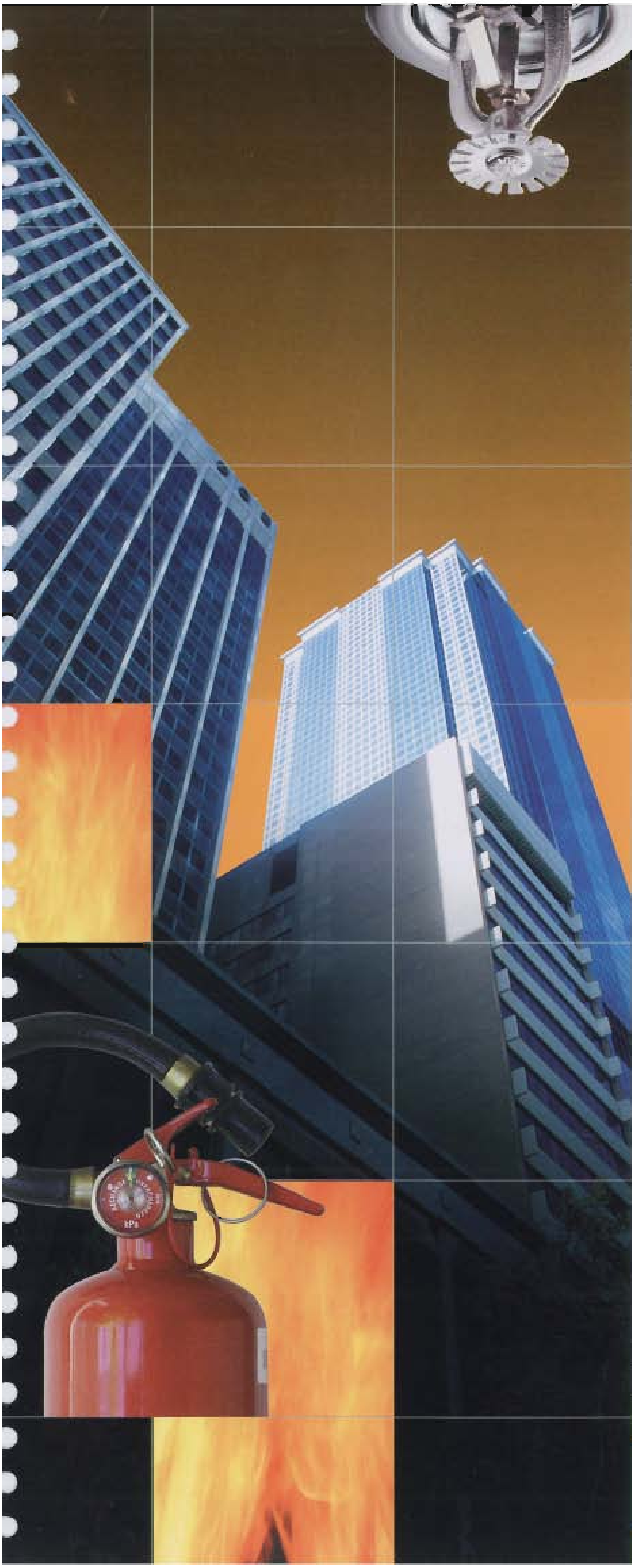

Fire Protection for High Rise Buildings

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BUILDING CONTROL

FIRE PROTECTION FOR HIGH-RISE BUILDINGS

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EXECUTIVE SUMMARY

This report investigates the fire protection issues relating to high-rise buildings.

It examines case studies of notable high-rise fires and statistical data. The fire hazards were identified as arising from limited means of escape, the presence of vertical shafts, greater potential for external (vertical) spread, large numbers of occupants and restrictions to fire-fighting operations. In general, though multiple fatality fires do still occur in high-rise buildings, trends indicate, where significant statistical data is available (e.g. USA), the number of fires, fatalities and subsequent costs are reducing. This is attributed to the increased use of sprinklers, fire resistant construction and smoke detection. From these hazards, issues are identified and fire protection methods used in high-rise buildings are discussed. The most effective protection methods were sprinklers, fire resistant construction, smoke detection and smoke management.

The regulatory requirements of various countries were reviewed in order to identify how they treat high-rise buildings. Generally, there are uo significant differences between the various codes of Australia, New Zealand, USA, England, Singapore and Hong Kong. Some notable features of overseas codes include, fire-fighting lobbies (England, Singapore), refuge floors (Hong Kong), no sprinkler requirement for residential high-rise buildings (England), fire-resistance levels not exceeding 60 minutes unless parts of the building are under separate ownership (New Zealand), and only one means of escape in a residential high-rise buildiug not exceeding 60 metres, provided it meets certain requirements (England, Singapore).

Human behaviour aspects are discussed. The actions of occupants in fires are complex and include rational escape behaviour, inappropriate behaviour leading to increased personal risk, and assisting others. This can lead to occupants taking the correct options for escape which can be immediate evacuation on alarm (tending to lead to safe escape), delayed evacuation (which may put them at risk), or staying put, which may also be a survival behaviour. The importance of accurate, understandable and timely information has been highlighted by case studies and recognised as an important safety issue.

The results of computer modelling of two high-rise buildings, an office (reconstruction of the Joelma Building fire) and an apartment are presented. The conclusion from this was that in high-rise apartment buildings, fire doors to each apartment are essential to provide a common corridor with a reasonable level of protection from smoke spreading from the apartment. This is considered necessary even with sprinklers installed. Pressurisation systems (in conjunction with fire doors to apartments and smoke detection) appear to be potentially the most effective method of maintaining tenability and good visibility in escape routes. Where sprinklers are installed in apartment buildings, fast response sprinklers are preferable to standard response sprinklers. The reconstruction of the Joelma Building fire incident is consistent with the observed reports. The effect of adding a sprinkler system to that building is predicted to have had only a small effect on the time to exceed the visibility criteria within the stairway due to the amount of smoke produced prior to activation of the sprinkler. Fire spread beyond the room of origin and between floors and the overall loss of life would have been dramatically reduced (if not prevented) if sprinklers had been installed. The effect of adding both sprinklers and lift/stairway lobby compartmentation would have most likely kept the escape routes tenable for more than 20 minutes. In high-rise office buildings, sprinklers and fire isolation of the escape route/exitway is essential.

A cost analysis is given of the fire protection in a high-rise building. The installation and commissioning costs for fire protection in a high-rise residential building are estimated at 6% of the total building costs; the costs for fire protection in a high-rise office building are estimated at 9% of the total building costs. The main cost contribution of fire protection for the high-rise office building was found to be for the extension of the air-conditioning system to a mechanical smoke control system. Removal of the cost of the smoke control system from the cost of the fire protection reduces the total estimated cost of the fire protection to approximately 6% of the total building cost, equivalent to that for the residential high-rise building.

Optimisation was discussed and considering that as the total cost of fire protection in apartments was 6%, there appeared to be little scope for reducing costs. One area for which costs were not fully analysed because of lack of data was in the zoned smoke control as specified in AS 1668.1 and indicative data was used. This showed that smoke control systems potentially represent a high cost element in the fire protection of a building and a reduction in this cost could have a significant overall effect on the total cost. To obtain a detailed cost optimisation a detailed design of a building and smoke control system would need to be carried out. Further work with the use of quantity surveyors would be valuable in identifying these costs and any possible optimisations.

A discussion is included on fire brigade intervention. It is recommended that the Building Control Commission consult the Metropolitan Fire and Emergency Services Board (MFESB) and the Country Fire Authority (CFA) to obtain their views on the issue of duplication of fire protection systems in high-rise buildings. It would also be possible for an external party to facilitate such a meeting and to develop the concepts discussed as a further project.

Recommendations are made for future research in the areas of smoke control and human behaviour, including occupant training and the establishment of a comprehensive evacuation scheme in high-rise buildings, making use of concepts of staged evacuation without the need for total evacuation. Issues such as sprinkler interaction with smoke control systems and possible increase in toxic products may also be investigated. Fire brigade intervention and risk assessment methods are also possible topics for future research.

It is concluded that due to diverse variances in high-rise buildings, the holistic approach when assessing high-rise building fire protection is too difficult and complex and therefore unable to produce clear outcomes. In the future it may be better to concentrate on each component, justify its necessity and inclusion in the overall fire protection of the building, then refine it.

In summary, arising out of this work the following recommendations are made:

1. Investigate the possibility of increasing permitted escape distances based on the fire protection systems installed, e.g. 50% increase for smoke detection.
2. Review the effectiveness and requirement for fire hose reels in first aid or operational fire-fighting.
3. Investigate the possibility of specifying fire protection requirements by graded building height, e.g. the higher the building the more protection required.
4. Investigate an increase in the definition of a high-rise building from 25 metres to 30 metres as practised in other jurisdictions.
5. Review the effectiveness and requirement for fire control centres and their relation to fire fighting operations.
6. Review the content and use of AS2220 for emergency warning systems and intercommunication systems in buildings.

7. Consult the Metropolitan Fire and Emergency Services Board (MFESB) and the Country Fire Authority (CFA) to obtain their views on the issue of duplication of fire protection systems in high-rise buildings.
8. Review the content and use of AS1668 for fire and smoke ventilation and air-conditioning in buildings.
9. Consider including a reqnirement for mandatory evacuation schemes in the Deemed to Satisfy Provisions of the Building Code of Australia.
10. Explore risk assessment methods for life safety and their use in the Deemed to Satisfy Provisions of the Building Code of Australia.
11. Investigate the inclusion of fire-fighting lobbies.

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CONTENTS

FIRE PROTECTION FOR HIGH-RISE BUILDINGS

1. FOREWORD

1.1 Client

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1.2 Introduction

The consequences of a fire in a high-rise building can be catastrophic. High-rise buildings contain a high population of occupants and, by the very nature of the type of building shape, do not provide easy egress in the event of a fire for those occupants. In addition, the very shape of the high-rise building (i.e. tower or shaft) assists the natural vertical spread of fire. It is not surprising therefore that fire protection provisions for high-rise buildings are numerous and stringent to prevent and control/mitigate a major fire.

Whilst the hazard is recognised, fire protection provisions have been derived over time and applied in a manner that may not be effective or rational. Therefore, there is a need to take a pragmatic approach to analyse the fire protection provisions required for high-rise buildings.

The deliverables of this stage were:

- Identification of fire hazards and protection methods with high-rise buildings.
- An analysis of fire protection systems for high-rise buildings.
- Provide an assessment of optimisation for fire protection systems in high-rise buildings.
- Identify consequent possible cost minimisation without compromising existing safety levels.
- Provide recommendation for where future research should be focused to back up this proposal.

2. AIM

The aim of the project is to undertake a pragmatic review of fire protection methods for high-rise buildings with a view to optimising their use and identifying possible cost savings to the building industry.

The fire protection methods are considered in relation to the life safety provisions of the Building Code of Australia.

3. SCOPE OF WORK

3.1 Tasks

The scope of work was as follows:

- Literature review of international and Australian fire data to :-
    - identify fire risks associated with high-rise buildings
    - identify fire protection methods used
    - review of regulatory provisions pertinent to high-rise buildings

    (The data was drawn from building and social environments similar to Victoria).
- Analyse the fire data from significant high-rise building fires to identify fire hazards.
- For the fire protection methods identified, analyse purpose and role.
- Undertake indicative modelling of interactions of fire protection systems to identify relationships.
- Identify possible optimisation issues for the fire protection methods.

3.2. Definitions

High-rise buildings

Different jurisdictions define high-rise buildings in different ways. Generally, and historically, a high-rise building was considered to be a building above which external fire-fighting operations and rescue by a ladder was considered to be impracticable because the ladder would not extend further. This limit was considered to be 100 ft or 30.5 metres (HMSO, 1971). The specific definitions within various jurisdictions are discussed in paragraph 6.4 of this report, but generally any building over 23 metres (75 feet) is defined as a 'high-rise building' building.

Fire protection system

Measures taken in a building to protect the occupants and building fabric and structure from fire. These can include sprinklers, fire brigade attendance, fire resistance levels, and provision of means of escape.

Fire-fighting lobbies

A protected lobby providing access from a fire-fighting (fire isolated) stairway to the accommodation area and to any associated firefighting lift (lift which can be controlled by the fire brigade). A fire-fighting lobby may contain a fire-fighting lift, an exit stairway doubling as a fire-fighting stairway and a valve for the rising main. (HMSO, 1971 and Lim, 1999)

Refuge floor

A refuge floor is a protected floor in a building where people may gather, without immediately making a final exit. Such a floor would not contain occupied accommodation or accessible mechanical plant room, except for the use of the fire brigade. The floor would be separated from the rest of the building by a minimum fire resistance level of 2 hours. (Lim, 1999A)

4. LITERATURE REVIEW

4.1 Introduction

Statistical data of building fires can be difficult to obtain in sufficient detail to identify specific high-rise building issues. Data contained within the Australian Fire Incident Statistics, the New Zealand Fire Service Emergency Incident Statistics and the UK Home Office Fire statistics do not accurately identify building categories in divisions that give specific data for high-rise buildings.

