitations. While it works well for the majority of our buildings, it becomes less so for unconventional design concepts and architectural forms. Increasingly, the use of performance-based fire safety design as an alternative to the prescriptive design is gaining popularity in several countries.

Performance-based provisions state the intent or performance requirements of fire safety, while leaving the means of achieving them to the Fire Safety Engineer (FSE). The FSE uses fire engineering principles and computer modeling tools to demonstrate that the performance requirements can be achieved. With the adoption of performance-based approach to fire safety design, innovative and unconventional designs are now possible.

In view of such developments, SCDF has introduced a performance-based regime in year 2004 as an alternative to the prescriptive approach. As fire safety engineering is a specialized field of study which involves the application of fire safety engineering principles and expert judgement of the effects of fire, only Fire Safety Engineers (FSEs), who are registered with the SCDF, are qualified to submit fire safety engineering plans to SCDF for approval.

There is a panel - called the Fire Safety Engineers Selection Panel – to assist the Commissioner to evaluate the suitability of applicants as FSEs. The panel conducts the interview on an annual basis and is chaired by the Director, Fire Safety and Shelter Department and comprises 2 other senior officers from the SCDF as well as appointed representatives from the professional institutions.

The applicant must generally possess relevant professional qualifications, i.e. at least a bachelor degree in fire safety engineering and has been practicing in this field for at least 5 years.

In addition to the fire safety engineers, the performance-based regime also requires a Peer Reviewer, i.e. another Fire Safety Engineer, to evaluate and assess the fire safety engineering plan put up by the FSE. The peer reviewer is expected to address the adequacy of the final solution and the methodology and calculations used in achieving the solution.

The introduction of a performance-based regime has certainly influenced the way individuals and organizations approach fire safety. While a fire engineering solution is not 100% fail-proof, there is a general consensus that fire safety in buildings has improved because of the increased awareness of fire safety across the building industry.

6. CONCLUSION

The self-regulation system has proven to be sustainable and by any yardstick, it is probably one of the most successful schemes implemented by SCDF in the administration and regulation of fire safety in buildings. The third party fire safety regulatory approach had indeed marked the beginning of greater recognition of industry involvement, partnership, responsibility, professionalism and competence in maintaining high fire safety consciousness. This framework has fostered greater interaction between practitioners and SCDF and enabled a higher level of service quality, effectiveness and efficiency being achieved for compliance of fire safety standards in buildings of Singapore.

The Self Regulatory System helps to facilitate earlier completion of buildings for occupation. Also because of the self-regulation scheme, our plans approving and inspection officers are now engaged in higher value-added work in the development of fire safety standards in Singapore. Working in close collaboration with the building industry and building professionals, SCDF is continually committed to making and enforcing rules appropriately without unnecessarily imposing on business costs nor compromising on safety standard.

APPLICATION OF MODELS FOR PERFORMANCE-BASED DESIGN

W.K. Chow[1], N.K. Fong[1], Edgar C.L. Pang[1], Fred K.W. Lau[1] and Kenny S.M. Kong[2]

[1]Areas of Strength : Fire Safety Engineering, Research Centre for Fire Engineering, Department of Building Services Engineering, The Hong Kong Polytechnic University
[2] DCL Consultants Limited, Hong Kong

ABSTRACT

Performance-based design for a designated project by following practices in Hong Kong is analyzed. The principal author and second author have served the government fire safety assessment committee since the fire engineering approach for passive protection on construction elements was implemented in 1998.

Keywords: Fire, performance-based design, evacuation, fire model, passive protection, active protection

1. INTRODUCTION

The objective of this case study is to undertake a performance-based fire safety analysis and design for a senior living facility. The performance-based fire safety analysis and design should meet the following fire and life safety goals as specified in the project brief:

- Safeguard occupants from injury due to fire until they reach a safe place.
- Safeguard fire fighters while performing rescue operations or attacking the fire.
- Avoid collapse of all or part of the structure in the event of a fire.

The project would be designed by following Hong Kong practices [1-4]. However, fire safety objectives for each type of buildings are not yet spelled out clearly. The objectives for fire service installations [4] are:

- Extinguishing, attacking, preventing or limiting a fire.
- Giving warning of a fire.
- Providing access to any premises or place for the purpose of extinguishing, attacking, preventing or limiting a fire.

The design principles for the proposed senior living accommodation [5] should include the following:

- Evacuation will not be conducted unless there is an imminent need.
- If necessary, phase evacuation will be executed.
- Since evacuation is not desired, in case of fire, the fire should be confined in the cubicle with appropriate fire rated door and building materials.
- All the cubicles on each floor will be divided into two portions with proper separations by a common lobby. In case of fire and if evacuation is necessary, patrons from the affected portion will be temporarily moved to the unaffected portion of the same floor for temporary stay and pending for rescue.
- Refuges floors at an interval of ten floors to be provided for temporary stay of the evacuees and rescuers in case of emergency.
- From the given layout plan, since there are two dead-ends on each floor, lobby approach is suggested at both ends in order to shorten the escape distance from each cubicle to the staircases.

For those projects having difficulties in complying with the prescriptive fire codes on passive fire safety designs [1-3] in Hong Kong, Fire Engineering Approach (FEA) [6,7] is accepted by the authority since 1998.

The fire safety objectives can be summarized as:

- Confine the fire in a cubicle.
- Separation by fire-resisting walls into different zones.
- Provide alternative exit routes.
- Provide sufficient fire service installations.

2. REGULATIONS IN HONG KONG

Fire regulations in Hong Kong were briefly summarized by Chow [8]. A summary is presented here:

The fire codes in Hong Kong are basically prescriptive following those developed decades ago in the UK with some slight modifications. Approval of fire safety designs and inspection of the buildings upon completion are held responsible by two government departments. The building design shall be submitted to the Buildings Department (BD) to check against all fire aspects for approval. The requirements and installation of fire protection systems are monitored by the Fire Services Department (FSD). A pictorial presentation of the application procedure is shown in Figure 1.

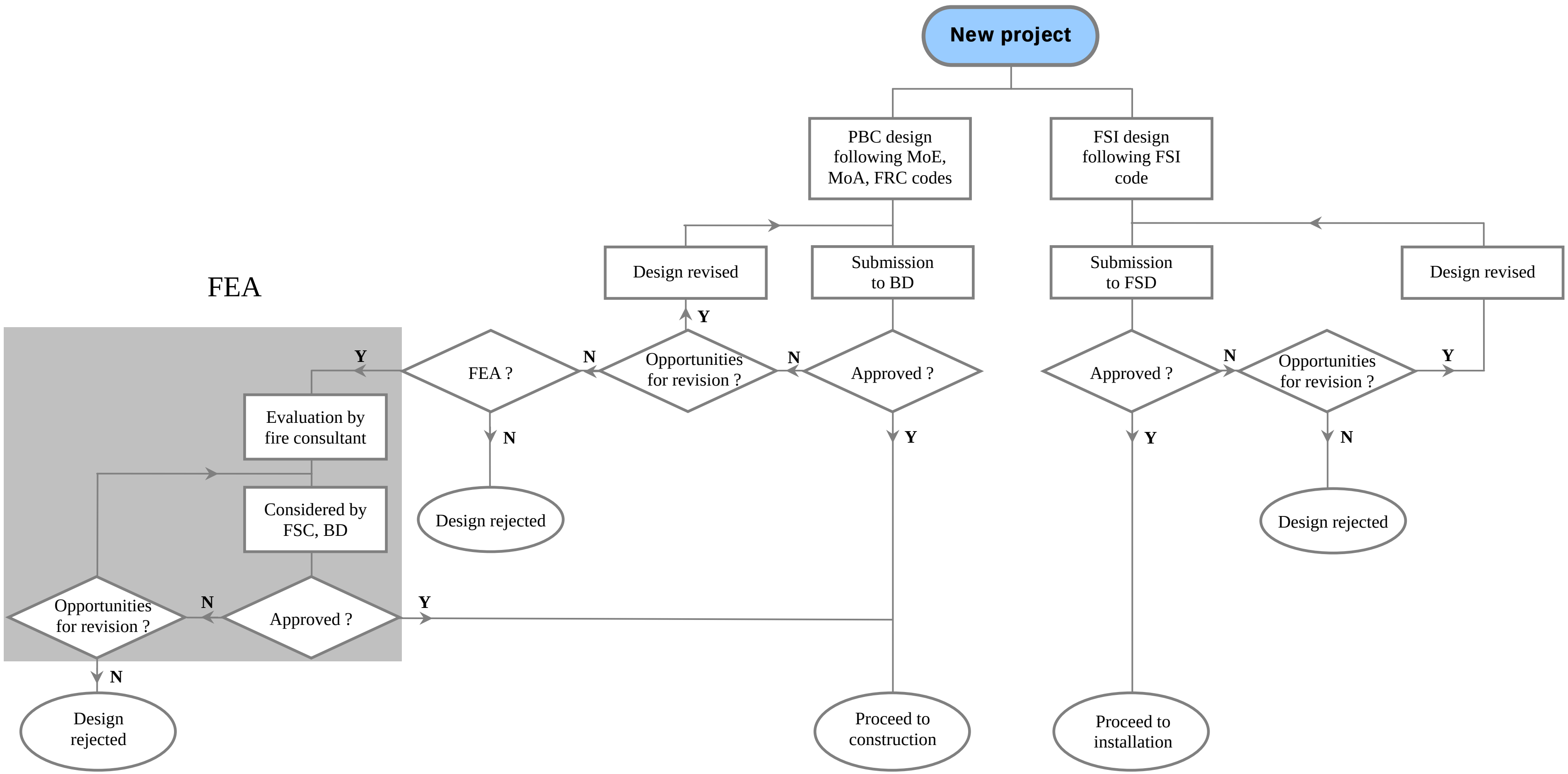


Figure 1: Process for Approving Fire Safety Designs

Codes on passive building construction [1-3] are Code of Practice for Fire Resisting Construction (FRC code), Code of Practice for Provisions of Means of Access for Firefighting and Rescue Purposes (MoA code) and Code of Practice for Provisions of Means of Escape in case of Fire and Allied Requirements (MoE code)

Code on active fire protection system or fire service installations (FSI) [4] is the Code of Practice for Minimum Fire Service Installations and Equipment and Inspection and Testing and Maintenance of Installations and Equipment (FSI code)

There is not yet Engineering Performance-Based Fire Code (EPBFC) in Hong Kong as implemented in places elsewhere. For those buildings having difficulties in complying with the prescriptive fire safety codes, FEA as shown in Figure 1 will be accepted by BD since 1998. Implementation of FEA will be discussed in the next section. FEA is similar to performance-based design (PBD). A Fire Safety Committee (FSC) was set up by BD in 1998 to consider fire safety designs with FEA when necessary. This committee is chaired by an Assistant Director. Members include a Chief Building Surveyor responsible for fire, other Chief Building Surveyors, Chief Structural Engineers, a representative officer from FSD, and two experts in fire engineering who are not government officers. There are not yet standard methods for assessing those designs. Approaches to PBD used overseas were applied. But in most of the submitted reports, the parts deviated from the prescriptive codes would be assessed. Non-compliance with FRC code for glazing walls in a double-skin façade is an example. In fact, application of the FEA for most projects is to demonstrate the equivalency to prescriptive codes.