In the Australian Fire Incident Statistics 1992-1993 (King, 1995) there is a statement that data from Australia, Canada, New Zealand and the USA were mainly similar. For the purposes of this project USA statistical data has been used as it represents a similar culture to that in Australia and the developed trends applicable to high-rise buildings in Australia.

An interesting observation however is that in the USA (Hall, 1997) most high-rise fires were in apartment buildings, whereas in the UK (Jackman, 1997) it was stated that the largest losses were in office buildings. This may be due to the potentially larger cost of an office fire and that apartment fires, though more numerous, may have a lower cost because of their greater compartmentation.

By far the most extensive data on high-rise building fires is held by the National Fire Protection Association, from whom most of this data is derived. In general the NFPA will investigate a multiple fatality fire anywhere in the world and also those fires it considers to be of significant technical and educational interest.

A comprehensive listing of high-rise building fires can be found in Council on Tall Buildings and Urban Habitat (1992), and covers the years 1967 to 1989. Since 1989 there have been at least seven major fatality high-rise building fires and numerous low or nil fatality ones. The literature carries extensive details of major fires in high-rise buildings where fatalities occurred. Examples of these are given in Appendix A. They vary in severity and fatality rate, and can be grouped into the following categories:

4.2 Well Documented Major Fatality Fires (Greater Than 10 Fatalities) 10 in Number

The fires exhibit generally common features which can be listed as follows:

- Lack of sprinklers.
- Lack of automatic fire or smoke detection.
- Delay in raising the alarms.
- Poor or inadequate smoke and fire separation (mainly through vertical services and shafts).
- Inappropriate use of HVAC.

These fires had significant fatalities ranging from 12 (Westchase Hilton) to 179 (Joelma, Sao Paulo).

The median fatalities is 53, which is a significantly high number.

4.3 Well Documented, Low or No Fatality Fires; 18 in Number, Median of 3 Fatalities

These generally showed similar patterns to the higher fatality fires with the same issues applying. The fact that the fatalities were low may have been just a circumstance on the day. The fatalities were often associated with direct involvement in the fire or were firefighter deaths. Where no fatalities were recorded the building was generally unoccupied.

4.4 Not Extensively Reported Fires

The NFPA Journal briefly reports fires in its "FireWatch" column.

These provide information of some of the more successfully controlled fires where sprinklers, smoke detection and first aid fire fighting played an important part. These include a fire on the 18th floor of a Nevada Hotel, in a 10-floor hospital in Missouri (extinguished by staff), and a facade (223 m^2) fire in a 28 floor hotel/casino (fire confined to outside so installed sprinklers played no part in fire control).

These fires only represent a small proportion of all high-rise building fires and may not be statistically significant to establish trends in the incidence of high-rise building fires. Many fires do not get beyond the incipient stage and many are controlled by active fire suppression systems and may not be reported (Melinek, 1992). They are also often confined to the room of origin.

4.5 Statistical Data

A more rigorous analysis was carried out by Hall, 1997. He analysed and reported on high-rise building fires between 1985 and 1995. In that report he states that high-rise building fires fell from approximately 25,000 in 1985 to 13,800 in 1995, with deaths down from 70-80 in 1985 to 55-60 in 1995. The range is used because of the statistical nature of the analysis and an estimate of all high-rise building fires based on the reported fires. These figures show that there is a declining problem of high-rise building fires, although the occasional multiple fatality high-rise building fire can still generate a large amount of documentation and comment.

To put high-rise building fires into perspective; in the USA, high-rise building apartment fires represent 1 in 12 of all apartment fires, in hotel fires it is 1 in 6 to 1 in 4, in offices, 1 in 10 and hospital and other care facilities it is 1 in 3.

From this data, and a recent communication with the author (Hall, 1999), general observations comparing high-rise building to low-rise fires in specific property classes are:

- Based on reported fires, the probability of a fire occurring in a high-rise apartment building is less than in any other apartment.
- Injuries (not fatalities) from a fire in a high-rise apartment building are similar to those in any other type of apartment.
- The probability of a fire in a high-rise office may be marginally less than in a low rise office building, though the data is inconclusive.
- The extent of flame damage tends to be less in a high-rise apartment building, hotel or office than in their low-rise counterparts.
- The probability of a fire in a high-rise hotel building is marginally greater than other hotels.
- Fires in high-rise hotel buildings are less likely to involve death.

These observations have been derived from an analysis of the data. The reasons behind them are not fully rationalised but may be that:

- There is a greater requirement for fire protection systems in a high-rise building than any other building, hence the lower incidence of deaths in hotels.
- By virtue of the construction, floors and walls may be fire rated, whereas they may not be in low-rise construction, hence lower flame damage.
- Injuries may occur in the space of fire origin, which would be similar in all properties.
- Fires in high-rise apartment buildings may not be reported due to the early control of fire by sprinklers, and hence show a lesser occurrence than in other apartment buildings.

4.6 Fire Risks Associated with High-Rise Buildings

From the data and the major incident reports, the fire risks associated with high-rise buildings are similar to those in low-rises, however there are specific factors which are peculiar to high-rise buildings.

These are:

- Limited means of escape. Escape from a building is by a common stairway(s) with higher numbers of people.
- Vertical shafts.
- Greater potential for external spread. In some cases external constructions, e.g. non fire rated spandrels and lack of fire stopping between curtain walls and floor slabs, can produce fire spread and 'leapfrogging'.
- Higher occupant loads. This is linked to the availability of means of escape creating queuing at stairways and extending total building evacuation.
- Restrictions to firefighting operations.

One feature of the literature review was that there were very few notable high-rise building fires cited in Europe compared to the USA and Asia. In the UK, until recently, sprinklers were seldom used in high-rise buildings and are still not required in residential buildings or those under 30 metres high (see chapter on Regulatory Provisions), although fire resistance levels of building components and structure could be up to 240 minutes. Compartmentation would still be on a floor by floor basis with fire isolated stairways. Currently, since 1992, except for residential buildings the use of sprinklers is mandatory over 30 metres with a fire resistance of 120 minutes, reduced to 90 minutes for non-structural elements. Fire properties of surface linings are also controlled, but small rooms of not more than 4 m^2 in residential buildings and 30 m^2 in non-residential, require materials with the least onerous classification. This is not considered to be a significant factor in increasing or reducing fire risk and is on a par with the practice in Australia.

5. ANALYSIS OF PURPOSE OF FIRE PROTECTION

There are numerous fire protection methods used in high-rise buildings. These may be specified in the building code or may be installed at the request of the owner or builder, or sometimes requested by insurers. These requirements have arisen more from notional concepts of fire safety or in response to reducing the risk of catastrophic failure and multiple fatality fires.

The purpose of this section is to analyse the purpose of those fire protection methods identified as likely to be installed in a high-rise building, by virtue of their inclusion in regulatory requirements.

The fire protection methods available for use in high-rise buildings include as follows:

- Sprinklers.
- Fire detection and alarm (smoke, heat, manual).
- Fire resistant construction (compartmentation, fire doors and fire separation)
- riser mains.
- Means of escape.
- First aid firefighting (fire extinguishers, hose reels, emergency lighting).
- Stair pressurisation.
- Smoke control systems.
- Voice communication and evacuation systems.
- Access and facilities for the fire brigade.

Although not specifically "fire protectiou systems" the following can contribute to the fire safety of occupants in high-rise buildings:

- Training (staff and occupants).
- Maintenance of essential fire protection systems.
- Fire safety and preparedness planning.
- Lifts and lift management.
- Duplication and redundancy of fire protection systems.

5.1 Sprinklers

Sprinkler systems have been used extensively as a fire protection method in buildings in Australia and New Zealand (Marryatt, 1988).

The purpose of a sprinkler system is to control a fire and in many cases it will also extinguish it. However another important purpose is fire detection and with associated equipmeut to alert the fire brigade and the occupants (NZS 4541;1996 and Nash and Young 1978). In the process of controlling a fire there will be the associated restriction of the production of flames, hot gases and smoke from the room of fire origin.

The issue of fire extinguishment is important and Marryatt records that approximately 60% of fires in which sprinklers activated were extinguished by the sprinkler system. Melinek (1992), used UK fire data for one year (1988). From this data he inferred that in 28% of fires where sprinklers activated, the fire was extinguished (even though it may have spread beyond the room of origin). This figure increases to 87% if sprinkler controlled fires are included.

Marryatt established a sprinkler effectiveness of 99.46%. There is an assumption in Melinek that 33% of fires in sprinklered buildings are not reported to the fire brigade. Using this figure and extrapolating on the assumption that all buildings are sprinklered, 98% of fires could be restricted to the room of origin by the use of sprinkler systems.

In terms of fatalities and casualties, Melinek estimates that 50% of fatalities and 25% of non-fatal casualties could be prevented by installing sprinklers.

Both Marryatt and Melinek's figures demonstrate that sprinklers can be effective in controlling fire and with a fairly high degree of reliability. Other figures (IAFSS bulletin board) suggest that sprinkler reliability may range from 95% to 98%. Whilst 95% is lower than Melinek's 98%, and Marryatt's 99.46%, sprinklers can still be considered a valuable fire control asset. The 98% figure is also supported by the US National Fire Sprinkler Association (NFSA, 1999) as given by the NFPA.

The difference between those figures given by Marryatt and other researchers is that sprinklers which did not activate were excluded by Marryatt.

Both Marryatt and Melinek considered all building fires, and especially as most fatalities occur in family dwellings, their applicability to high-rise buildings may seem doubtful.

The USA data (Hall, 1997) estimates that automatic suppression accounts for a reduction of 71% in the rate of deaths per 1000 fires and at least 42% in the economic loss per fire. The reduction in deaths is greater than calculated by Melinek and may be due to the particular nature of a high-rise fire.

In looking at some of the actual fire data (Council on Tall Buildings and Urban Habitat, 1992), most multiple fatality fires have occurred in unsprinklered buildings. There are cases of fire in an unsprinklered building (NFPA Journal, 1997A), people have survived or fatalities were limited to those directly involved in the fire. But these should not be taken as representative of the whole.

The effectiveness of sprinklers can be demonstrated by the Meridian Plaza fire (Klem, 1991). This was a partially sprinklered building, unoccupied at the time of the fire. The fire started in an unsprinklered part of the building and moved through the floors until it reached the sprinklered floor.

Where a building was sprinklered as in the World Trade Center, 1975, (Council on Tall Buildings and Urban Habitat, 1992), there was comment that certain floors of the building were needlessly evacuated. This leads to the concept of defence in place and that staged evacuations could be feasible with a sprinklered building.

The detection aspect of sprinklers is also important in that it makes the occupants, and fire brigade aware of a fire. For this to work properly the system has to be configured to alert the whole building and the fire brigade.

There is no guarantee that fatalities will be prevented in a sprinklered fire but the installation of sprinklers will significantly reduce the incidence of fatalities in bnilding fires (Hall, 1997) and can eliminate multiple fatalities. [The NFPA has no record of multiple fatality fires in a sprinklered building NFPA 1986]. Sprinklers therefore provide effective fire protection for a high-rise building.

It is interesting to note that Hall (1997), reports that two thirds of fires in high-rise apartments in the USA and one quarter to one tenth in hotels and aged care buildings, occurred in unsprinklered buildings. This means that in unsprinklerd buildings more fires could be reported than in sprinklered buildings, even if the number of fire starts were the same. There is no reason to suppose that the number of fire starts should be different given the same occupants. For apartments this may be due to the phenomenon stated by Melinek that 33% of fires in sprinklered buildings go unreported. Perhaps the incidence of fires in unsprinklered buildings would tend to be larger with greater numbers of casualties and higher economic loss and therefore are more likely to be reported.

In high-rise buildings it is usual for the sprinkler system to conform to the standard current in the country for full sprinkler systems, e.g. AS 2118 in Australia and NZS 4541 in New Zealand. Residential buildings can have sprinklers installed to other standards such as NFPA 13D/13R which offer a lesser, though not necessarily lower, standard of sprinkler coverage. These standards are restricted in building height and area and do not apply to high-rise buildings. Installing a residential sprinkler system in say a high-rise apartment building or hotel may make them more economical to install but issues such as valve numbers (one on each floor perhaps) and maintenance may preclude their use. The currently available fast response sprinkler heads as used in residential systems also confer advantages compared with standard sprinklers by being able to attack a fire earlier and therefore reduce heat and toxic gas emissions.

Another option for sprinkler systems is to combine them with a wet riser main. This could ensure that there is always water in the system, yet may offer some economies in pipe work supply and installation.

Water supplies for ultra high-rise, i.e. above 60 metres, may be difficult and stored water tanks and booster pumps or connections at the 21st floor may need to be considered (Cheung,). The 21st floor represents a height of approximately 60 metres, and may be a limit for Fire Brigade pumps. The location of booster pumps would therefore be dependent on the availability of suitable pumps. Cheung also suggests that a limited sprinkler system be installed in the apartments, behind entrance doors and in lift lobbies, fed from the wet riser main. His instructions for fighting a fire include the requirement that two portable pumps should be taken to the intermediate fire brigade inlet, which would be on the 22nd floor in a 40 floor building. These features may be worth considering for inclusion in a high-rise building.

5.2 Detection and Alarm

Smoke detection has been associated with sprinkler systems in the life safety of occupants. Smoke detection will respond faster in detection of a fire than sprinklers, though their contribution is to alert occupants rather than to control the fire.

The effectiveness of smoke detection can be shown by fires in high-rise apartments which alerted the fire brigade and occupants (NFPA Journal, 1997A). A bedding fire caused by a discarded cigarette, resulted in a fire. The 600 occupants of the 10-floor building were successfully evacuated. Smoke detectors were only installed in the corridors, but the fire brigade arrived to restrict fire damage to the room and apartment above. Significant property damage occurred and 11 occupants suffered various injuries.

Another incident occurred in a Wellington, New Zealand apartment (Pope, 1999) where a fire started in a kitchen but the smoke detection alerted the occupants and the fire brigade. Neither of these buildings were sprinklered and early detection was effective in providing for life safety. However the response of occupants to an alarm is important in maintaining their life safety (see Human Behaviour Chapter).

A high-rise building will often not have a complete smoke detection system. Sometimes it is restricted to the corridors and stairway. A complete building system, especially in apartments building can cause problems. Some systems can be so sensitive that they will alarm on minor incidents, e.g. cooking. Alerting a whole building because of a small cooking failure can become tiresome and lead to desensitising the occupants to an alarm, slowing their response. However occupants may not necessarily become desensitised and in the case of the Japanese high-rise fire (Sekizawa et al. 1998) where there was a history of false alarms and fires, occupants responded well to an alarm and evacuated the building before life threatening conditions. This fire was characterised by significant fire spread through external balconies. (Hokugo et al, 1999). One solution to the problem of false alarms is to provide local smoke alarms for an apartment alert and heat detectors or corridor smoke detectors to give a whole building alarm.

A fire detection system will not control a fire and to be effective a system of alerting firefighters is necessary. In some cases the management of a building will respond by investigating the fire first before notifying the fire brigade. This can result in two relative occurrences. The first is that it puts those investigating the fire at jeopardy, and secondly it delays firefighting operations and allows the fire to grow to such an extent that it increases the hazard for occupants.

A detection system only becomes effective if its operation is trusted by those in the building. This means having a reliable system which is not prone to unwanted alarms, and which can alert the fire brigade.

Heat detectors are seldom used in high-rise buildings and may be restricted to kitchens, and service areas where smoke detectors may give too many unwanted alarms.

Manual alarms in the way of pull handles or switches, are a common feature of high-rise buildings and are often the only alerting device in the building. These rely on the occupant response and are only effective in occupied buildings. These would not be recommended as the sole means of raising a fire alarm in a high-rise building as they require people to physically break glass to operate them, which the occupants may be reluctant, or unable to do. BGAs can also be unnoticed in the haste to escape.

5.3 Fire Resistant Construction (Fire Compartmentation, Fire Doors and Fire Separation)

By its nature it would be reasonable to expect that a high-rise building has an inherent fire separation between floors. This is true in the main, and floors would provide snfficient fire resistance in a concrete structure. Until recently steel beams would have needed a fire protection coating to provide the often high, e.g. up to four hours, fire resistance necessary. Work carried out by BHP (Thomas et al, 1992) for the William Street project, suggests that additional fire protection to structural steel is unnecessary where the building is sprinklered. Recent work being carried out by the Building Research Establishment, Fire Research Station (FRS), (Robinson, 1997), even snggests that no sprinklers are necessary. FRS is currently carrying out Work and the LPC have a guide for construction of buildings, which includes high-rise (Fire Protection, 1997). There have been fires in high-rises where the fire has caused significant damage to the building structure (One New York Plaza 1970, One Meridian Plaza (Klem 1991)).

The main penetrations in compartmentation occur at the shafts, i.e. stairways, lifts and services, and at the outer walls of the building. Failure of these has been implicated in many of the multiple fatality fires and adequate fire separation is needed at these locations. This includes fire resistance construction at the shafts, which is usually guaranteed, and for fire doors at stairways and lifts. The latter is also often guaranteed but when improper use has left them open then this reduces the degree of compartmentation.

Fire-stopping of services is also important in maintaining fire separation. This is very true at the floor slab/external wall junction and the LPC guide and research has considered this aspect of construction (Jackman, 1998).

The effect of flame spread from windows has been of interest for some time (Oleszkiewicz, 1991 and Galea, 1999). The outcome of this is that spandrels and aprons become a feature of buildings, although, this only applies in unsprinklered buildings as given in C2.6 of the Building Code of Australia Deemed to Satisfy Provisions (Australian Building Codes Board, 1996).

The above applies in general to all high-rise buildings, but where a floor is divided into separate compartments, e.g. a hotel or apartment building, further fire separation is provided by wall and doors between different occupiers. Fire doors being left open is often a cause of fire spread. Fire doors can be left open because it is the practice of occupants to do so (Wolf, 1999), or they may be left open during escape or can be difficult to close under normal use (Las Vegas Hilton, Fire Journal, 1982). An encouragement to leave doors closed to maintain their operation and practice good evacuation procedure would assist in increasing the fire safety of occupants. Fitting closers to doors, and in some of the multiple fatality fires room and apartment doors were not fitted with automatic closers, can be a valuable fire prevention measure. However this did not help one occupant who died when he left his apartment to enter a smoke filled corridor and could not return as the door slammed shut behind him (Lathrop, 1976). This should not be taken as a representative model for establishing fire safety and door closers are considered an important part of any high-rise buildings fire safety.

The issue of the stair doors raises interesting questions, as it is through those that the fire brigade mounts its fire fighting operations. Hoses run through an open door will permit smoke to move into the stairway and the idea of a fire-fighting lobby may be feasible, with riser mains in the lobby and separate doors to the stairway and the floor. This would not be attractive to architects and owners as it uses up valuable space, and is not currently considered in any of the codes.

It is interesting to note that most of the multiple fatality fires have occurred in apartments and hotels; there have been are very few recent multiple fatalities in office buildings, possibly due to apartments and hotels being sleeping occupancies, or where people are relaxed and less alert. There may also be a tendency to regard the home as being a safe place and people being reluctant to leave thus delaying evacuation. Hotels and apartments tend to have more compartmentation than offices, yet have the greater number of multiple fatalities. This indicates that human behaviour may have a more significant influence on fire fatalities than fire separation.

Fire resistant construction becomes important where there are large service areas at a lower level. Two fires, the Dupont Plaza Hotel (Klem, 1987) and the Royal Jomtien Hotel, Thailand (Martin, 1998), showed the importance of separating lower service areas from the high-rise tower block. In both fires, lack of adequate fire separation, amongst the lack of other fire protection e.g. sprinklers, caused significant fire and smoke spread to the upper levels.

Fire separation becomes an important feature once a fire has been established. This can occur when the alarm and occupant evacuation is delayed. Before that smoke spread and occupant behaviour is important to survival.

5.4 Riser Mains

Their function is to provide fire fighters with water and are usually at each floor level; their number depending on the requirements of the building code. They become essential in fire fighting and lack of water through the riser main or its improper set-up has hampered fire-fighting capability (Klem 1991, One Meridian Plaza).

Issues relating to the riser main are:
- Wet or dry system.
- Connections to a sprinkler system or fire hose reels.
- Water supply, tank or pump.

The wet system is generally favoured as it can offer greater security of operation in that any leaks can be detected by suitable pressure sensors. It can be pressurised from the normal town water supply using a jockey pump and in firefighting operations fed from the fire brigade pump or installed pumps and storage tank.

Dry riser mains can be disabled by all riser main floor valves being left opened and it could delay fire fightiug if they have to be closed before being used. This could also cause a hazard to fire fighters by having to enter a possibly smoke logged area. This problem can be eliminated by correct maintenance procedures.

A wet system can also be used to supply water to a sprinkler system or fire hose reels, though hydraulic calculatious would need to be carried out to ensure au adequate water supply for both sprinkler and fire fighter operations.

Water storage aud the provision of pumps is of major concern to architects and owners as they add cost to a system. If the fire brigade can provide adequate pumps then there should be no need for additional pumps in the building (see Fire Brigade Intervention). However if building heights increase significantly then permanently installed pumps may become necessary.

5.5 Means of Escape

These are normally well covered by the Building Code of Australia with at least two means of escape and limits on distances specified. The purpose here is to limit the time people may be subject to the products of a fire. This is achieved by ensuring that distances are kept to a limit where they could safely escape. There does not appear to be any technically reasoned justification for the values that are used in the Building Code of Australia, nor in any building code. Concessions may be given for travel distance if various fire protection systems are installed, e.g. 50% increase for smoke detectors or sprinklers, 100% increase for both as in the New Zealand Acceptable Solutions C2/AS1 (BIA, 1992). Another approach used in England (Home Office 1987) is that single means of escape are permitted in high-rise if travel distance do not exceed a certain value.

There could be a case of permitting a single means of escape if sprinklers are fitted, but this might not be acceptable as the two means of escape would be necessary in the event of one being blocked, or required for firefighter's use.

A significant feature of a high-rise building is the number of occupants at several levels and the limited possibilities for escape (windows are not an option, but balconies may be). One solution is staged evacuation with the occupants on the fire floor and those on the floors above and below instructed to leave first. They may either be directed to exit from the building or move to a lower floor first before proceeding. This advice has currently been reinforced with additional advice in an article by Wolf in the NFPA Journal (Wolf, 1999). The suggestion here is that it is not always necessary to leave a high-rise building as its fire resistance construction, provided it has been adequately built and maintained, will prevent fire spreading rapidly to other floors, particularly those remote from the fire floor. Staged evacuation can certainly be applied effectively in a controlled environment, e.g. office or hospital, but in apartments it may be more difficult.

This type of evacuation requires good communication with the occupants and proper fire education and training. Whilst it might be the duty of management to provide this, fire brigades have become more proactive in fire safety. For the building control authorities to enforce this, some form of legislation, such as the New Zealand Fire Safety And Evacuation Regulation 1992 (Dept of Internal Affairs, 1992), would need to be enacted. The fire safety and evacuation regulations require that all high-rise buildings have an evacuation scheme unless fitted with an approved i.e., complying with NZS 4541, sprinkler system. Where more than 100 people can congregate an evacuation scheme is required regardless of a sprinkler system. The evacuation scheme calls for the appointment of fire wardens, training of occupants and regular trial evacuations. Such a system has its merits and could still apply, though not so rigorously, where a building is sprinklered. The application of an evacuation scheme can help to ensure that the occupants of a building are more aware of the actions necessary in the event of a fire. This can be achieved through education and preparation. There would also be an advantage in the fire brigade having a ready means of establishing the extent of evacuation of a building through the fire wardens and possibly a tally system.

Whilst evacuation drill may involve some risk by conditioning people to follow certain routes, rather than be guided by more critical analysis of safe routes in a fire, evacuation schemes, however limited can work if supported by management.

Access and egress for the disabled also needs to be considered and an assisted evacuation or defend in place option could be considered.

5.6 First Aid Fire Fighting

This includes fire extinguishers, fire hose reels and fire blankets. It is not clear for whose use these are provided. It is possible that the fire hose reels are intended for fire brigade use, though whether they will is another matter. Whilst these may be suitable for a small fire, occupants can put themselves in danger if they do not succeed. If first aid fire fighting is provided then so should training in their use, otherwise they may be ineffective. In the work place, e.g. offices, there may also be issues of occupational health and safety. If an employee is injured whilst using a fire extinguisher then the owner may be considered at fault under any occupational health and safety legislation.

First aid fire fighting, though it can be helpful, cannot be relied upon to significantly improve fire safety and if installed should include precise instructions and warnings. Where possible, training should also be provided.