3. ACTIVE PROTECTION SYSTEMS

Active protection systems or fire service installations (FSI) required are specified in the Code of Practice (COP) issued by the Fire Services Department (FSD) [4], known as the FSI code. The building in this project is regarded as a high-rise institutional building and the following are the units required as stated in the FSI code [4]. They are Audio/Visual Advisory Systems, Automatic Actuating Devices, Automatic Fixed Installations other than Water, Emergency Generators, Emergency Lighting, Exit Signs, Fire Alarm Systems, Fire Control Centre, Fire Detection Systems, Fire Hydrant/Hose Reel Systems, Fireman's Lifts, Portable Hand-operated Approved Appliances, Pressurization of Staircases, Sprinkler Systems, Ventilation/Air Conditioning Control Systems. Detailed information on this particular case are:

- Audio/Visual Advisory System - For audio alarm system, there should be a Public Address System to guide the staff and occupants how to react in emergency conditions besides the alarm bells. Visual alarm system involves flash lights which can warn occupants with hearing impairment.
- Automatic Actuating Devices - There are some installations involved like fire shutters, fire stop doors, fire dampers, fire curtains and smoke vents, etc. In this case, fire dampers would be required to install in the ventilation air ducts.
- Automatic Fixed Installations other than Water - It can be generally regarded as gaseous extinguishing systems such as carbon dioxide, nitrogen or clean agent heptafluoropropane FM200. Since there may be some oxygen containers for those requiring special medical care, it is necessary to provide this system to prevent any explosion of the container room.

- Emergency Generator - It is required to sustain the full load power for not less than 6 hours for all installations stated in this report.
- Emergency Lighting - This system is designed according to BS5266:Part 1 [9] except exit signs to provide sufficient illumination for evacuation within the building.
- Exit Signs - Some modification is made in applying BS 5266:Part 1 [9] in order to suit local situations while the directional signs would follow BS5499:Part 1. All signs are to help the occupants to escape in emergency.
- Fire Alarm System - Manual fire alarm system should follow BS5839:Part1 [10] with alarm gongs installed at all hose reel points and main exits of the premise for the people to notify others in the building. Visual fire alarm should conform to Clause 6-4 of NFPA 72 [11] which would also be actuated to inform the deaf.
- Fire Control Centre - A location placed at ground floor near the main entrances to house the equipments of fire service systems to be inspected and used by fire brigades for their ease to understand the situations of all installations and prepare for fire fighting and evacuation process.
- Fire Detection Systems - It is necessary to install heat or smoke detection devices throughout the building for early detection of any fire according to FOC Rules 12 [12].
- Fire Hydrant/Hose Reel Systems - Fire hydrant is designed with reference to BS5041:Part 1 [13] to equip fire brigades for fire fighting while hose reels are installed every 30 m to let the people have a hands-on means in fire control.
- Fireman’s Lifts - Based on the occupancy loading, fireman lifts would reach each floor. Firemen would use them to evacuate the people inside the building and arrive at their desired location to fight against the fire.
- Portable Hand-operated Approved Appliances - Various types of hand-operated fire extinguishers would be placed inside each plant room and every convenient location for them to carry out first-round fire fighting.
- Staircase Pressurization - Staircases are used as means of escape for the occupants and means of access for firemen. It is designed in accordance with BS5588:Part 4 with some amendments made to suit local situations. Pressurization can enhance the safety for the people using the staircases.
- Sprinkler Systems - Sprinkler system is designed with reference to Loss Prevention Council Rules for Automatic Sprinkler Installation and alternations are stated in FSD Circular Letter No. 2/94 [14].
- Ventilation/Air-Conditioning Control Systems - Air flow introduced by ventilation would help the spread of toxic gases and fire to other compartments. Also, air jet from the air-conditioning system would disturb the stability of the smoke layer and enhance the entrainment of ceiling jet. Therefore, the ventilation/air-conditioning would be cut-off partially or wholly subjected to the severity of fire.

4. MEANS OF ESCAPE AND MEANS OF ACCESS

The means of escape and means of access were illustrated in the given drawings. The layout was changed to include the lifts and escape routes for daily operation and emergency conditions as in Figure 2. There are four staircases (each 2 m wide structurally) with two for normal operation and two for emergency connecting to each floor, four lifts (two 2 x 2 m and two 4 x 2 m) and an escape ram for 2nd floor of width 3 m with a slope about 1:20. Such staircase design is to avoid dead-end effect of the corridor. The maximum number of residents is only 812 for the whole building. According to the local MoE code [1], the number of staircases, the width of each staircase and the total width of staircases comply with statutory requirement for the discharge rate of 1000 persons per floor. Normally, it is not the case to gather all of them on the same floor in daily operation. However, the travel distance of evacuation for most rooms is far longer than 30 m under this design. This does not comply with the local MoE code and will be discussed in a later section.

In order to provide evacuation design for occupants in the building in the case of fire, two design approaches to evacuation are reviewed. This included the use of traditional prescriptive approach as stipulated in the local code of practice and the use of fire engineering approach. From current review, it showed that there is a large variation of design parameters considerations when fire engineering approach is adopted.

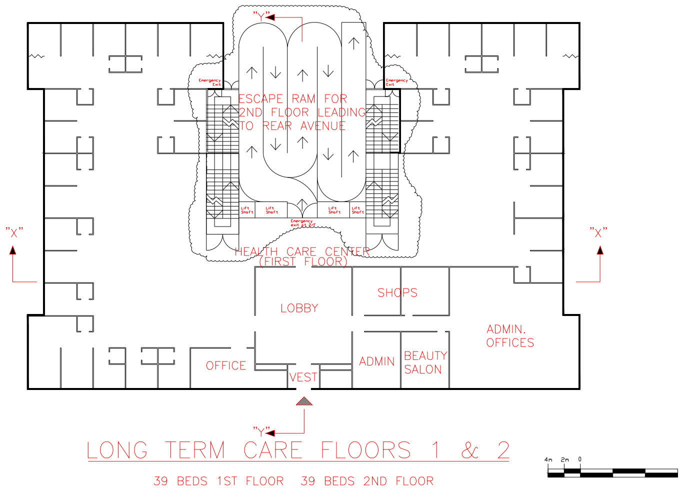


Figure 2: Long Term Care Floors 1 & 2

5. ADDITIONAL POINTS

Since the headroom is taller than 3 m, there is sufficient clearance to facilitate the smoke traps or smoke extraction system at high level. Calculation can be based on the largest fire load of the floor. The total fire load on each floor will be the total fire load of combustibles on the floor. For simplicity, each floor is assumed to be identical as the building is an elderly home. When considering the total fire load on each floor, the normal type of conbustibles as listed in Chapter 7 of the Code of Practice for Residential Care Homes [5] is assumed.

Each compartment should be fire rated in order to make some refuge area and the roof can be used as a refuge floor. Each floor will be partitioned into portions with lobby, common area and recess area such that it will be easier to carry out evacuation for the patrons within available resources and manpower. Total evacuation in such building will take a considerable time. If evacuation is absolutely necessary, evacuation by phase will be more appropriate. Like other types of buildings in Hong Kong, refuge floor for such building has to be provided. It is suggested preferably to be provided at intervals of every ten floors. Since management forms the core part of the performance-based design, therefore apart from ensuring the effectiveness of the passive and active fire protection systems, the routine management in the building is also very important. These include staff training on fire safety; regular fire talks and drills to the patrons; conduct joint exercises with local fire department and other local authorities; and limit the amount of combustibles on each floor. Combustibles such as polyurethane foam (PUF) mattresses and upholstery should comply with BS 7176 [15] and 7177 [16]. Only safe fuels, such as town gas, piped LPG system and electricity will be used. All these are shown in Figures 3 and 4.

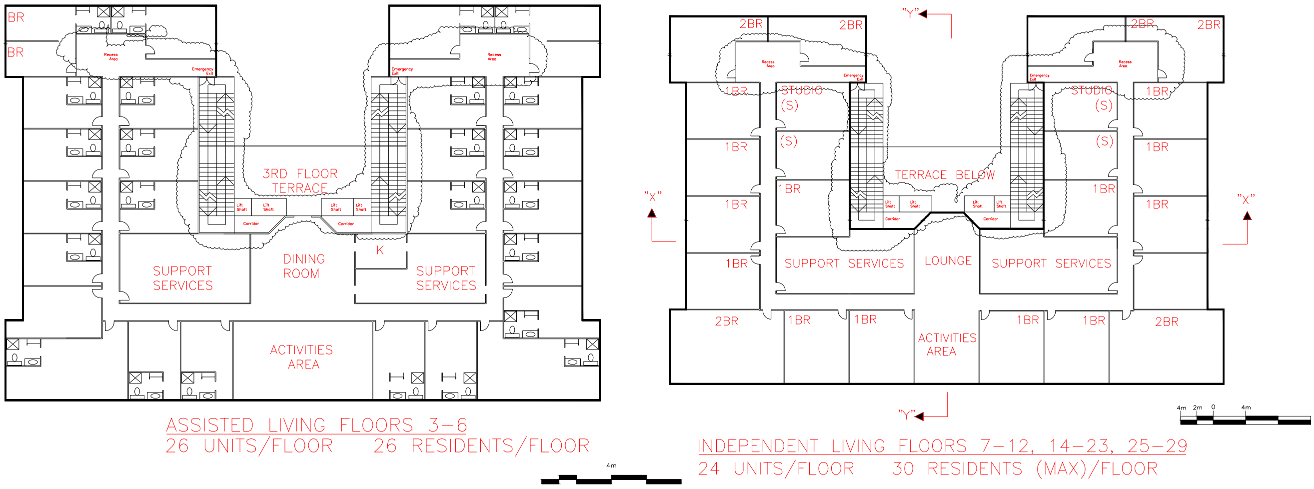


Figure 3: Modifications Suggested

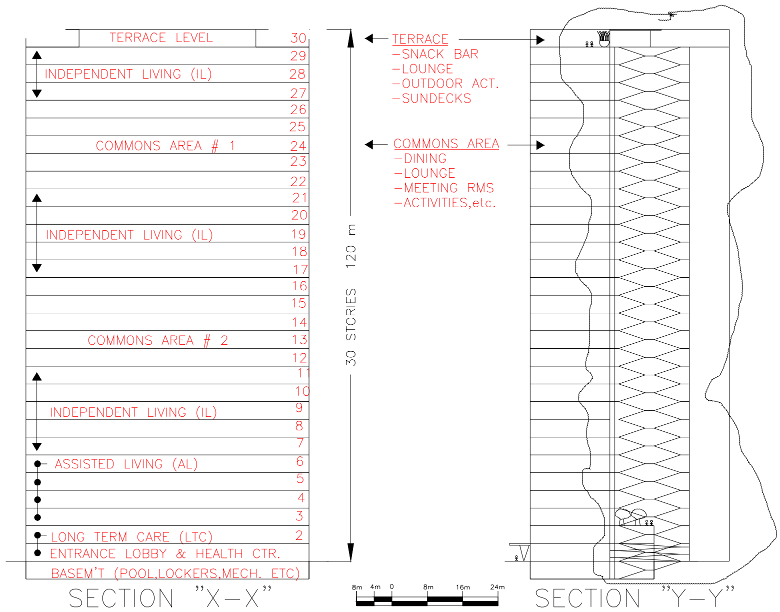


Figure 4: Evacuation

6. PERFORMANCE-BASED DESIGN

In Hong Kong, escape routes of a building can be designed based on prescriptive approach or fire engineering approach. With prescriptive approach, the designer or architect would follow the guidelines laid down in the codes of practice, practice notes for authorized persons, circular letters, etc. For most buildings in Hong Kong, the escape routes designs are still based on these codes of practice to obtain the "deem to satisfy" provision. The three codes of practices issued by the BD and one code of practice issued by the FSD have to be complied with in designing escape routes.

In following MoE code [1], prescribed figures are specified for the building designer to determine the occupant density of the building, number of staircases in both sprinklered and non-sprinklered buildings, discharge values, travel distance and staircase width, etc. As stated in this code of practice, the evacuation time for each storey to a protected area (e.g. the staircase leads to the exit) should be within a notional period of 2.5 minutes (150 s) for non-sprinklered buildings. While in the FRC code [3], the provisions for the protection of building and escape route using suitable non-combustible materials which possess a specified fire resistance period for different construction elements and resisting the action of fire are described. The integrity, stability and insulation requirements for the building elements are also stipulated. Designs following these codes of practice are presumed to provide sufficient protection to the occupants and the building in the case of fire. Under the prescriptive approach, designers or engineers will design the escape route based the requirements stated in the code of practice without questioning the actual performance of these escape routes and its interaction with the occupants and other building features.

However, for buildings with special features such as in this example, the escape route is not designed by following the requirements prescribed in the codes of practice. FEA has to be adopted in designing the escape route. Under the fire engineering approach, there are no standard figures for the design of escape route. A common practice is the time line approach to estimate the evacuation time of the building occupants. In such an approach, fire engineers will normally study the probable fire scenarios by reviewing the features, function of the building and the characteristics of the occupancy. The compliancy of active fire service installation design will also be checked against the existing code of practice. The fire engineers will then determine the design population and the proposed means of escape. The worst credible fire scenarios and fire location will be determined (have to convince the Authority later in presentation) by considering the function and operation of the building. After choosing the fire location for the study, a design fire size will be determined. The determination of a suitable design fire size always leads to vigorous arguments between relevant parties. Fire engineers will usually refer to the NFPA, CIBSE and journal papers for the rationale of design fire determination. Wind and stack effects affecting the fire development and smoke movement will also be considered. All factors concerned will be used as input parameters for fire and smoke spread calculation. The calculation may rely on empirical equations provided in the standard and design guides such as CIBSE TM19 or CIBSE Guide E [17]. Some engineers may prefer to use zone models such as CFAST [18] or field models such fire dynamics simulator (FDS) [19] to estimate the tenability conditions of the building in the case of fire. The untenable conditions might be determined by the smoke layer clear height, thermal radiation from fire and enclosure temperature. The time from ignition to the occurrence of untenable conditions will be estimated and taken to be the available safe egress time (ASET) for the building occupants. For example, from PD7974-6:2004 of BS7974 [20], the proposed tenability limits for smoke is Dm^{-1}=0.08 (visibility 10m). Other proposed tenability limits are $2.5kWm^{-2}$ for exposure to radiant heat, $115^{o}C$ for up to 5 minutes exposure to convected heat etc.

In estimating the evacuation time of the occupants, designers/engineers will first determine the ultimate place of safety. They will normally use empirical equations from the Handbook of Society of Fire Protection Engineers (SFPE) or evacuation software such as SIMULEX, STEPS and EXODUS [21,22,23] to calculate the total evacuation time (travelling time) of the occupants. Congested areas, dead-ends and extended travelling time of the occupants are identified. The difference between ASET and the required safe egress (escape) time (RSET) of the occupants will then be calculated. If the value of ASET is larger than the value of RSET, the escape route design will be considered as appropriate. One of the comprehensive documents available for providing a systematic approach to the calculation of escape time is BS7974:2002 [20]. The following formula is proposed in BS7974:2002 [20].

$$RSET = \Delta t_{det} + \Delta t_{alarm} + \left(\Delta t_{pre} + \Delta t_{trav}\right)$$

where Δt_{det} is the time from ignition to detection determined from engineering tools such as the empirical model by Alpert, Δt_{alarm} is the time from detection to a general alarm, Δt_{pre} is the pre-movement time (recognition time and response time) for the building occupants and Δt_{trav} is the travel time of the building occupants which is determined from the evacuation software such as SIMULEX and STEPS. After estimating RSET, the difference between ASET and RSET will be used as one of the acceptance criteria for the fire safety design. After the calculation, the results will be submitted to the BD and related authorities for discussion and approval. Based on the above formula, it is apparent that a great delay in initiating evacuation (i.e. large value of Δt_{pre}) would lead to a considerable vulnerability of the occupants. Behavioural response of the occupants is one of the important factors affecting the evacuation time in the case of a fire and would be dictated by their physical and psychological states at the time of fire awareness, e.g. whether they are asleep, just awake and not dressed, or dressed and awake, the severity of threat posed by the fire, the building design and the fire protection devices installed. The reaction of occupants after the perception of fire would be affected by their perception of the seriousness of the fire. Before egress, many people tend to take preservative actions, e.g. collecting important/valuable items. In estimating Δt_{pre}, the cognitive functioning ability of the occupants is very important. Some people would treat the audible fire alarm sound as a warning and wait for further information, e.g. notified by neighbour, clarified with management personnel via phone calls before starting to evacuate. Therefore, in using this fire engineering approach for escape route design, it is important to understand the behaviour of the occupants in the case of fire emergency such that Δt_{pre} can be determined and included in egress time calculations. However, the value of Δt_{pre} varied with considerable uncertainty and it is important to obtain accurate information of occupants. The determination of Δt_{pre} always leads to vigorous arguments between the designers/ engineers and the authority. Physical conditions, occupant distribution, gender, age, etc. are very important input parameters for the estimation of Δt_{trav}. However, in the existing fire engineering approach design, no universal guideline was developed in the determination of these input parameters This again leads to arguments between the designers/engineers and the approving authority.

7. EVACUATION SIMULATION

In order to estimate the ASET, computer software such as the Fire Dynamics Simulator (FDS) is used to simulate the fire environments of different fire scenarios. In current example, a simplified floor 1 layout is used for estimation of the fire scenarios. 144 x 80 x 20 grid cells are used to perform the calculation. A fire size of 4 MW is used in each of the simulations. All the cubicles are assumed open. To estimate the RSET, floor 1 with a 2 m exit is considered in the simulation by Simulex. The total number of occupants on floor 1 is 39. The simulation setup is shown in Figure 5. In the simulation, the response time of the occupants is based on random distribution with mean value equal to 1 min/s. Two occupant types are considered: office staff and the elderly. For the office staff, the total evacuation time is 46 s. For the elderly, the total evacuation time is 63 s. This shows that by changing simply the occupant type, the simulated evacuation time is doubled. The evacuation pattern is shown in Figure 6 which illustrated the time required for the occupants to pass through the exit on floor 1 and the smoke propagation patterns are shown in Figure 7. The values are less than the MoE code specification of 150 s. Although the travel distance is longer than the specified value, the evacuation time can still be satisfied. However, based on the results of the fire simulation, it is found that the location of the fire source would provide a significant difference in the estimation. The main exit is affected by smoke within a very short period. Therefore, it is suggested to provide additional exits for the building. From this study, it shows that the calculations of RSET and ASET of a performance based design are affected by input data of evacuation model and fire model factors such as occupant type, travel speed, fire size, fire location etc. Therefore, care must be taken when fire model and evacuation model are applied to do a performance design.

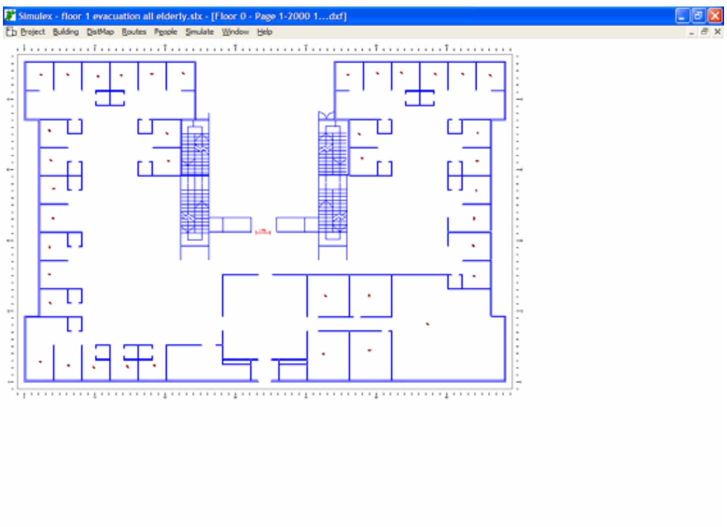


Figure 5: Layout and Occupant Distribution on Floor 1

Figure 6: Figure Evacuation Time Estimation for Floor 1
with a Single Exit (2 m Wide) Using Simulex