5.7 Stair Pressurisation

This is a form of smoke control whose aim is to exclude smoke from the escape stairways. Smoke entering the stairways has been a feature of several of the multiple fatality fires, usually as a result of poorly considered, and applied, fire and smoke stopping.

Aspects of stair pressurisation to be considered in the design of a building are pressures to be applied, method of activation and type of system (multiple or single injection). A properly designed system will provide an even pressure distribution and take into account the likelihood of a specific number of doors being open. One problem with this is over-pressurising part of the stairway such that the doors cannot be opened by the young, infirm or elderly.

The most common method of activation is by smoke detectors, though a manual system can be used. This relies heavily on the reliability of the detection system but can also be manually activated. No reported problems have been found in buildings with pressurisation.

For a high-rise building a multiple injection system would be used where air is supplied at several floors, and not just one as in the single method. This will provide a more even pressure distribution, which will not be as sensitive to doors being opened as the single injection.

Being a mechanical system it will be subject to the same reliability issues, for example, will the fans operate and will there be available power supply on demand? A method of combating concerns about the availability for operation of the fans is to use them for normal venting and on alarm to go into fire mode.

The problems do not detract from stair pressurisation being an effective means of keeping the escape stairways clear of smoke and are a valuable fire protection method.

5.8 Smoke Control

Mechanical smoke control systems can be used for several purposes. They can aid in the evacuation of occupants for a limited time, assist in preventing smoke damage to contents, and help firefighters carry out rescue and fire suppression operations. Stair pressurisation as discussed above is one example of smoke control.

Smoke movement can be managed by one of the following:
- compartmentation
- dilution
- airflow
- pressurisation (see stair pressurisation)
- buoyancy

Compartmentation is providing fire and smoke resistant structures, which has been discussed above, by limiting fire spread. An important aspect here is to identify leakage paths through floors, walls, windows and doors. Sometimes the correct operation of stair pressurisation relies on a reasonable leakage path. However protection of occupants in different compartments must not be affected by providing leakage paths, which could cause smoke to move between the occupied compartments.

Dilution covers aspects of smoke purging, removal and extraction. This only works if the compartment is remote from the fire and smoke leakage into a space is low compared with the extraction rate. However there are problems associated with such systems at or near the fire locations. (Klote and Milke, 1992). Klote and Milke state that there is no theoretical or experimental evidence that using a building's heating ventilating and air-conditioning system for smoke dilution will result in any significant improvement in tenable conditions within the fire space. They recommend that smoke purging not be used to attempt to improve hazardous conditions within the fire space.

Airflow can be used where there are long passages and tunnels. Sufficient air flow is provided to direct smoke, hopefully away from occupants and keeping their escape paths clear. This would not be applicable to high-rise buildings.

Buoyancy, where the smoke rises due to its temperature, is used for smoke control in large spaces such as atria and shopping malls. Except where these are included as a feature of a high-rise building, atria and shopping malls are not considered further.

AS/NZS 1668.1 (1998) describes a method of fire and smoke control based on the concepts of zoned smoke control as described by Klote and Milke (Klote and Milke, 1992). The purpose here is to isolate and clear smoke from the fire compartment, usually a floor of a building, so that over-pressurisation does not occur and heuce lead to smoke leakage into other compartments. This is combined with pressurising the compartments on either side so that smoke does not leak into them. Some of these systems can become complex with sophisticated control systems to identify the location of the fire and to operate a system of dampers to direct the smoke and hot gases from the fire to the outside.

In one reported fire at the World Trade Center (Lathorp, 1975), a smoke extraction system was found to he effective in clearing smoke from all floors except the fire floor. No specific details are given by Lathorp (1975), but it appears that the building was unoccupied and the HVAC shut down. Smoke detectors in the building were uot initiated and the system was activated manually. The building was 110 storeys high and the office area could be put into 100% exhaust with the core receiving 100% fresh air. This incident shows that a zoned smoke control system can clear smoke from non-fire floors, but as the building was unoccupied and the fire floor did not contain sprinklers (sprinklers only fitted in areas below ground level) it would be difficult to use as an example of the effectiveness of all systems.

With the increased complexity of systems, reliability becomes more important. A simple approach could be to deactivate the system and close all dampers, however this does not address the issue of over-pressurisation in the fire compartment and possible smoke leakage to others as it would be impossible to seal all leakage paths.

5.9 Voice Communication Systems (EWIS)

Voice communication systems have essentially two functions. They can impart information to the occupants and may be known as voice alarm systems, or they may be used as a two-way communication system between, for example, a control room and the occupants. A two-way communication system appears to have merits as it can keep occupants informed of the progress of a fire, and the occupants in turn can let those in charge of firefighting know of their situation. However problems can arise and in one case (NFPA, 1995) the occupants did not know how to use the system and relied on radio and television broadcasts for their information on the fire.

A two way communication system also may tend to delay any actions, for example escape, on the part of the occupants, which could lead to injuries or fatalities. These systems are best used by trained personnel such as in hospitals or offices where individuals can be assigned to the operation of the system.

A voice alarm may prove more effective as it is can impart more information than a system based on sounders. It does not rely on human interaction during an evacuation, but would need to be correctly set up to be effective. Occupants do not need to interact directly with the system (i.e. use an intercom) and clarity and audibility can be established beforehand. EWIS systems are specified in

AS 2220 (1989) and may suffer from the deficiencies discussed above. A review of its use in the BCA may be appropriate.

5.10 Other Fire Protection

Each of the other fire protection systems listed above can play an important part in the fire safety of a high-rise building. Training of occupants and staff can make evacuation easier and combined with a comprehensive fire plan or evacuation scheme would provide a strong basis for the safety of occupants. Training can include fire prevention and opportunities can be taken to promote fire safety at any training or information event.

Lifts are often a problem in evacuation of building occupants and can be used inappropriately by occupants in a fire. Nowadays the technology of lifts is such that they could be used safely in an evacuation and rescue by the fire brigade, provided their use is managed. If the power supply is maintained lifts are not likely to be affected by the fire, however water is a problem and can interfere with their electrical operation.

Maintenance is essential in ensuring the operation of fire protection systems. Particularly smoke control systems, which although reliable on commissioning can deteriorate if they are not maintained, affecting the fire safety in the building. Sprinklers and in fact any mechanical and electrical system may suffer, by poor 'on demand' from lack of maintenance.

High-rise buildings are often located in crowded central business districts and fire brigade access can be difficult. Within the building, rescue and fire fighting can often conflict and providing secure staging areas for fire-fighting can be a problem, though fire fighting lobbies are considered within the UK (BS5588, Part 5, 1998). Further discussion of fire brigade operations is given in the chapter on Fire Brigade Intervention.

Duplication (the same again) and redundancy (same function but different method) of fire protection systems is an issue which can be linked to reliability and risk analysis. Some systems are already duplicated and emergency power supplies and duplicated water supplies for sprinkler systems are not uncommon. This concept can be extended to any of the fire protection methods in particular to smoke control systems where reliability may be a problem.

Fire control centres, required by the Building Code of Australia, are a feature of high-rise buildings. They may not serve as functional control centres for fire brigade operations and they may choose to guide their activities from a remote site, but a common location where the fire alarms and sprinkler valves are located may be useful.

5.11 Summary

There are numerous systems which can be used to provide for life safety in a building. The interaction between the various systems is very rarely taken into account in building design and each system is installed without reference to others. There has been some work, and much discussion on the interaction of sprinklers with smoke (Morgan, 1997), but this is often in large spaces such as atria where there is concern that the water from the sprinklers will cause the smoke to descend and make the ventilation ineffective. There is also the unanswered question of whether sprinklers may increase the toxicity of smoke by limiting combustion.

In analysing the purpose of various fire protection methods, the most essential aspects are sprinklers, fire resistant construction and smoke detection. These have been identified by Hall (1997) as the three most important aspects of high-rise building fire prevention whose use can provide significant contributions to life safety. Smoke control appears to offer significant life safety benefits, but there is little evidence of what effect they have in a sprinklered building. The use of a simple HVAC shutdown and fire damper activation in a sprinklered building would be sufficient to control smoke.

6. REGULATORY PROVISIONS

6.1 Introduction

To identify means in which the use and cost of fire protection systems can be optimised, an investigation of the code requirements for systems is required. The building codes of Australia, New Zealand, the United States of America (NFPA), England and Wales, Hong Kong and Singapore are reviewed to identify the requirements for fire protection systems in high-rise buildings. The codes are compared to establish where regulations vary between countries. Identifying the variations in fire safety code requirements between countries will enable identification of features of Australian fire safety requirements which can be enhanced or eliminated. The New Zealand 'Deemed-to Satisfy' requirements are known as the 'Acceptable Solutions' and are not part of the Building code, however for the purposes of this work they are referred to as such in this report.

6.2 Procedure

A review of the regulatory codes of Australia, New Zealand, United States of America (NFPA), England and Wales, Hong Kong and Singapore was undertaken to investigate the requirements for the installation of fire protection systems in high-rise buildings. The codes reviewed were:

- **Australia** - The Building Code of Australia, as amended by, Amdt No. 5 (1996)
- **New Zealand** -The New Zealand Building Code (1992)
- **United States of America** - NFPA 101 Life Safety Code (1997)
- **England and Wales** - The Building Regulations (1991) for the Department of the Environment and The Welsh Office
- **Hong Kong** - Code of Practice for the Provision of Means of Escape in Case of Fire (1996), Code of Practice for Fire Resisting Construction (1996), Code of Practice for Means of Access for Firefighting and Rescue (1995), Codes of Practice for Minimum Fire Service Installations and Equipment and Inspection, Testing and Maintenance of Installations and Equipment (June 1998)
- **Singapore** - The Code of Practice for Fire Precautions in Buildings (1997) and the Building Control Act & Regulations of Singapore

Particular attention was paid to the requirements of each code for the installation of fire protection systems. Attention was also paid to elements of building construction which contribute to fire safety.

A matrix of code requirements was made to compare Australian, New Zealand, American and the English and Welsh requirements for fire safety (Refer Appendix B - Matrix of code requirements).

To form the matrix, the elements of the fire protection system were split into four sections: Means of Escape, Active Protection, Passive Protection and Access and Facilities for the Fire Service. Requirements for the fire protection systems were distributed within the matrix according to the specifications of each code.

Code requirements for high-rise fire protection systems in Hong Kong and Singapore were assessed by summarising each relevant code requirement (Lim, 1999A and Lim 1999B).

6.3 Results

Summary Matrix of Code Requirements

Fire Protection Feature	Australia	New Zealand	USA	England & Wales
Means of Escape				
Fire isolated stairways/corridors	X	X	X	X
Signs	X	X	X	X
Emergency Lighting	X	X	X	X
Travel Distance	X	X	X	X
Active				
Smoke Detection	X	X	X	
Smoke Control	X	X		
Alarm	X	X	X	
Sprinklers	X	X	X	X
Hose Reels	X	X		
Extinguishers	X	X	X	
Hydrant/riser System	X	X	X	X
Voice Communication	X	X	X	
Emergency Power Supply	X	X	X	
Fire Control Centre	X	X	X	
Passive				
Fire Resistant Construction	X	X	X	X
Access and Facilities for the Fire Service	X	X	X	X

The matrix is a simplification of the code requirements for fire safety. The list of fire protection features indicate where consideration has been given to design of these features in high-rise buildings. Due to the simplification, variations in fire protection requirements as described by occupancy and building heights above the minimum for a high-rise building, are not detailed in the matrix. The fire protection features distributed are only according to their consideration for high-rise buildings in general.

The code requirements for high-rise buildings constructed in Hong Kong and Singapore are included in the discussion section and are detailed in Lim (1999A and 1999B).

Note, there may be requirements for fire safety, which are required by other Acts. For example, requirements for fire safety in England and Wales are also encompassed by the Fire Precautions Act, Health and Safety at Work, Housing Act and a number of other Statutes enforced by local authority (Refer to Section B1 of the Regulations for England and Wales - Guidance, Interaction with other legislation 0.20-0.24).

6.4 Discussion

Australia and New Zealand classify a high-rise as a building exceeding 25 metres in effective height. Effective height is defined as the height of the building from the lowest level of fire service vehicle entrance to the floor of the top storey (excluding plant rooms). The United States NFPA code classifies a high-rise building as a building exceeding 75 feet in effective height which corresponds to 23 metres in metric measurement, two metres lower than the classifications of Australia and New Zealand. The regulatory code for England and Wales does not define a height whereby a building can be classified as a high-rise. Requirements for fire protection features imply that more stringent requirements, such as automatic sprinklers and phased evacuation, are to be provided for buildings exceeding 30 metres in height. Therefore, the height of high-rise building in England and Wales can therefore be taken to be nominally thirty metres. The 'Code of Practice for Fire Preeautions in Buildings, 1997' (fire code) and Building Control Act & Regulations of Singapore does not have a specific definition for high-rise building. By implication of the need to provide internal fire fighting facilities and equipment in the buildings attaining a certain building height; it is possible to identify buildings more than 24 metres in height as high-rise buildings in Singapore (Lim 1999A). Hong Kong defines a high-rise as a building of whicb the floor of the uppermost storey exceeds 30 metres above the point of stairway discharge at ground floor level.