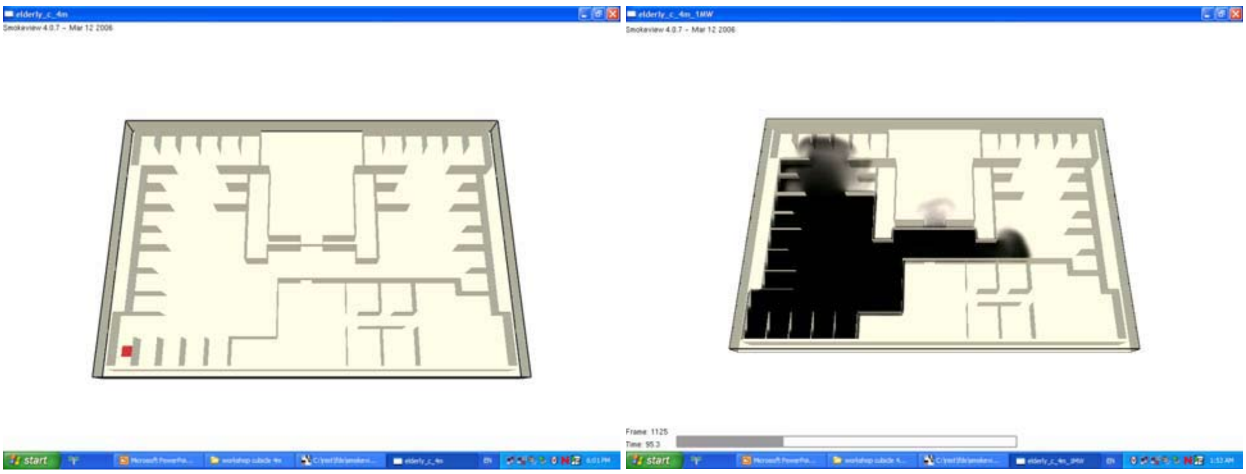


Figure 7 (a): Smoke Propagation Pattern from 1MW Fire

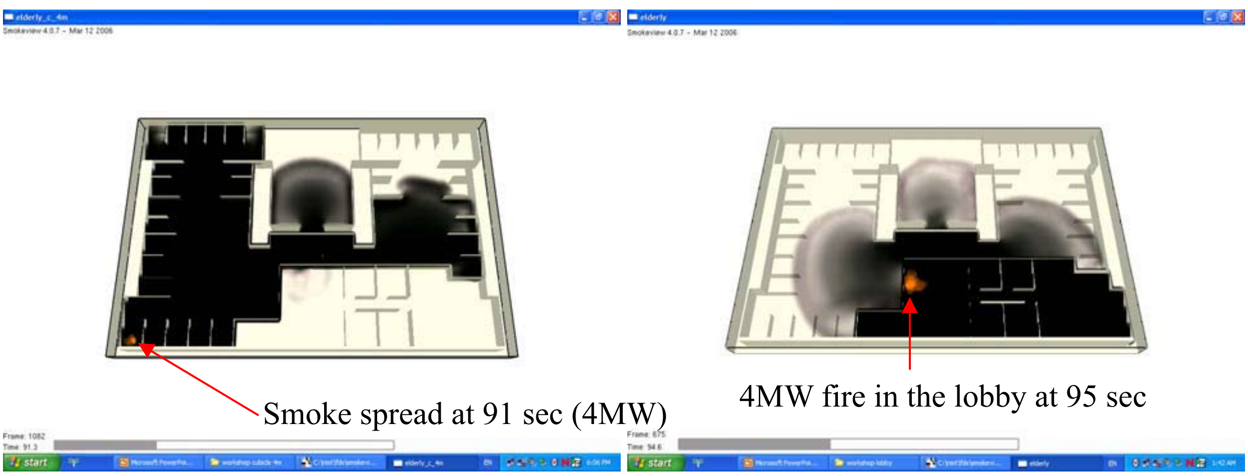


Figure 7 (b): Smoke Propagation Pattern from 4MW Fire

8. CONCLUSION

In this study, it shows that there are a lot of factors affecting the results of the fire engineering approach / performance based fire design especially in the application of fire model and evacuation model. Therefore, it is important for the designers to consider the following points when fire model and evacuation model are applied. They are:

- Checking the completeness of technical documentation;
- Checking the scientific ground by independent experts;
- Source code checking by independent experts;
- Analytical solution comparison;
- Benchmark fire code comparison;
- Grid size and time step refinement exercise;
- Monitoring the residual error of governing equations;
- Validation with experimental results.

REFERENCES

1. Codes of Practice for the Provision of Means of Escape in Case of Fire, Buildings Department, Hong Kong, 1996
2. Code of Practice for the Provision of Means of Access for Firefighting and Rescue Purposes, Buildings Department, Hong Kong, 1996.
3. Code of Practice for Fire Resisting Construction, Buildings Department, Hong Kong, 1996.
4. Codes of Practice for Minimum Fire Service Installations and Equipment and Inspection, Testing and Maintenance and Equipment, Fire Services Department, Hong Kong Special Administrative Region, 1998.
5. Codes of Practice for Residential Care Homes for Persons with Disabilities, Social Welfare Department, Hong Kong Special Administrative Region, March 2002.
6. Practice Note for Authorized Persons and Registered Structural Engineers: Guide to Fire Engineering Approach, Guide BD GP/BREG/P/36, Buildings Department, Hong Kong Special Administrative Region, March 1998.
7. Chow, W.K., Fire Safety in Green or Sustainable Buildings: Application of the Fire Engineering Approach in Hong Kong, Architectural Science Review, Vol. 46, No. 3, pp. 297-303, 2003.
8. Chow, W.K., Fire Engineering Approach and Discussion on the Design Fire, 6th International Conference on Performance-Based Codes on Fire Safety Design Methods, June 14-16, Tokyo, Japan – Accepted to present, January 2006.
9. BS 5266-1, 2005, Emergency Lighting Part 1: Code of Practice for the Emergency Lighting of Premises-Supersedes CP 1007:1955.
10. BS 5839-1, 2002, Fire Detection and Fire Alarm Systems for Buildings Part 1: Code of Practice for System Design, Installation, Commissioning and Maintenance-AMD 15447: December 16, 2004.
11. NFPA 72, National Fire Alarm Code®, 2002, National Fire Protection Association, USA.
12. FOC Rules 12, Rules of the Fire Offices' Committee and Fire, Offices’ Committee of Ireland for Automatic fire, Alarm Installations for the Protection of Property, 12 edition, February, 1985.

13. BS 5041, Part 1, 1987, Fire Hydrant System Equipment Part 1: Landing valves for wet risers (AMD 5912), September 30, 1988-Amd 1.
14. FSD Cicular, Fire Services Department Circular Letter No. 2/94, Letter No.2/94 Rules for Automatic Sprinkler Installations, September 16, 1994.
15. BS 7176, 1995, Specification for resistance to ignition of upholstered furniture for non-domestic seating by testing composites-AMD 14587: October 17, 2003.
16. BS 7177, 1996, Specification for resistance to ignition of mattresses, divans and bed bases-AMD 14586: October 17, 2003.
17. CIBSE Guide E 1997: Fire Engineering, The Chartered Institution of Building Services Engineers, London, UK, 1997.
18. Jones, W.W.; Peacock, R. D.; Forney, G. P.; Reneke, P.A., CFAST-Consolidated Model of Fire Growth and Smoke Transport (version 6) Technical Reference Guide, NIST, December, 2005.
19. McGrattan, K.B. et al, Fire Dynamics Simulator (version 4) Technical Reference Guide, NIST Special publication 1018, NIST, March 2006.
20. BS 7974: 2001 Application of Fire Safety Engineering Principles to the Design of Buildings - Code of Practice, British Standards Institute, UK.
21. Owen et al., The Exodus Evacuation Model Applied to Building Evacuation Scenarios, Journal of Fire Protection Engineering, Vol. 8, No. 2, pp. 65-84, 1996.
22. Spearpoint M., The Effect of Pre-evacuation on Evacuation Times in the Simulex Model, Journal of Fire Protection Engineering, 14:1, pp.33-53, 2004.
23. Nilsson et al, Validation of egress models – Simulation of Cinema Theatre Evacuations with Simulex, STEPS and buildingEXODUS, 9th IAFSS Symposium, Karlsruhe, Germany, 2008.

IDENTIFICATION OF RISK OF INTERACTION AMONG UNDERGROUND UTILITY INFRASTRUCTURES FOR EFFECTIVE FIRE ENGINEERING PRECAUTIONARY MEASURES

Simon Ngo

The Hong Kong & China Gas Company Limited

ABSTRACT

Hong Kong is a small but densely populated and highly developed metropolitan city. On its some 1100 square kilometres of land, there are over 7 million people. Hong Kong is hilly thus lands are precious and the majority of the road infrastructures are built with narrow footpath. Due to the customer density, utility services are usually of relatively larger sizes and they all go underground competing for space mostly in the narrow strip of footpath. Under the ground in its some 2000 km of road infrastructures, it is quite common that various kinds of utility services cluster together. The situation has been further aggravated since 1995 after the government liberalized the telecommunication market. It started a new era as all of a sudden the number of Fixed Telecommunication Network Service (FTNS) providers, who are allowed to dig and lay telecommunication utilities in the roads, was dramatically increased from one to 10. The problem of underground congestion, which is difficult to be appreciated by the general public who walk above it, is perhaps one of the toughest of its kinds in the world. Utility undertakings not only need to resolve conflicts during the construction stage, but also have to face the challenges of domino effects in case any of the utility infrastructures ages, deteriorates or be damaged in future. This paper reviews these likely interactions and how the utility undertakings work together to minimize the adverse effect. Through the lessons learned from the previous incidents in the past few years, the paper diagnoses some of the key problems including excavation damage to existing utilities and manhole explosions and explores how these problems could be resolved or mitigated with the joint collaboration of all stakeholders. It demonstrates that the success in solving these problems among the utility infrastructures requires mutual appreciation, early vision, cooperation, joint effort and a genuine willingness to seek a solution.

Keywords : Utility, underground, damage, manhole, explosion, duct, sealing, safety, risk

1. BACKGROUND

Hong Kong is a small city with a total area of slightly more than 1100 square kilometers, but in this small piece of land there are some 7 million people living on it. On this humble 1100 square kilometers of land, the population is mainly concentrated in urban areas in Hong Kong Island, Kowloon Peninsula and the satellite towns in the New territories developed in the recent decades. The congestion in these built up areas is perhaps one of the highest in the world. In the past three decades, Hong Kong has gone through a rapid transformation from a developing port to a world-renowned metropolitan city and financial centre. The rapid economic growth has brought a great improvement to the quality of living of its people. To keep up with this fast pace of development, there has also been a tremendous growth in underground utility infrastructures. The expansion of essential underground services, in number and in size, has been unprecedented in recent years and utility operators often find themselves competing with each other for space to accommodate new facilities in already narrow and congested footpaths. Table 1 gives a brief account on how rapid the underground congestion grows in the past two decades. Underground utilities have become more and more congested. The public risk is increasing due to potential external damage to the utilities and the interaction among them, and the risk has become more and more eminent.

Table 1 : Rapid Growth of Underground Utilities in the Past Two Decades

Year	1984	2007
Population	5.4M	6.95M (+29%)
Permanent Quarters	1.5M	2.5M (+67%)
Length of Roads	1,279km	2009km (+57%)
Electricity Consumption	56,829TJ	161,598TJ (+184%)
Gas Consumption	6,907TJ	27,041TJ (+292%)
Internet Cyber Traffic Volume	None	2,573,219Tb
U/G Utility Undertakings	8	17 (+143%)

2. THE IMMEDIATE RISK CAUSED BY DAMAGE TO UNDERGROUND UTILITIES

It is natural to appreciate that in such a congested underground environment coupled with the extremely active roadwork activities in Hong Kong, damage to underground utilities have always been one of the major risks. Among these damages, the major concern is always with those on the two energized utilities – gas pipes and power cables. Figure 1 gives the statistics of these damages in the past two decades. One will be surprised to see that all these damages have been reduced dramatically in the recent years. There are a number of contributing factors for this tremendous success, viz.:

2.1 Legislation Provides a Deterrent Effect Against Negligent Damage

One of the key success factors was the government's determination to criminalize negligent damage to underground gas pipes and electricity cables. The enactment of the corresponding ordinances has brought a tremendous difference to the situation. The idea of the government was stemmed from the successful experience in places like Singapore. The legislation in the gas sector started off a bit earlier. In 1996, after a long period of consultation, the Regulations for works in the vicinity of gas pipes was enacted, and a

Code of Practice was issued as guidelines on the safety measures required under the Regulations. The essence of the regulations lies in two principal requirements. Firstly, a party who carries out works in the vicinity of a gas pipe must carry our reasonable steps to identify the locations of the gas pipe, and secondly it must take all measures to prevent damage to the gas pipe in the course of its work. Contravention of the ordinance would be subjected to prosecution leading to different levels of fine and, in the very serious negligent cases, imprisonment. The Electricity Supply Lines (Protection) Regulations, prescribing similar requirements, were enacted four years later in 2000. These new regulations have posed significant deterrent effect to negligent work. Though these legislations could only be part of the reasons for the success, the impact from them was overwhelming. By comparing the current number of damages for both gas and electricity with those before the legislation, a dramatic reduction of some 90% has been realized (Figure 1).

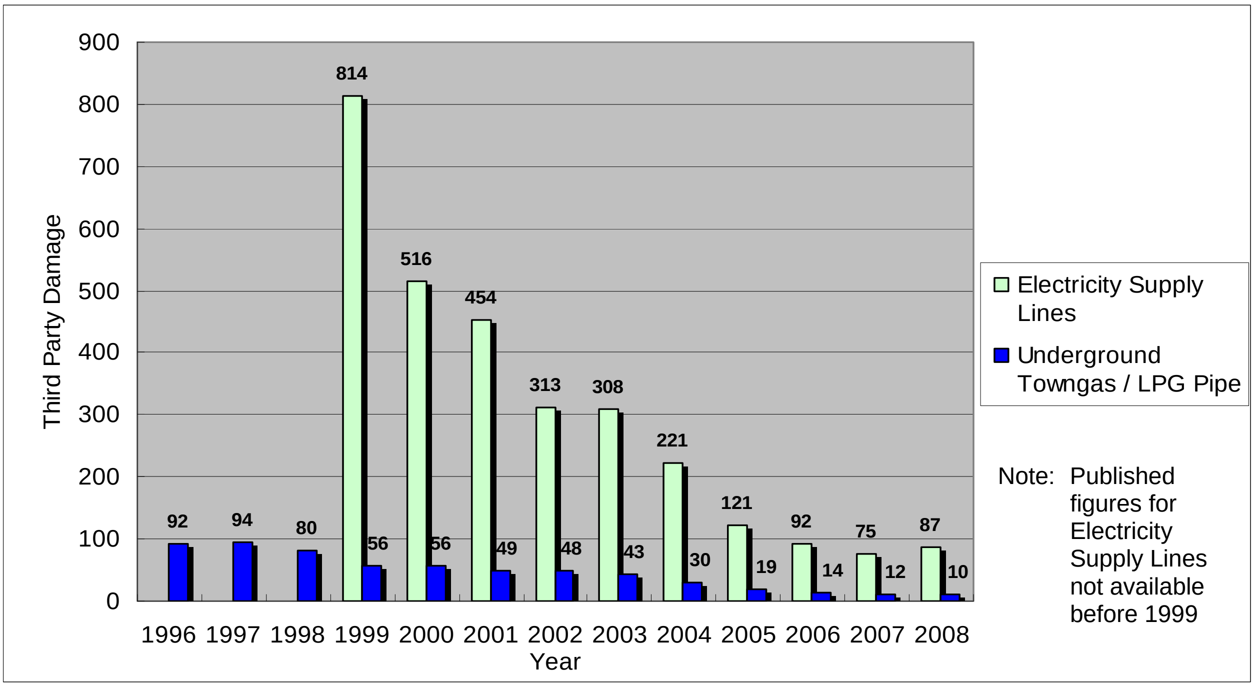


Figure 1: Statistics of Third Party Electricity Supply Lines / Underground Gas Pipe Damage Incidents (Ref. 6)

2.2 Enhancement of the Surveillance Measures

While it is indisputable that criminalizing the negligent acts is one of the major contributing factors for the success in reduction of damage to underground gas pipes and power cables, the contribution of the utilities owners, viz. the gas company and the two power companies also played a significant role in the success. Manpower and resources were increased to cope with the more stringent inspection requirements. New and more effective protection means were employed. New inventions for more accurate location of underground facilities were utilized, such as the 3M pipeline markers which enable the alignment of a buried service to be easily located by a detector responding to a radio frequency designated to the type of utility. The gas companies, in particular, even initiated to carry our in-situ pipeline alignment detection for the road work parties prior to their excavation.

2.3 Better Communication

It takes two to tango. The improvement of the gas company and the power companies' communication with the roadwork parties in Hong Kong has also contributed far-reaching positive effect in the damage reduction campaign. Through cooperation with the Electrical and Mechanical Services Department, the Construction Industry and other institutes, the companies have conducted numerous training sessions for the management as well as fore-front workers of roadwork companies. Other effective means of communication include safety posters, booklets and training videos. A system was also established in Highways' computerized Utilities Management System (UMS) to enable any roadwork to be commenced in two days time be captured at the utility companies' desk-top so that they could dispatch their inspectors to site to coordinate for the safety measures at the most appropriate time. The statistics of the damages to underground facilities, including those culprits who repeatedly caused damages, are also discussed in the Joint Utilities Policy Group (JUPG) and utilities technical Liaison Committee (UTLC) which comprises all the utilities and major government departments involved in roadwork and meet quarterly to review policy and technical issues (see Figure 2 – sample of the table of damages discussed in the Joint Utilities Policy Group (JUPG) meeting)

UNDISPUTED damage caused by contractors of	No. of cases of damage to utility services of														Total no. of damage cases in January 2009	Total no. of damage cases in December 2008
	CLP	DSD	HEC	HGC	HKBN	HKC	HKCG	HKCN	HyD/Ltg	NWT	PCCW	Towngas Telecom	WSD	WT&T		
CLP	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	(0)
DSD	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	(0)
HEC	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1	(0)
HGC	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	(0)
HKBN	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	(0)
HKC	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	(0)
HKCG	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	(0)
HKCN	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	(0)
HyD	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	(2)
NWT	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	(0)
PCCW	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	(0)
TowngasTelecom	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	(0)
Tramways	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	(0)
WSD	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1	(4)
WT&T	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	(0)
Sub-total of the above	1	0	2	0	0	0	0	0	0	0	0	0	0	0	3	(6)
ArchSD	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	(2)
CEDD (incl. CED & TDD)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	(0)
District Lands Office	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	(0)
Home Affairs Dept.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	(0)
HD	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	(0)
KCRC	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	(0)
MTRC	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	(0)
Transport Dept.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	(0)
Urban Renewal Authority	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	(0)
Other companies or corporations	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	(3)
Responsible party not identifiable	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	(0)
Total no. of damage cases	1	0	2	1	0	0	0	0	0	0	0	0	2	0	6	(11)

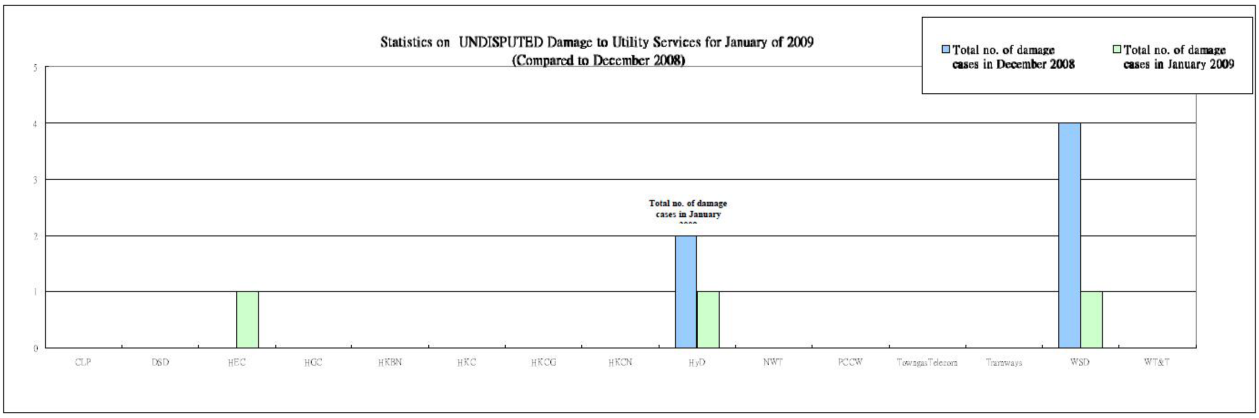


Figure 2: Sample of Summary Table of Damages discussed in JUPG meeting

3. THE POSSIBLE UNAWARE TIME BOMB

While the effort to reduce third party damage has yielded encouraging results in the recent years, there are great concerns on those unaware damages. These damages are not noticed because they are superficial only thus do not create immediate gas leak, power cable blast/trip or water main burst, but all these could come at last when the superficial damages deteriorate to the failure stage. Damage may also cause breakage on low-energy services, typically sewage ducts and telecommunication ducts. Though these damages may not be too harmful by its immediate nature, the consequential effect due to the interaction with the utilities in close vicinity could be dreadful to imagine. Just imagine the situation of a metallic gas or water pipe with its coating damaged in close proximity to a broken sewer pipe. The coating damage rendered the metallic pipe to lose its corrosion resistance; the highly corrosive sewage flowing out from the sewer could then attack the unprotected metallic pipe and cause accelerated corrosion which eventually lead to leakage/breakage within a unpredictable short period of time. The high pressure water jet resulted from the ultimate leak of the water main would cause damage on the adjacent cables and gas pipes, and the gas pipe when leak would result in gas ingress into the sewer system through the broken holes already there, so on and so forth. The congested underground environment in Hong Kong just provides a condition to make this kind of mishap highly probable, and it represents a silent time bomb if the stakeholders do not devote their joint effort to minimize the risk.