New Zealand splits the height of the high-rise again into sub-sections; 25 m not > 34 m, 34 m not > 46 m, 46 m not > 58 m and 58 m and greater, with the comprehensiveness of the fire protection system increasing with the height of the building. The Australian building code, except for the requirement that in buildings over 50 m height Fire Control Centres need to be a fire isolated room with impact resistance from falling debris, and the USA (NFPA) fire code, in their requirements for fire protection systems, refer only to one level of high-rise building height.

A common feature of the reviewed codes is that the complexity of the level of protection provided by the fire protection system is influenced by the occupancy of the building. The following occupancy classifications for each code are those relevant to high-rise buildings:

Australia

Class 2 Apartment building, a building with two or more dwellings.
Class 3 Residential building which is a common place of long term or transient living for a number of unrelated persons.
Class 5 Office building used for professional or commercial purposes.
Class 6 Shop or other building of the sale of goods by retail or the supply of services direct to the public.
Class 9 A building of a public nature (including hospitals).

New Zealand

CS Occupied spaces with occupant loads up to 100.
CL Occupied spaces with occupant loads exceeding 100.
CM Spaces for displaying, or selling retail goods, wares or merchandise.
SC Spaces in which principal users, because of age, mental or physical limitations require special care or treatment.
SA Spaces providing transient accommodation, or where limited assistance or care is provided for principal users.
SR Attached and multi-unit residential dwellings.
WL Spaces used for working, business or storage - light fire hazard.

United States of America

Assembly Occupancies
Hotels and Dormitories
Apartment Buildings
Mercantile Occupancies

England and Wales

2(a) Residential (institutional)
2(b) Residential (other) e.g. hotel, boarding house
3 Office
4 Shop and commercial
5 Assembly and recreation
7(a) Storage and other non-residential (any building not within the purpose groups 1 to 6).
7(b) Storage and other non-residential (car parks).

Each occupancy considers the interaction of the occupants with the building, and the fire protection system is designed specifically to consider occupants response to fire. New Zealand and England and Wales are specific with their definitions of occupancy group classifications; Australia and the United States have more broad classifications.

The reviewed codes all look at the combination of passive protection, egress, active protection and access and facilities for the fire service, to define their fire protection systems. The degrees to which the protection system design is influenced by each component, active, passive, egress and access, is dependent on the code requirements of the country. Active protection enables trade-offs against the passive protection requirements, for example, sprinklers enable reductions in fire resistance ratings. The regulations of England and Wales are predominantly focussed on passive protection. The lack of active protection required by the England and Wales codes is compensated for by an increase in fire resistance rating. Where compartments in New Zealand require a one hour fire rating and a sprinkler system, compartments in England and Wales are required to have 1½ to 2 hours fire rating with no automatic sprinklers installed. Automatic sprinklers are required in England and Wales in buildings which exceed 30 metres in height.

Common features of the regulatory codes concerning fire safety include requirements for:

Egress - All codes require high-rise buildings to have emergency lighting installed in exitways along with exit signs. Egress capacity is dependent on the occupant load of the high-rise, with minimum widths assigned to the exitways. Travel distance to exits is considered, with each code restricting the maximum travel distance for an occupant before they reach a safe path or exit. In some instances, travel distances can be increased if more active protection is provided. For example, in New Zealand, if automatic sprinklers are installed, maximum travel distances can be doubled. All codes require high-rise buildings to have an alternative means of exit from each floor. Exceptions where two means of escape are not required occur in residential buildings not exceeding a height of 60 metres in Singapore. The number of exits, in excess of the minimum of two, is dependent on the occupant load for the building.

Riser System - All codes require high-rise buildings to have a riser system installed. Variations occur in the specification of wet or dry risers. Dry risers are required where temperatures are likely to reach below freezing.

Fire resistance Rating and Fire Resistant Construction - Each code uses fire ratings and fire resistant construction to limit the spread of fire both internally and externally. Requirements are in place for the type of materials used (e.g. linings, interior finish), sealing of penetrations, lift shaft and stairwell construction. Some jurisdictions permit a trade off between active fire protection and passive protection; the more active protection, the less degree of passive protection required.

Automatic Sprinkler Systems
All regulatory codes require automatic sprinkler systems to be installed in high-rise buildings. Exceptions to this are residential high-rises in Singapore, which do not exceed 60 metres in height and some residential high-rise buildings in England and Wales. Domestic high-rise buildings in Hong Kong are not required to have an automatic sprinkler system installed regardless of height.

Access and Facilities for the Fire Service - Each code gives consideration to access and facilities required by the fire service to conduct fire fighting and rescue operations. High-rise buildings are required to be fitted with equipment which aids fire fighting operation including riser mains and fire-hose connections. Access to the building must be provided for fire service vehicles.

Features of the Australian code requirements for fire safety which contrast the requirements of other codes include:

Fire Control Centres are required by the Building Code of Australia for high-rise buildings. The Fire Control Centre, as defined by the requirements of the Building Code of Australia, must provide an area from which fire-fighting operations or other emergency procedures can be directed or controlled. The Fire Control Centre must contain controls, panels, telephones, furuiture, equipment and the like associated with the required fire services in the building. The centre must not be used for any purpose other than the control of fire-fighting activities and other measures concerning the occupant safety or security. The Fire Control Centre for high-rise buildings in Australia is similar to the requirements of the NFPA code, with their control centre incorporating operator controls, alarm indicators and manual communications capability. High-rise public and commercial buildings in Singapore are required to have a Fire Control Centre. Requirements for the control centre in Singapore include:

- Buildings with a habitable height between 24 m and 60 m - an ordinary public address system and two way emergency communication system between the fire command centre and every fire fighting lobby.
- Buildings of more than 60 m in habitable height - one way communication system and two way emergency communication system between the fire command centre and every fire-fighting lobby, all essential plant rooms and all lift machine rooms.

A Fire Control Centre is required in high-rise buildings in Hong Kong with the exception of high-rise domestic buildings.

A Fire Control Centre is not required for high-rise buildings iu New Zealand or England. As an alternative, New Zealand has fire service command vehicles which function as the Fire Control Centre.

Emergency Electrical Power Supply
The Building Code of Australia has requirements for emergency electrical power supplies in high-rise buildings for essential safety systems. The New Zealand building code requires buildings exceeding

58 metres to have an emergency electrical power system installed. The USA code specifies cases where high-rise buildings are required to have emergency electrical power supplies.

Heat Detection
Heat detection is not required for high rise buildings as its function is provided by other active fire protection systems such as sprinklers and smoke detectors.

Automatic Alarm System
The Australian Building code requires an automatic alarm system to be installed in all high-rise buildings. The New Zealand Building Code varies its requirements for alarm systems. In some instances manual alarm systems are specified; in some instances automatic alarm systems are specified. The New Zealand Building code (AS 2220 1989).

Fire Fighting Lobbies
Codes in Singapore, Hong Kong and England and Wales require high-rise buildings to have fire-fighting lobbies situated on every floor. Fire fighting lobbies in Singapore are to be at least 2 x 3 m^2 and contain a fire fighting lift, an exit stairway doubling up as a fire fighting stairway and a landing valve from the rising mains. England and Wales regulations require a fire-fighting lobby to be a protected lobby providing access from a fire-fighting stairway to the accommodation area and to any associated fire fighting lift.

Classification of building height
The classification of the height of a high-rise building varies between countries. The height classification of a high-rise building in Australia is comparative to the height classification of a high-rise building in New Zealand. America, with their imperial system, classifies a high-rise building as a building exceeding 23 metres in height, also comparative to New Zealand and Australia. Singapore does not have a specific definition for a high-rise building. By implication of the need to provide internal fire fighting facilities and equipment in the buildings attaining a certain building height; it is possible to identify buildings more than 24 metres in height as high-rise building in Singapore. The height of this high-rise building classification is comparative to those of other countries. Hong Kong classifies a high-rise building as a building exceeding 30 metres in height.

Specification of building occupancy
The definitions of occupancy groups vary between countries. Descriptions of occupancy vary in the level of detail they define. The Building Code of Australia considers the purpose groups of residential, office, shop and buildings of public nature. The New Zealand building code segments the same broad occupancies used in Australia by, for example, allocating occupant loads and fire hazards to their occupancy groups.

6.5 Conclusion

A fire protection system designed to the requirements of the Australian Building Code has little variation to a system designed to the requirements of the New Zealand, USA, England and Wales, Singapore and Hong Kong regulations. All codes use a combination of egress, facilities for the fire service and active and passive protection to design the fire protection system for a high-rise building.

Common features considered for fire protection systems in all countries surveyed include: egress, fire hydrant system, fire resistance rating and fire resistant construction, automatic sprinkler systems, access and facilities for the fire service.

Aspects where the Building Code of Australia varies from requirements of the reviewed codes include provisions for: fire control centres, emergency electrical power supply, automatic alarm system, fire fighting lobbies, classification of building height, specification of building occupancy. These may be worthy of reconsideration within the Building Code of Australia.

7. FIRE MODELLING

COMPUTER SIMULATION OF FIRE AND SMOKE SPREAD IN HIGH-RISE BUILDINGS

7.1 General

Computer simulations of fire and smoke spread in two high-rise buildings were carried out. The buildings were an apartment building and an office building.

The aim of these simulations was to objectively assess the relative importance (and effect) of various fire protection systems that could be expected to be present as part of the fire protection features of high-rise buildings. The potential effectiveness of these systems is measured in terms of their contribution in preventing or delaying the occurrence of untenable conditions in common escape routes or exitways. Systems mainly considered were sprinklers (standard and fast response), compartmentation (fire doors), and smoke control (pressurisation of stairways or common corridors) as these were able to directly impact on either the development of the fire or the spread of smoke through the buildings and could be modelled. The combination of systems selected was chosen by the authors as being appropriate for this indicative study.

The main difference between an analysis of the type carried out here, for a high-rise building and a low-rise building, is the requirement for escape routes to remain tenable for longer periods of time to allow for the longer evacuation times expected for a taller building. The longer evacuation time in a high-rise building is due to longer travel distances within the exitways and due to larger numbers of people in the building creating possible congestion and delays caused by occupants attempting to gain access to the stairway. This is more significant for office buildings than for residential buildings due to the greater occupant densities.

In this analysis, evacuation time estimates have not been carried out, but instead it has been assumed that a 30 minute period is sufficient for complete evacuation, and escape route tenability is compared for various fire protection options over this time-frame.

7.2 The Buildings

Office Building – This building was a 25-storey (approx 65 m high) office building being the "Joelma Building" in Sao Paulo, Brazil that was involved in a disastrous fire in 1974. The first floor and basement were used for storage of office records. The second through tenth floor was used as an open air parking garage and floors 11 to 25 contained offices.

Apartment Building - A 14-storey (approx 51 m high) apartment building with six apartments per level served by a common corridor at each level leading past a lift lobby to gain entry to a fire isolated stair shaft.

Further details of the buildings are provided in Appendix C.

7.3 Tenability Criteria

The occurrence of untenable conditions within the building escape routes may be due to a number of different factors. The following were considered in this study (Purser, 1988; Buchanan, 1994; Fire Code Reform Centre Limited, 1996):

- Radiant heat from a hot upper layer will cause pain to the occupants if the upper layer exceeds about 200°C.
- Convective heat will cause injury to occupants if they are required to breathe hot gases. The temperature criterion varies depending on the length of time occupants are exposed and the moisture content of the gases (e.g. 30 minutes at 60°C or 5 minutes at 130°C – for water vapour content < 10%). Conservatively, a criterion of 60°C was adopted here.
- Occupants are provided with a visibility of not less than 5 m while escaping.
- Occupants are exposed to safe levels of narcotic gases (carbon monoxide, carbon dioxide and depleted oxygen), as represented by a fractional effective dose (FED) for incapacitation of less than 1.

For the purpose of this study, a nominal reference height of 1.5 m above floor level was taken for evaluation of the FED and visibility. For actual design purposes, a higher reference height may be appropriate. Therefore the occupants may be directly exposed to either the upper or lower layer in the compartment depending on the estimated position of the smoke layer interface. The FED calculation is also based on a continuous exposure period commencing at the start of the simulation. In reality, occupants will most likely be exposed for a lesser duration, depending on travel speeds, congestion and queuing within the escape routes.