4. MANHOLE EXPLOSION, ONE OF THE MAJOR RISKS REVEALED IN RECENT YEARS

In the past few years, there were several serious manhole explosion incidents in Hong Kong. In one of the most serious cased happened at Tai Po Road, Shatin in 2004, the covers of 14 manholes along a one-kilometre-long road strip were blasted up. It was so fortunate that and there was nobody injured, mainly because the multi-manhole explosion occurred in a rather rural road, but if the same mishap happened in a busy district, the outcome would be dreadful to imagine. The blasting up of manhole covers, some weighing over 50 kg, can obviously lead to serious injury, or even fatality, though fortunately the latter has not actually happened in the territory. Nevertheless, this possibility has given rise to serious concern – and quite rightly so.

The increase of potential risk is not only attributable to over-congestion of the underground environment, where damage or unintentional interaction is possible, but also to the liberalization of the telecommunication market, dating back as far as 1995. This latter policy created an overwhelming transformation to underground works as all of a sudden the number of telecom operators licensed to install facilities in the street increased from one to about ten. The result has been the introduction of numerous telecommunication manholes and, with this, a large increase in the chance of manhole explosions.

In the past, there were many manhole explosion incidents involving telecommunication manholes (Figure 3 – Statistics of Manhole Incidents in Hong Kong since 2003). The liberalization has brought immense financial benefits to society, but it has also created an underground environment that is getting ever more overcrowded. This is partly due to the installation of reserved ducts connecting manholes so telecommunication companies have the means to facilitate future operations and development, and thereby maintain market competitiveness. However, this makes not only difficulties for daily maintenance but also complications for future construction by other utilities.

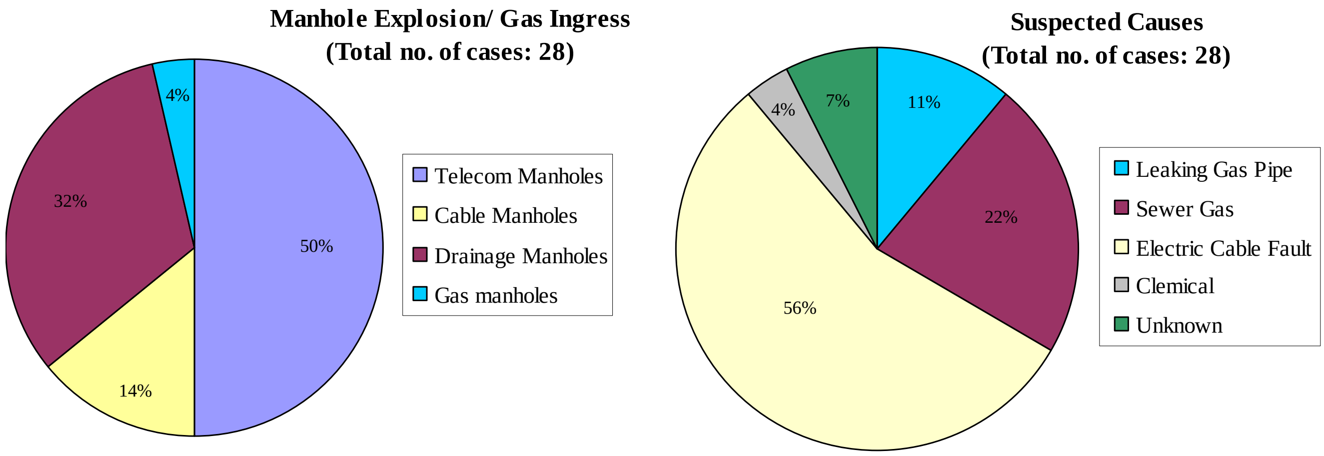


Figure 3: Statistics of Manhole Incidents in Hong Kong since 2003
(Source of information from media report)

Responsible public utilities always endeavour to ensure the integrity of their facilities during construction but subsequent third party excavations around the same locations can, and do, occasionally damage PVC ducts running between manholes leaving cracks and holes on the duct wall. Gas pipes, cables, water pipes or other facilities in the vicinity can also be damaged. All this is beyond the control of the owners of the utilities who are often unaware that their non-energized or non-pressurised facilities or pipe coatings may have been damaged in some way. The reason this often goes unreported is because there is no immediate impact to public safety. Nevertheless, in the long term, impairment of any description – however small or large - could create a safety hazard involving surrounding underground utilities.

4.1. Some Major Factors Causing Manhole Explosions

If an excavator accidentally damages underground telecommunication PVC ducts leaving broken cracks and holes, and at the same time also damages a gas pipe leading to a gas leakage, flammable gas could enter the telecommunication system and accumulate inside manholes through the broken PVC ducts. An explosion could occur if there happens to be an ignition source. The longer the leaking gas has to spread around, the greater the accumulation of gas and the stronger the explosion and higher the chance of having multi-manhole blasts.

There are also other underground sources that could generate combustible gases such as naturally occurring methane, landfill gas, illegally deposited petroleum products, LPG and so on. In addition, research undertaken in the USA has shown that explosive gas and smoke may originate from faulty underground power supply cables. Papers in the Institution of Electrical & Electronic Engineers (IEEE) transactions also point out that combustible gases, such as H_2, CH_2, C_2H_2, C_2H_6, can be created if faulty cable sheaths decompose under anaerobic pyrolysis at high temperature. If any of these gases entered telecommunication manholes through broken telecom ducts that could also lead to the risk of manhole explosions.

5. REDUCTION OF MANHOLE EXPLOSION RISK – MUTUAL EFFORT FROM ALL PARTIES

The only way to completely avoid such risks is for public utilities, roadwork contractors and government departments to mutually co-operate and work towards eliminating situations that may give rise to blasts. Public utilities should put prime emphasis on the design, operation and maintenance of their facilities to prevent leakage from their assets; roadwork contractors should actively minimize disturbance to underground facilities; whilst government should seek to improve over congested underground situations.

Given this kind of effort needs time, commitment and willingness from all parties, it is bound to be an ideal, long-term solution. Therefore, for the present, more practical, faster methods are required to alleviate the risk of manhole explosions.

Underground manholes are effectively confined spaces with the potential to burst open if a flammable mixture accumulates inside. The larger the manhole volume, the greater the blast effect. To prevent this, ingress of gas should be stopped by sealing duct entries connecting into the manholes. This is the simplest and most cost-effective solution to avert any risks.

It is true that some ducts leading into manholes, such as drainage and sewer pipes, cannot be sealed, but as these contain running water, damage is easily identifiable from water leakage. Besides, ingress of any flammable gas into water or pressurized systems is rather difficult. In contrast, ducts feeding into electricity and telecom manholes are used for installing cables and thus roadwork damage is not easy to detect (Figure 4). If these duct entries were sealed, the risk of manhole explosions would be significantly reduced.

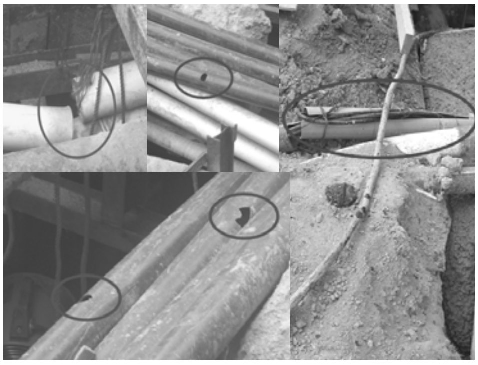


Figure 4: Typical cracks or holes in PVC ducts caused by roadwork which provide passage for the ingress of gas into manholes

There are two kinds of ducts on site. One is a reserved duct with no cables inside and the other is a duct with cables present. To seal reserved ducts, a simple few-dollar-worth duct plug (Figure 5) and appropriate sealing material would achieve gas tightness. To seal duct cavities containing cables, expansion foam (Figure 6) could be applied. These sealing materials can easily be removed and have only minimal effect on the daily maintenance of manholes, but the chance of gas ingress and the risk of explosion could be substantially reduced.

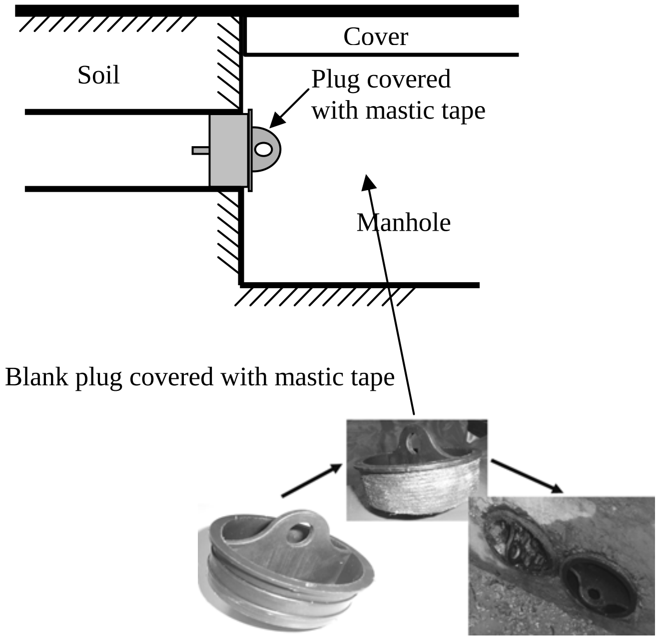


Figure 5: Gas Ingress can be Effectively Prevented by Sealing with a Few-dollar-worth Plug

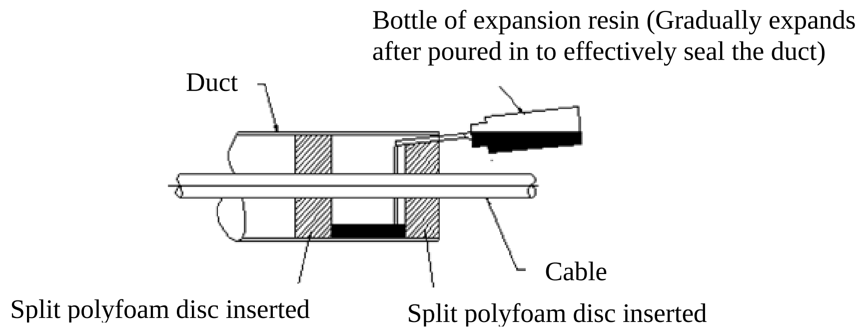


Figure 6: Duct Inserted with Cables can be Sealed with a Small Quantity of Economic and Effective Expansion Resin

5.1 Trade Practice and Regulatory Requirement

There are no regulations at present covering the safe design of manholes against explosions, nor is any designated government authority responsible for such action. The closest mandate at present is the Office of the Telecommunications Authority (OFTA)'s requirement to seal duct entries into buildings to prevent gas and water ingress. In contrast, in mainland China, duct sealing inside manholes is already part of telecommunication industry standards (GB50373 and GB50374).

5.2 Highways Department's Consultancy Report

The Highways Department hired a consultant in 2005 to conduct a detailed study on the risk of manhole explosions in Hong Kong. Their report published in 2006 recommended sealing duct entries, whether cabled or unoccupied, inside all newly constructed telecommunication manholes. It was also suggested that all the utilities which own manholes should carry out a risk assessment of their existing structures according to methods specified in the consultancy document such as duct sealing, filling to reduce volume, or tethering the manhole cover with a chain. It was encouraging to see that since the publication of Highways' report, many utilities undertakings, including Towngas, CLP, Hongkong Electric, concerned government departments and some telecom operators, have reacted positively to the recommendations with risk assessment conducted and retrospective measures applied to at least to their relatively risky manholes. Highways, for instance, has targeted to complete the retrospective measures for their 90,000+ traffic signal cable manholes in 2009. However, there are still some utility companies that still remain reluctant to implement these basic suggestions, presumably because these are not legally mandatory.

6. CONCLUSION AND WAY FORWARD

Hong Kong is a unique city in terms of the congested underground utilities condition. The damage to the underground utility infrastructures and the subsequent interaction among them pose a significantly risk to the general public. We have learned from the past how the stakeholders jointly worked together to successfully reduce the number of third party damage. Unnoticed and unreported damage, which does not pose an immediate in-situ risk, could possibly create a time bomb in the road infrastructure. Manhole explosion occurred in the recent years has raised an alarm to all concerned. Duct sealing is a simple, straightforward and effective measure to prevent gas ingress into manholes hence eliminate the chance of subsequent ignition and detonation. Duct sealing is already a trade practice in the construction industry for facilities entering into buildings. OFTA and certain government departments also require telecom ducts entering buildings to be sealed. The same standards of safety however are not yet applicable to street manholes. As of this moment, some public utilities do seal their own duct entries inside manholes whilst the Highways Department has issued a consultancy study recommending such measures. The national government has also made duct sealing mandatory. Therefore, there seems no reason why the HKSAR government and all public utilities should not decisively promote the adoption of the sealing of duct entries inside new as well as existing manholes in order to better safeguard the public from potential manhole explosions. It's already an effective Fire Engineering precautionary measures to prevent gas ingress into buildings thus should be considered to extend to the utility and road infrastructures in this new era to enhance public safety under the unique congested environment of Hong Kong. With the lessons learned from the successful story of third party damage reduction, it is believed that the risk could be eliminated or at least substantially minimized with the joint effort of the stakeholders.

REFERENCES

[1] Abdolall Khaled, Buchholz Vern L., Cartlidge Dennis M., Morton Christopher P., Armanini Gary B., Harris Alan and Valli Gino F., B.C. Hydro 15kV Cable Explosion, IEEE Transactions on Power Delivery, Vol. 17, No. 2, 2002.

[2] Harris Bob and Tonen John, Underground Congestion, IGEM Journal, Vol. 44, No. 7, 2004.

[3] Ngo Simon, The Risk of Flying Manhole Covers. Asia Pacific Risk Management and Safety Conference, 2005.

[4] Ngo Simon, Flying Manhole Covers – Their Causes and Preventive Measure. Conference on Utility Safety and Management 2007.

[5] Walsh Bryan P. and Black W.Z., Thermodynamic and Mechanical Analysis of Gas Explosions in Underground Vaults, IEEE Transactions on Power Delivery, vol. 17, no. 1, 8-12, 2002.

[6] Wong Chris KP and Wong Simon Y.K., Protection of Underground Electricity Supply Lines and Gas Pipes in Hong Kong, The First International Conference on Utility Management and Safety, ICUMAS 2009

[7] Connell Mott, Prevention of Gas Explosion in Utility Manhole (Consultancy Report of Highways Department), 2006.

AECOM


Wanchai Development Phase 2, Hong Kong


Saadiyat Island, Abu Dhabi

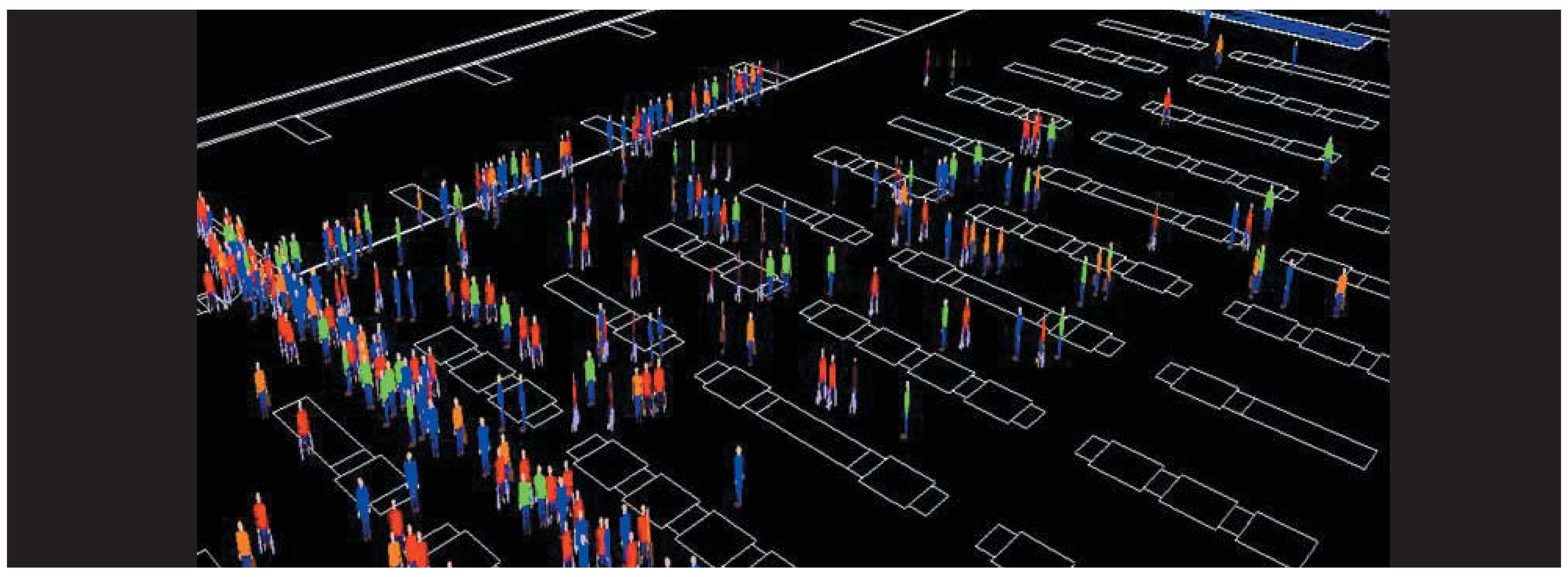
AECOM 's Fire Engineering Team, possesses strong skills and extensive experiences in providing fire engineering consulting services in fields of building facilities, infrastructure and transportation, allowing fire safety challenges to be approached in a way to permit the buildings to function and maximize commercial opportunities.

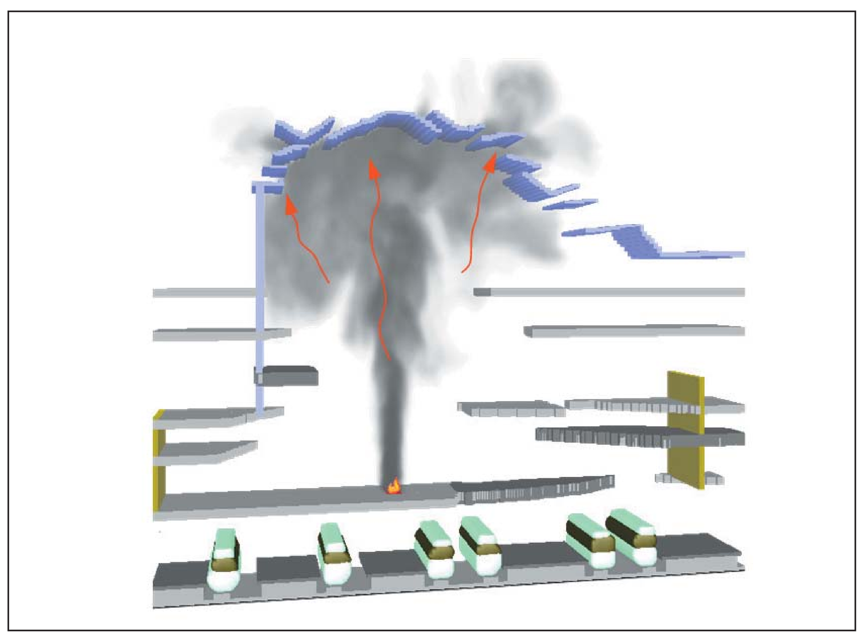
Key services includes:

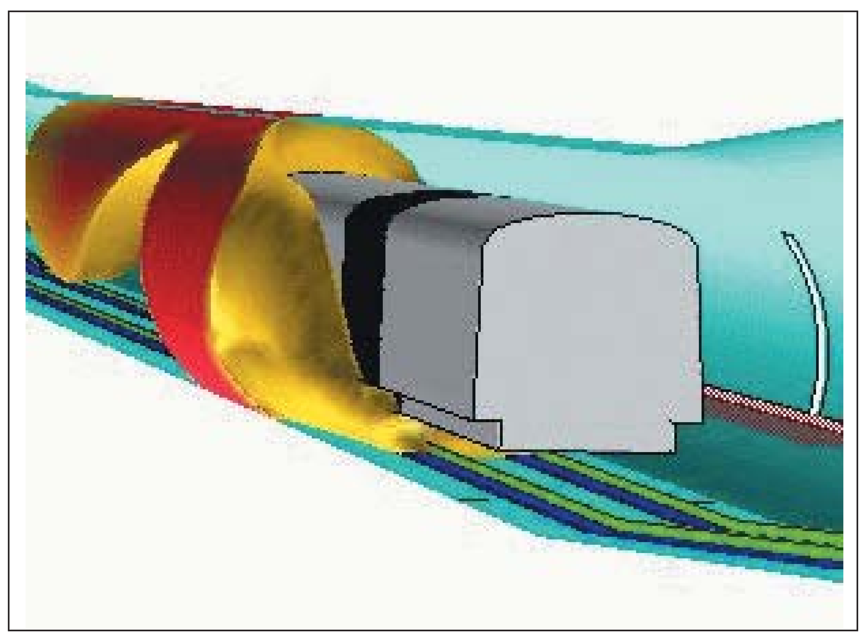
- Fire Safety Strategies
- Performance-based Building Fire Safety Design
- Codes Interpretation
- Fire and Smoke Analysis
- Evacuation Analysis
- Computational Modelling
- Fire Risk Assessment
- Fire Hazard Assessment
- Structural Fire Analysis