7.4 The Fire Model

The simulations used the fire software BRANZFIRE Version 99.002 developed by the Building Research Association of New Zealand (Wade, 1996; Wade, 1997; Wade et al, 1997; Wade, 1999). This is a multi-compartment zone model based on conservation of mass and energy that calculates a range of variables (including visibility and toxic gas concentrations) describing the physical environment within the compartments.

For each building, a range of different fire scenarios involving different combinations of fire protection systems was simulated. A description of the scenarios for each building is provided in Appendix C.

7.5 Results

The results are presented (in Appendix C) in the form of graphs describing the change in the environment in the escape route (exitway). These include time-history plots of upper layer temperature, smoke layer position, carbon monoxide concentration, visibility through smoke and fractional effective dose. Tables summarising time to reach the tenability criteria are also provided.

7.6 Summary of Conclusions

1. The modelling confirmed that in high-rise apartment buildings, fire doors to each apartment are essential to provide a common corridor with any reasonable level of protection from smoke spreading from the apartment. This is considered necessary even with sprinklers installed because there may still be significant smoke spread through an open door prior to the operation of the sprinklers resulting in poor visibility (smoke-logging) of the corridor within a short period of time.
2. Pressurisation systems (in conjunction with fire doors to apartments) appear to be potentially the most effective method of maintaining tenability and good visibility in escape routes. However there could also be greater variability in performance as the actual number of doors open to the stairway at any one time may be quite different from the number assumed in the design. Further investigation of this variability and the sensitivity of the modelling results to it, is warranted.
3. If pressurisation systems are to be used in either stairways or common corridors then smoke detectors in at least the corridors are essential for early activation of the system.
4. Where sprinklers are installed in apartment buildings, fast response sprinklers are preferable to standard response sprinklers for the additional time provided for evacuation.
5. To improve visibility in escape routes that are not pressurised, illuminated exit signs are recommended in preference to reflective signs.
6. The reconstruction of the Joelma Building fire incident is consistent with the observed reports. The effect of adding a sprinkler system to the building is predicted to have only a small effect on the time to exceed the visibility criteria within the stairway due to the amount of smoke produced prior to activation of the sprinkler. However it is likely that the extent of fire spread beyond room of origin and between floors and the overall loss of life would have been dramatically decreased (if not prevented). The effect of adding both sprinklers and lift/stairway lobby compartmentation would have most likely kept the escape routes tenable for more than 20 minutes.
7. In high-rise office buildings, sprinklers and fire isolation of the escape route/exitway are essential. Smoke detectors in fire isolated exitways are strongly recommended.
8. High-rise apartment buildings require a smoke detection system within corridors and stairways for building alert and evacuation. Smoke detectors within apartments are strongly recommended for early warning within the apartment.

8. HUMAN BEHAVIOUR

8.1 Introduction

Human response to a fire is more critical in a tall building than in a low-rise structure because margins for safe exiting are more limited (Council on Tall Buildings and Urban Habitat, 1992). Limited building exits can mean they are congested, restricting egress and heightening the sense of urgency to escape. The nature of high-rise building construction often means occupants are unaware of the location and severity of the fire. Occupants can potentially increase their personal risk if decisions made are based on incomplete information.

This chapter investigates the human behavioural characteristics which influence the behaviour of occupants in high-rise building fires. Established human behavioural concepts are described and reference to their effect on human behaviour in high-rise buildings is made. The options for evacuation are described, with reference to decision making when assessing the best option. Elements of building construction which aid and impede the safe egress of humans from a high-rise building fire are outlined. Familiarity with the building layout influences escape behaviour of occupants. Some case studies are used to highlight the importance of building familiarity and the importance of trained staff to assist evacuation. Computer modelling can give an impression of how humans interact with their environment during building evacuation. Some commonly used computer models are listed.

8.2 Human Behavioural Characteristics

Human behaviour influences the two stages of evacuation; pre-movement and movement.

The pre-movement stage is concerned with the interaction of occupants with fire related cues; how the clarity of information from the fire influences the way people behave during the early stages.

The movement stage is concerned with the options for escape; how people behave once movement to exits has begun.

Laboratory experiments, evacuation research, computer simulations, questionnaire surveys and case studies through interviews have established six identifiable human behavioural concepts. The six behavioural concepts are:

- Investigation - responding to fire related cues, looking for the source, clarifying information with others.
- Alerting - sounding the alarm and/or alerting others.
- Fire fighting - an attempt to control/extinguish the threatening fire.
- Refuge/evacuation - moving to a designated safe place, i.e. another floor or exiting a building.
- Convergence clusters - assembling at a perceived safe place, i.e. someone else's apartment/room within a building, also indicative of altruistic behaviour where occupants assist others to places of refuge.
- Re-entry - re-entering a building for the purpose of rescue or fire fighting.

The first three are predominantly associated with the pre-movement stage of evacuation; the latter three are predominantly associated with the movement stage.

Investigation, alerting, fire fighting are all common features of human behaviour in a high-rise building. Convergence and re-entry are less common, though the literature is sparse on these matters.

There are psychological, sociological and cultural variables relative to each of the above human behavioural concepts, which influence the way in which an individual will react. For example, consider the case of re-entry into a burning high-rise building. An office worker, or person in a professional role, is less likely to re-enter a burning bnilding to retrieve their computer than a parent, or member of the family group, re-entering the building to rescne a child. Another example is the concept of investigation. Experiments (Lantane, 1968) show that a person alone in a room will respond more quickly to smoke as a fire cue than a group of people where reassurance from others is often sought before action is taken.

The success of evacuation from fire in a high-rise building is assessed according to the number of injuries and fatalities. Injuries and fatalities are often dependent on the choices occupants make for their means of escape. Once occupants have been alerted to the fire, they have options for reaction. The options include immediate evacuation, staying put and relocation. Immediate evacuation is the most common reaction to a continuous fire alarm or interaction with the fire created environment. Often, due to the nature of a high-rise building, it is not feasible, or necessary, for all occupants to evacuate immediately. In the case of a fire in a residential high-rise building in the USA (NFPA 1995), once aware of the fire, some residents attempted to evacuate early in the incident and were successful. Other residents who attempted to evacuate minutes later were unable to do so. Some residents moved through worsening smoke conditions only to be forced to abandon their attempted escape and seek refuge in apartments. Many residents who sought refuge in their apartments or in apartments of other residents (convergence) were able to stay safely in the apartments where they were rescued by the fire brigade. Some residents moved from the apartments to their balconies. In many instances, the people who remained in their apartments or moved to the balconies were exposed to less risk to their safety than those who attempted to escape. However, those residents that left upon activation of the alarm bells were able to get out of the building safely. Case studies highlight the necessity for constant re-evaluation of actions during the movement stage of evacuation (Wolf 1999). Studies also emphasise the importance of training and education prior to the fire event; wben is it best to evacuate, stay put or relocate to a plaee of safety within the building. Siegel-McKelvey (1999) lists some recommendations concerning the steps of evacuation from residential high-rise buildings and hotels. The steps include ways which judgement can be used to determine if evacuation, staying put or relocation is the best decision when confronted with a high-rise building fire.

8.3 Building Characteristics

In order to achieve a degree of fire safety in a high-rise building, an understanding of the way occupants use the building is required. Sime (1994) states that escape behaviour design requires an understanding of:

1. The normal use of a building (for example which routes are most familiar); and
2. The fact that a building or setting is not only a physical structure, but an information and communication system.

The latter is related as much to information technology, such as alarm sirens, electronic visual displays and public address systems, as the spatial layout and design of features, such as 'landmarks' which help people to orientate themselves in the building. Design of high-rise buildings can rely on the altruistic behaviour between occupants but to ensure safer egress, occupants should also depend on sound design features and good emergency planning.

The Building Code of Australia requires high-rise buildings to have at least two means of egress from each floor. Additional exits are designed on the basis of building size and occupant load. Studies in human behaviour have found that there are factors which influence exit choice. These factors include (Sime, 1994):

1. Advice provided (guidance prior to fire)
2. Role (for example staff or public)
3. Escape route familiarity and building layout
4. Group dynamics and attachments
5. Characteristics such as age, infirmity and disability
6. Location and proximity to exit
7. Information/communication on fire in progress
8. Smoke obscuration (visibility, irritancy and toxicity)
9. Fire characteristics (such as heat and smell)
10. Light levels and light sources

The design of exits in high-rise buildings must consider the human behavioural factors which influence exit choice.

8.4 Emergency Planning

The actions and reactions of building staff are extremely important in high-rise fires. In large high-rise building fires, the performance of staff has rarely been adequate in the early stages, usually due to inadequate emergency training (Council on Tall Buildings and Urban Habitat, 1992). As well as training of staff, it is imperative that occupants be familiar with evacuation procedure. Familiarity with fire safety procedure reduces the potential for confusion and behaviour which increases risk.

An example of a case where staff training was important is the case of a fire in a residential high-rise building in North York, USA. Six residents were killed. No one in the building was trained to use the emergency voice communication system so it was not used during the initial stages of the fire thereby delaying evacuation and information to the occupants, and contributing to the fatalities. When the emergency voice alarm communication system was used at some point later in the fire, many residents did not hear or could not understand the messages. Perhaps if the staff were trained in the use of the communication system and residents were familiar with its use, residents would not have been reliant on radios and televisions to provide information of the fire; occupants may not have died (NFPA 1995). Tbis case study highlights the importance of being able to reliably communicate information and tbe need for training.

8.5 Computer Modelling

Computer modelling can only provide an indication of how people might respond in a high-rise building fire. There are too many variables associated with each individual to enable modelling of every possible evacuation scenario. Variables which influence how an individual is going to react in the event of a high-rise building fire include:

- Physiological - including mobility, sight, hearing, drugs, intoxication and exhaustion
- Cultural - whether the individual has a primary group role (family affiliation) or a professional role
- Psychological - levels of stress or anxiety
- Experience - involvement in false alarms or previous fires
- Educational - levels of training such as fire drills

Computer modelling can guide in predicting evacuation times for high-rise buildings if the critical predictors of the fire development, the building/structure, the occupancy and the psychological/cultural characteristics of the population are assessed. The more accurate the assessment of the occupant profile and the occupant scenario, the more accurate the results of the computer modelling will be. Computer models in common use include: EVACNET+, SIMULEX, EXIT89, EXITT, EXODUS.

8.6 Conclusion

Human behaviour plays a fundamental role in the function of fire protection systems in high-rise buildings. Established human behavioural concepts can be used to help understand how humans use and interact with their building in a fire situation. Consideration of human behaviour is required in the design of a fire protection system for a high-rise building which will best protect and assist occupants in the event of a fire. Case studies emphasise the importance of training in fire safety procedure.

9. FIRE BRIGADE INTERVENTION

From a firefighting perspective, combating a high-rise building fire is one of the most logistically difficult firefighting scenarios. There are many reasons for this: the fire's location and extent is not always evident upon arrival; the concern of a significant occupant load and resultant search and rescue requirements; fire-fighters may need to manually take equipment to the fire (which can be both time consuming and exhausting) and the confined environment in which firefighting needs to be undertaken.

More than any other type of building, fire-fighters rely upon the fire protection systems in high-rise buildings *intended for fire-fighter use*. These systems typically comprise: internal hydrant systems, booster connections, specific fire-fighter lifts and communication systems. (MMFB, 1996).

The predominant nnmber of high-rise buildings are situated in large cities and these large cities will almost certainly have a full-time, well trained and resourced professional fire brigade.

The Melbourne Metropolitan Fire and Emergency Services Board (MFESB) and the Country Fire Authority (CFA) have dedicated fire-fighters and modern firefighting resources which are available 24 hours a day, 365 days of the year. It is assumed that the MFESB has resourced and equipped itself in the knowledge that, within its jurisdiction, it may need to combat a fire in a high-rise building.

A subject that is worthy of review is:

Is some of the modern equipment that the fire brigades have, duplicating the equipment that the Building Code requires in a high-rise building?

Examples of this may be:

- The need for pumps on hydrant and sprinkler systems when fire trucks also have large pumps.
- The need for an internal hydrant system to already contain water (wet risers) when a fire truck is capable of pnmping (charging) a hydrant system in time for use by the fire-fighters.
- The need for a control centre within the building when the fire brigade has it own mobile operational command control units?

Other areas that it would be of value to review are: communication systems; fire-fighter lifts; hydrants and fire hose reels; and the issue of mechanical smoke control in light of breathing apparatus.

With the contemporary view of the MFESB towards fire safety engineering and the development of this expertise within that service, this review would best be undertaken with their involvement. It should be borne in mind that it would be their personnel that would be involved in combating high-rise building fires.