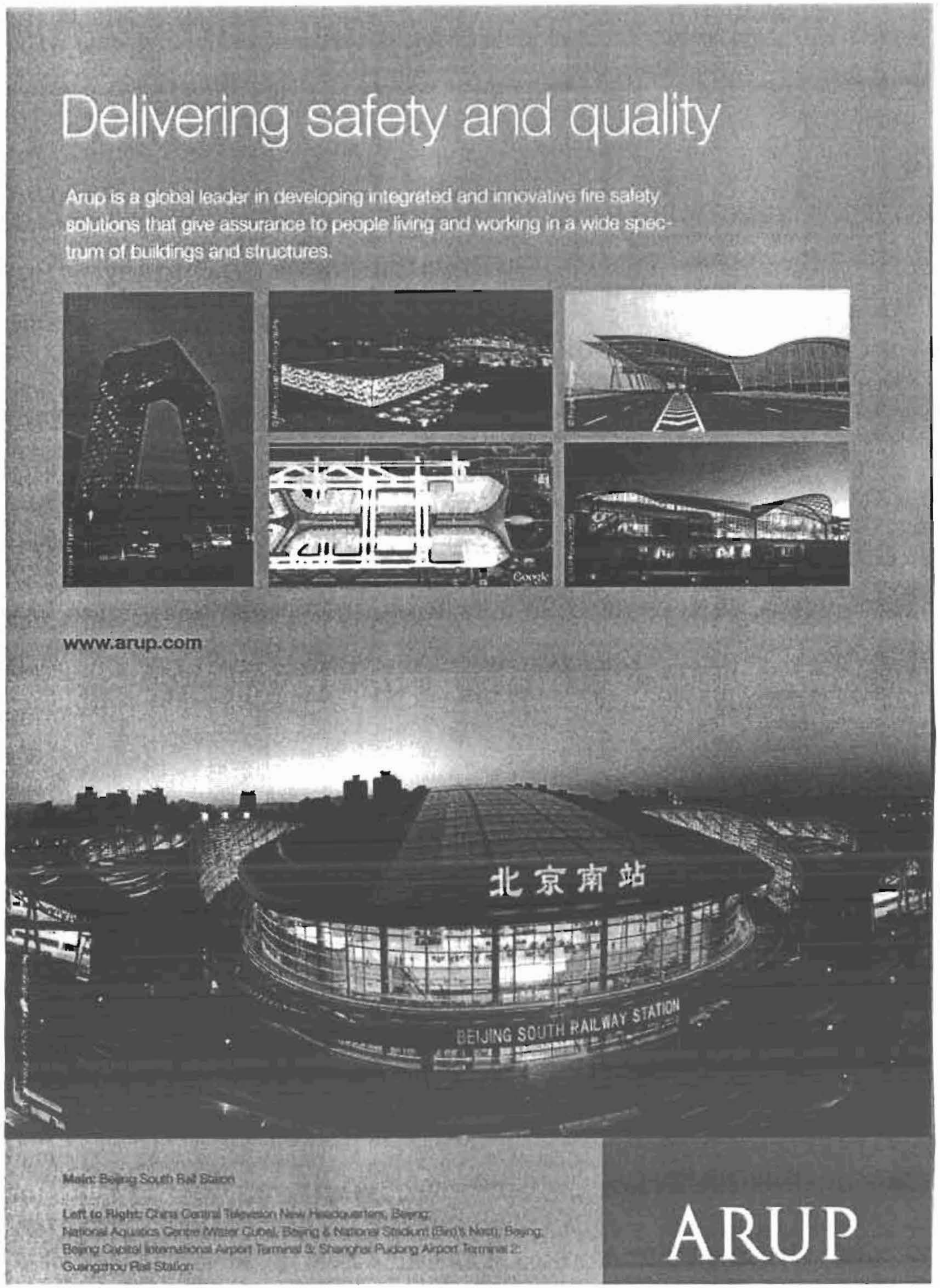
To discover more, visit us at www.aecom.com

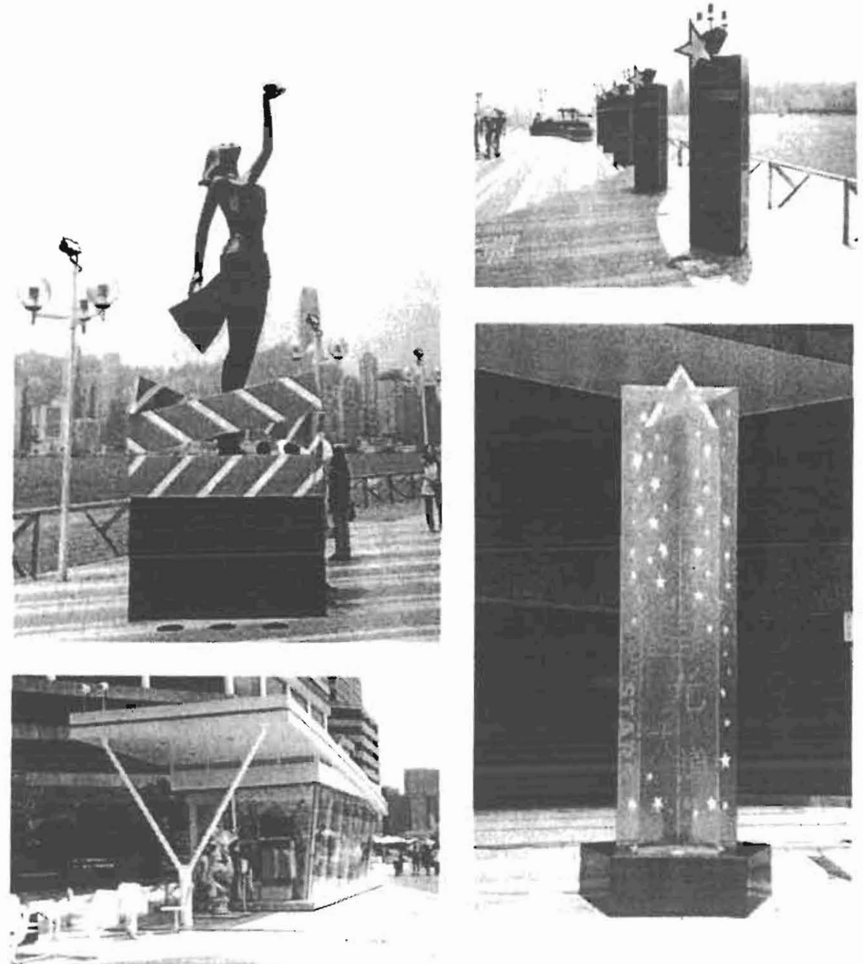

Shenzhen Jing Ji Dameisha Sheraton Hotel








Delivering safety and quality
Arup is a global leader in developing integrated and innovative fire safety solutions that give assurance to people living and working in a wide spectrum of buildings and structures.
www.arup.com
北京南站
BEIJING SOUTH RAILWAY STATION
Main: Beijing South Rail Station
Left to Right: China Central Television New Headquarters, Beijing; National Aquatics Centre (Water Cube), Beijing & National Stadium (Bird's Nest), Beijing; Beijing Capital International Airport Terminal 3; Shanghai Pudong Airport Terminal 2; Guangzhou Rail Station
ARUP



List of Committee Members, Session 2008/2009

Post	Name	Organisation
Chairman	Ir WONG Chi Kwong	Meinhardt China Ltd
Deputy Chairman	Ir Prof Paul PANG Tat Choi	Buildings Department
Honorary Secretary	Ir Paul CHAN Yim Cheong	Wong & Ouyang (Building Services) Ltd
Honorary Treasurer & Community Service Committee Representative	Ir Charles CHU Man Chun	--
Committee Member & Continuing Professional Development Committee Representative	Ir Dr Eric LEE Wai Ming	City University of Hong Kong
Committee Member & Public Relations Committee Representative	Ir Gilbert LAW Kam Cheong	Swire Properties Ltd
Committee Member	Ir Victor LAW Wei Tak	ATAL Engineering Ltd
Committee Member	Ir CHOY Kin Kuen	Buildings Department
Committee Member	Ir Dominic CHEUNG Yat Cheong	Fire Services Department
Committee Member	Ir Dr LUO Ming Chun	Ove Arup & Partners
Committee Member	Ir WONG Hon Kwok	Architectural Services Department
Committee Member	Ir Dr Dee WONG Hak Ki	MTR Corporation Ltd
Committee Member	Ir Wilson TSANG Sau Kit	Airport Authority Hong Kong
Committee Member	Ir Dr FONG Nai Kong	The Hong Kong Polytechnic University
Committee Member	Ir LAU Chi Kin	Sun Hung Kai Properties Ltd
Committee Member	Ir Simon TSANG Siu Fai	Chubb HK Ltd
Ex-officio Member (Discipline Representative)	Ir Anthony LAM Chun Man	--
Ex-officio Member (AMC Representative)	Mr Johnny SHING Wai Lam	The Hong Kong and China Gas Company Limited
Ex-officio Member (YMC Representative)	Miss Sally LEUNG Suk Yan	Meinhardt (Hong Kong) Ltd
Co-opted Member	Ir TAM Tai Keung	Fire Services Department
Co-opted Member	Ir Sam LOK Siu Ming	Shinryo (Hong Kong) Ltd
Co-opted Member	Ir Colin CHUNG Chi Leong	Parsons Brinckerhoff (Asia) Ltd

NOTIFIER's ONYX Series of Intelligent Fire Alarm Control Panels

NOTI•FIRE•NET

Unified Command and Control
Flexible, Expandable, Backward Compatible
Advancing Fire and Life Safety through Technology

NOTIFIER®
by Honeywell

Suite 706, Wharf T&T Centre, 7 Canton Road,
Tsimshatsui, Kowloon, Hong Kong • Tel:2730 9090
www.notifier.com