9.1 Recommendation

It is therefore recommended that the Building Control Commission consult with the MFESB and Country Fire Authority to obtain their views on the issue of dnplication of fire protection systems in high-rise buildings. It would also be possible for an external party to facilitate such a meeting and to develop the concepts discussed as a further project.

10. ECONOMICS

10.1 Introduction

To enable identification of methods for possible cost minimisation without compromising existing safety levels of fire protection systems, an analysis of current costs for the system is required. This section itemises the costs for two fire protection systems in high-rise buildings; one for a 14-storey residential building and one for a 14-storey office building. Costs for the fire protection systems are expressed as a proportion of the total construction cost of the building to indicate their influence on the overall cost of a high-rise building.

10.2 Procedure

For the purposes of estimating the costs for the installation of a fire protection system in a high-rise building, a generic building plan was chosen. The generic building has a footprint of 400 m^2 and is 14 storeys high. The ground floor has a height of 4.1 m with subsequent floors 3.2 m tall, making the building height, nominally, fifty metres. Each floor is assumed to have an identical layout, with stairways positioned at opposite sides of the building, providing two means of egress. This may seem a small floor area but as the costs are pro-rata on floor area and expressed as a percentage, the figure has been used for calculation purposes only.

A purpose group was required to be assigned to the 14 storey high-rise building to determine what fire protection was necessary. The two most common uses for high-rise buildings are residential, incorporating hotel and private accommodation, and offices. The purpose groups, residential (Class 2) and offices (Class 5), were assigned to the building to assess two combinations of fire protection systems. The two purpose groups demand different use of the space within the high-rise building. When assigned residential (Class 2), each floor of the high-rise building has a central corridor spanning between stairways and linking six, self-contained flats; when assigned office (Class 5), each floor is an open plan office, with exits provided by the stairways. The building height, purpose group classification and layout enabled the fire protection for the high-rise building to be determined from the requirements of the Building Code of Australia.

Costs for fire protection systems were taken from values provided by Rawlinsons Construction Handbook (1998). Rawlinsons' provides a range of prices indicative of the in-place cost of the fire protection feature; the prices are based on a per unit or per square metre rate, as appropriate. Prices for the cost estimate of the high-rise building fire protection system were taken as the average for construction and installation in Melbourne, Australia. Quantities for the elements of the fire protection system were based on the building design and the requirements for installation as defined by the Building Code of Australia.

To determine the proportion of the total building costs spent on fire safety, an estimate of the construction cost for the high-rise building was required. Rawlinsons' provided a cost per square metre for construction of a residential building and an office building and these values were used to estimate the total cost for construction of the 14 storey high-rise building. Each feature of the fire protection system can be described as a proportion of the total cost for the construction of the high-rise building.

10.3 Limitations

Limitations arise from the use of general estimate prices. Aspects which influence the accuracy of the estimate include:

- The cost estimate of the fire protection system did not include the costs for maintenance of the system over the building's life span.
- Prices are based on the units of per square metre floor area and per item.
- Dollar values taken as the average from the Melbourne range of figures.
- Two purpose groups were considered, Residential (Class 2) and Open Plan Offices (Class 5). High-rise buildings may be constructed for a wider variety of purpose groups with varying fire protection system requirements.
- The chosen generic building has a relatively small footprint (400 m^2). Increasing the size of the footprint will influence the cost of the fire protection system, particularly for items with price calculated on a per square metre floor area, but as proportion of the total building costs, the figures are representative.
- Based on the requirements of the Building Code of Australia.
- Prices used in the cost estimate are based on 1998 figures.
- It is recommended, by Rawlinsons, that building costs per square metre be used only for initial feasibility studies of buildings in Metropolitan areas.
- Prices are required to be amended for special circumstances such as sloping sites, unusual shape, high wall to floor ratio.
- For the total building cost - price excludes external services outside 3 metres from the outside face of the building, external works other than those immediately adjacent to the building, car parks, land, demolition, balconies, loose or special equipment, furniture, furnishings, legal and professional fees.

10.4 Results

The building characteristics and fire safety design characteristics used to determine the required fire protection and the conclusive fire safety precautions are described in Table 1.

BUILDING CHARACTERISTIC	OPEN PLAN OFFICE	APARTMENT
Height (m)	50	50
Number of Floors	14	14
Floor Area (m^2)	400	400
Total Floor Area (m^2)	5600	5600
Number Offices / Apartments	14	84
Number Offices / Apartments per floor	1	6
Area per Office/Apartment	400	67

Table 1 Building Characteristics

Rawlinsons' Australian Construction Handbook is used to determine the prices for the elements of the fire resistance rating, alarm type and fire protection required for the two high-rise buildings. The prices for the fire protection systems are compared with the total price for the high-rise construction to illustrate the proportional distribution cost of each. Estimation of the cost of the fire protection system resulted in the following (prices quoted are in Australian dollars):

	Office	% Total Cost	Apartment	% Total Cost
Estimation of building costs per square metre	$8 960 000		$8 960 000	
Estimation of costs for installation of fire protection				
Smoke Control	$280 000	3.13	N/A	N/A
Automatic Sprinkler Systems	$222 600	2.48	$162 400	1.81
Detector and Alarm Systems	$94 120	1.05	$108 400	1.21
Fire resistance Rating	$68 880	0.77	$145 740	1.63
Hydrant Points, Hose Reels, Cabinets	$40 120	0.45	$40 120	0.45
Stair Pressurisation	$34 000	0.38	$34 000	0.38
Power and Lighting Equipment	$26 880	0.30	$26 880	0.30
Extinguishers	$5 625	0.06	$15 750	0.18
TOTAL	**$772 225**	**8.62**	**$533 290**	**5.95**

Summary of Results

	Total	FSS	FSS % Total
Cost per Office	$640 000	$55 160	8.6
Cost per Apartment	$106 000	$6 350	6.0

Prices quoted are an estimate, providing a general guide to the proportional distribution of fire precaution costs. For more accurate results, a complete design of a fire protection system for a building would be required, with prices for each feature determined by quantity surveyors.

10.5 Discussion

For the purposes of this discussion fire protection systems cover those costed above in section 10.4.

It was found that the cost of the fire protection system contributed to approximately 6% of the total cost of the construction of the high-rise residential building. This figure corresponds well with the findings of a study at the Victoria University of Technology (Moore et al, 1992) where the cost of fire protection for an office building in 1989 was estimated to be approximately 6% of the total building costs. For the high-rise office building, the cost of the fire protection system contributed to approximately 8.6% of the total cost of building construction.

The cost of the fire protection system for the residential high-rise building was found to be 5.95%, with the cost for the office high-rise office building being 8.62%. It can be concluded that the costs for installation of a fire protection system for the two high-rise buildings are equivalent to approximately 6%, for the high-rise residential building and 9%, for the high-rise office building.

Analysis of the distribution of the cost of the components of the protection system finds the automatic sprinkler system and the mechanical smoke control system to contribute to the highest proportion of the costs for the high-rise office building; the automatic sprinkler system and the detection and alarm system contribute to the highest proportion of the costs of the fire protection system in the high-rise residential building.

The cost of changing the air conditioning system to a mechanical smoke control system in the high-rise office building, contributed to the significant difference between the cost of the fire protection system for the two buildings. The mechanical smoke control system, at an estimated $50/m² of floor area, increased the cost of the fire protection system by 3% of the total building cost, contributing to over one third of the total cost of the complete fire protection system. The high-rise residential building is reliant on pressurisation of stairways and natural ventilation, generally in the form of windows, for smoke control.

Exclusion of mechanised smoke control in the high-rise office building influences, significantly, the cost of the fire protection system. Removing the cost of the smoke control system reduces the total cost to approximately 6% of the total building cost, making the cost of the fire protection in the high-rise office building equivalent to that of the residential high-rise building.

Other differences between the distribution of the cost of the components for the high-rise residential building and the high-rise office building occur predominantly in the cost for the fire resistance rating. The difference in cost can be accounted for by the number of fire doors required for each building. The high-rise office building requires fire doors to enclose the stairways; the high-rise residential building requires fire rated doors entering each apartment as well as the stairways, greatly increasing the quantity required and subsequently, the cost. The hazard classification of each high-rise building influences the cost of the automatic sprinkler system. The high-rise residential building is classified as extra light hazard; the high-rise office building is classified as an ordinary hazard. Rawlinsons' price ordinary hazard sprinkler systems at a higher monetary rate, per square metre of floor area, than extra light hazard, hence contributing to the variation in cost between the buildings. Other features of the fire protection system, when compared between the buildings, correspond well in price.

10.6 Conclusion

An estimate of the cost for a fire protection system to be installed in a 14-storey residential building and a 14-storey high-rise office building, found the costs to be approximately 6% and 9% respectively, of the total construction cost of the building. The antomatic sprinkler system and the mechanical smoke control system contribute to the majority of the cost in the high-rise office building. The automatic sprinkler system and the fire detection and alarm system contribute to the majority of the cost of a fire protection system in the high-rise residential building at a combined approximate of 3% of the total building cost. Removal of the cost of the mechanical smoke control system for the high-rise office building, reduces the cost of the fire protection system for the building to approximately 6% of the total building cost, equivalent to that for the high-rise residential building.

11. OPTIMISATION

In order to identify the likely optimisation possible with fire protection for high-rise buildings the value, both operational and economic must be considered. The greatest economic benefit would be to eliminate the high cost items, however tbis should not be done at the expense of providing less than adequate safety. It may mean that some of the higher cost items must remain in order to provide at least a basic level of life protection. It then would be appropriate to consider for elimination those systems with a higher cost but low impact on safety.

The following tables summarise the cost of the various fire protection systems on the basis of total building costs (Table 11.1) and as a percentage of the total cost of fire protection in the building (Table 11.2).

System	Office	Apartment
	% of total building costs	% of total building costs
Smoke Control*	3.13	N/A
Automatic Extinguishing Systems (Sprinklers)	2.48	1.81
Detector and Alarm Systems	1.05	1.21
Fire Resistance Rating	0.77	1.63
Hydrant Points, Hose Reels, Cabinets	0.45	0.45
Stair Pressurisation	0.38	0.38
Power and Lighting Equipment	0.30	0.30
Extinguishers	0.06	0.18
TOTAL	**8.62**	**5.96**

Table 11.1

System	Office	Apartment
	% of total fire protection cost	% of total fire protection cost
Smoke Control*	36	N/A
Automatic Extinguishing Systems (sprinklers)	29	30
Detector and Alarm Systems	12	20
Fire Resistance Rating	9	27
Hydrant Points, Hose Reels, Cabinets	5	8
Stair Pressurisation	4	6
Power and Lighting Equipment	3	5
Extinguishers	1	3
TOTAL	**100**	**100**

*Estimate only. Full HVAC to AS/NZS 1668.1 zoned smoke control system.

Table 11.2

From these tables the greatest cost saving would arise from eliminating smoke control systems in offices and sprinkler systems in apartments. But this would have a significant effect on fire safety as sprinklers and smoke control are high ranking fire protection. Smoke control systems may be worthy of further investigation as their effectiveness in a sprinklered building could be limited and a simpler system proposed using fire dampers and system shutdown could be of a greater cost benefit.

The optimum fire protection would therefore be considered irrespective of monetary costs and rely on life safety issues.

The figure of 6% for the total cost of fire protection does not seem to be high, but to a building owner if a $50,000 system can be excluded, despite the fact that in a $1.6 M building it would not be proportionately high, it would be a worthwhile exercise to attempt. The 8.6% for office buildings could represent a significant proportion of the total costs and optimisation may be possible in this area.

Putting these costs into perspective gives little scope for optimisation, however the smoke control system appears to offer an area where economies could be made though accurate figures that would need to be established to give a more reasonable value.

A fire protection item not covered by the above, because it would not normally be associated with bnilding construction, is the unquantified factor affecting human behaviour such as fire education and training (e.g. trial evacuations) and modification of peoples response to a fire through dissemination of iuformation and comprehensive fire planning. This could be done at a relatively low cost, yet provide significant improvements to fire safety. Fire brigades are attempting such methods (Wolf, 1999) and could yield positive results for a relatively low cost solution.

12 SUMMARY AND RECOMMENDATIONS

The literature review identified various issues surrounding fire safety in high-rise buildings and with the analysis of international regulatory requirements and fire protection methods, three fire protection methods were identified as the most significant. These were:

- sprinkler systems
- fire resistant and smoke stopping construction
- smoke detection and alarm.

Combined with these, stair pressurisation and possibly more complex mechanical smoke control systems would assist in maintaining safe conditions in building fires. Other fire protection methods such as first aid fire fighting were minor in comparison.

The computer modelling which was carried out, found that stair pressurisation was an effective method of maintaining tenable conditions in a fire isolated stairway but further modelling would need to be carried out to establish the sensitivity of such systems. The conclusions of the modelling also stated that sprinklers and fire isolated exitways were essential in offices. Though carried out in isolation to the literature review and the fire protection systems analysis, the fire modelling conclusions are not dissimilar to those derived from that study.

An area where it would be possible for greater improvements in fire safety is hnman behaviour. This topic is just beginning to be more rigorously explored and the modification of people's responses to a fire, and to fire prevention, is worthy of fnrther study. Though not considered a subject yet for inclusion in the 'Deemed to Satisfy' provisions of the Building Code of Australia, it may be possible for this to happen. In New Zealand the *Fire Safety and Evacuation of Buildings Regulations, 1992*, is an example of such an approach, where a "deemed to satisfy" provision applies. This legislation is mandatory and expressed in prescriptive terms, not in performance terms as understood in today's fire safety engineering community.

The Fire Brigade plays the role of firefighting in high-rise buildings and their involvement is complex. As was indicated in the Fire Brigade Intervention chapter, further work is needed in this area to fully understand its effects.

Risk Assessment methods for life safety and specific sprinkler performance based design have not been addressed by this report as they would not normally be included in the'Deemed-to-Satisfy" provisions. They have been the subject of recent interest but have not been developed to an extent where they may be extensively used in buildings as a valid addition to the Building Code of Australia. However they may be worthy of further study.

Recommendations

The main areas of fire protection considered worthy of future research are:

- Smoke control in relation to whether a simplified approach would be effective, rather than the methods proposed in AS 1668.1.
- Human behaviour including occupant training and the establishment of a comprehensive evacuation scheme in high-rise buildings, making use of concepts of staged evacuation without the need for total evacuation. The possibility of including such features in the "Deemed to Satisfy" provisions could also be explored.
- Consider entering into extensive discussions with the Fire Brigade on high-rise firefighting.
- Explore risk assessment methods for life safety and sprinkler design.

*NB (Further recommendations are presented in the executive summary.)

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APPENDIX A Significant High Rise Fire Incidents

Date	Place	Floors	Fatalities	Fire Protection	Factors
25-Dec-71	Tae Yon Kak Hotel, Soeul, Korea	21	163	Basement only sprinklered. Heat detectors in rooms Manual call points. Automatic evacuation alarm	Locked stairway Fire and smoke spread through stair
24-Feb-72	Andraus Building, Sao Paulo, Brazil	31	16	Manual alarm	Lack of any fire protection systems Combustible finishes on walls and ceilings
30-Nov-72	Baptist Atlanta, USA	11	11	1 not connected 11,12 1 hour FRL	Delayed alarm Open door Corridor make up air Wind Subducts
1-Feb-74	Joelma Sao Paulo, Brazil	31	179	Manual alarm	Lack of safe exit paths(one only) No automatic alarm
21-Nov-80	MGM Grand, Las Vegas, USA	23	85	Manual alarm, partial sprinkler system	Lack of comprehensive fire protection systems Smoke movement throughout building
6-Mar-1982	Westchase Hilton, Houston, USA	13	12	Sprinklers in linen chutes only Smoke detection, broken	Room door left open Poor staff reaction Exits not clearly marked
21-Dec-86	Dupont Plaza, USA	20	97	Manual alarm (not working)	No sprinklers No smoke detection No evacuation plan Lack of adequate exit width lack of adequate fire separation in lower area Smoke spread through service shafts
11-July 1997	Pattaya, Hotel, Thailand	17	78		No sprinklers Lack of fire separation in lower floors No stairway pressurisation Lack of self closers on doors Lack of fire stopping in service shafts

There have been may more high rise building fires which are listed in *Fire Safety in Tall Buildings* (Council on Tall Buildings and Urban Habitat 1992), and Martin (1998) also identifies various multiple fatality fires (including some of the above) and for which there are no details. Two more recent examples of high rise apartments fires are given by Wolf (1999), where three firefighters in one fire and four occupants in the other fire died.

Appendix B1 MATRIX OF CODE REQUIREMENTS

		NEW ZEALAND																												AUSTRALIA				ENGLAND							USA									
																																									Assembly Occupancies		Hotels and Dormitories		Apartment Buildings		Mercantile Occupancies		Business Occupancies	
Height Classification of High Rise		25 m not > 34 m							34 m not > 46 m							46 m not > 58 m							58 m and greater							25 metres																				
Purpose Group Classifications		CS	CL	CM	SC	SA	SR	WL	CS	CL	CM	SC	SA	SR	WL	CS	CL	CM	SC	SA	SR	WL	CS	CL	CM	SC	SA	SR	WL	2	5	6	9	2(a)	2(b)	3	4	5	7(a)	7(b)	N	E	N	E	N	E	N	E	N	E
Means of Escape																																																		
Evacuation	Drills	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X			X	X	X	X
Stairwell	Safepath/fire isolated	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
	Pressurisation	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X																	
Exits	Minimum widths	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
	Signs	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Emergency Lighting		X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Alternative Means of Escape		X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Open Path Length and Travel Distance Limitations		X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Requirements for Doors on Escape Routes (eg opening, hardware)		X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Lifts	Fire Protection of Lift Installations	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X										
Active																																																		
Smoke	Detection				X		X	X					X			X	X	X	X	X	X		X	X	X	X	X	X	X	X	X	X	X								X	X	X	X	X	X				
	Control in Air Handling System	X	X	X	X	X		X	X	X	X	X	X		X	X	X	X	X	X		X	X	X	X	X	X		X	X	X	X	X								X	X	X	X	X	X	X	X	X	X
	Zoned Smoke Control System																													X	X	X	X																	
Manual Call Points		X	X	X		X			X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X								X	X	X	X	X	X	X	X	X	X
Sprinkler System		X	X	X		X			X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X		X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Fire Hose Reels		X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X																	
Fire Extinguishers		X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X										X	X				X	X	X
Fire Hydrant System		X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Hold Open Devices		X	X		X	X			X	X		X	X			X	X		X	X			X	X		X	X			X	X	X	X																	
Voice Communication Systems (EWIS)				X	X	X					X	X	X					X	X	X					X	X	X			X	X	X	X								X	X	X	X	X	X	X	X	X	X
Emergency Electrical Power Supply																									X	X	X			X	X	X	X								X	X	X	X	X	X	X	X	X	X
Fire Control Room				X	X	X	X				X	X	X	X				X	X	X	X				X	X	X	X		X	X	X	X								X	X	X	X	X	X	X	X	X	X
Passive																																																		
Fire Resistance (Construction, doors, walls, penetrations, stairs)		X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Materials (Linings, Interior Finish etc to reduce flame spread)		X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Access and Facilities for the Fire Service																																																		
Firefighting	Vehicle Access	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X										
	Shafts																													X	X	X	X	X	X	X	X	X	X	X										
	Telephone Communication (Part of EWIS)			X	X	X					X	X	X					X	X	X					X	X	X			X	X	X	X								X	X	X	X	X	X	X	X	X	X
	Lifts	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X'	X'	X'	X'	X'	X'	X	X	X	X	X	X	X	X	X	X	X

Appendix B2 MATRIX KEY

Country	Key	Definition
New Zealand	CS	Occupied spaces with occupant loads up to 100
	CL	Occupied spaces with occupant loads exceeding 100
	CM	Spaces for displaying, or selling retail goods, wares or merchandise
	SC	Spaces in which principal user because of age, mental or physical limitations require special care or treatment
	SA	Spaces providing transient accommodation, or where limited assistance or care is provided for principal users
	SR	Attached and multi-unit residential dwellings
	WL	Spaces used for working, business or storage - light fire hazard
Australia	**2**	**Residential building containing two or more sole-occupancy units each being a separate building (eg an apartment).**
	5	**Office building used for professional or commercial purposes**
	6	**Shop or other building of the sale of goods by retail or the supply of services direct to the public**
	9	**A building of a public nature**
England and Wales	2(a)	Residential (institutional)
	2(b)	Residential (other) eg hotel, boarding house
	3	Office
	4	Shop and Commercial
	5	Assembly and Recreation
	7(a)	Storage and other Non-residential (any building not within the purpose groups 1 to 6)
	7(b)	Storage and other Non-residential (carparks)
USA	N	New Buildings
	E	Existing Buildings

APPENDIX C FIRE MODELLING

Part 1 - Fire Safety in a High-Rise Apartment Building

Aim

The aim of this part of the study is to assess the relative importance of various fire protection systems that might be present in a high-rise apartment building in terms of their influence in preventing the occurrence of untenable conditions in common escape routes and exitways. Computer simulations of smoke spread from an apartment to a common corridor and stair shaft have been carried out.

Building Characteristics

The building under consideration is a 14 storey apartment building with 6 apartments per level served by a common corridor at each level which leads past a lift lobby to gain entry to a fire isolated stair shaft. Leakage of smoke from the corridor to the lift shaft has not been considered for the purposes of this analysis. This is a conservative assumption.

Typical apartment – 47 m^2 floor area and 2.4 m ceiling height (floor level 7.3 m above stair shaft floor).

Public corridor – 24.2 m^2 floor area and 2.4 m ceiling height (floor level 7.3 m above stair shaft floor, and connected to the apartment).

Stair shaft – 11.5 m^2 floor area (2.4 m x 4.8 m x 51 m high and connected to the corridor).

The stair shaft and all floors are assumed to be of concrete construction, while the corridor and apartment walls and ceiling are assumed to be of gypsum plasterboard materials.

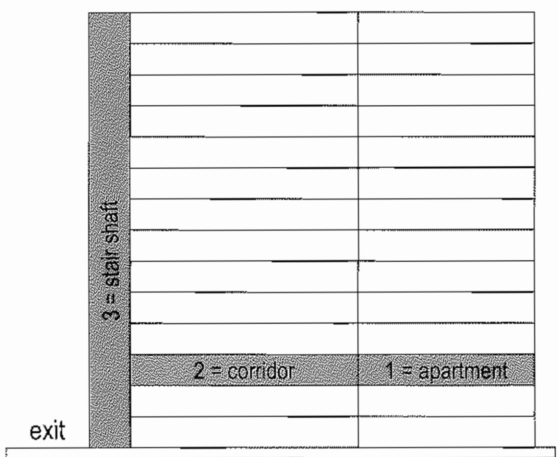

Figure C1 : Apartment Building

Fire Scenarios and Assumptions

Nine alternative fire designs have been considered using a combination of sprinklers, pressurisation, type of signage and fire doors. A matrix describing the fire protection systems for each scenario is given in Table C1. Heat and smoke detectors are not included in this table as they do not directly impact on the development of untenable conditions. They would however be considered in an analysis of egress. Where pressurisation systems are included it is assumed they will be activated by smoke detectors installed within stairways and corridors.

In all cases, the apartments are assumed to be fire separated from the corridor and other apartments with fire resistant construction meeting at least 30 minutes.

When a fire door is assumed to be present as the entry door to the apartment, the door is assumed to be closed except for evacuation of apartment occupants (from 60-80 seconds). To allow for smoke leakage around the door, gaps of 3 mm at the top and each side of the leaf are assumed, with a 10 mm gap under the sill. These gaps are maintained for the 30-minute duration of the simulation. The fire resistance level of the door is taken to be at least -/30/30. Any direct smoke contribution from a burning fire door is not considered. This would be a non-conservative assumption where the door is of combustible construction.

Where either the stairway or corridor are pressurised, the increase in pressure is modelled as being approximately 30 Pa. The pressurisation fans are assumed to operate when the upper layer temperature in the corridor has increased by ~10°C (simulating smoke detector activation). This occurs at about 80 seconds. It is also assumed that the fans take 30 seconds to reach their full speed.

In all cases it is assumed that the door between the corridor and the stairway is a fire door with the same performance and leakage characteristics as for the apartment door. The door is assumed to be closed except for evacuation purposes (from 70-100 seconds). This door may be subject to further opening/closing if used by the occupants of other apartments on the fire floor, however with respect to the occurrence of untenable conditions in the corridor it is conservative to ignore any subsequent door opening/closing.

Where sprinklers are used, it is assumed that the radial distance between the fire plume and the sprinkler head is 3.2 m (i.e. located between sprinkler heads and not directly beneath a sprinkler head). Conduction losses from the sprinkler head to the pipework are ignored. Response time indices of 200 and 50 $ms^{1/2}$ are taken for standard and fast response sprinklers respectively. Activation temperatures of 74 and 68°C are used for standard and fast response sprinklers respectively. On activation of the sprinkler system, the design fire is modified using a suppression algorithm based on a water spray density of 2.7 mm/min ($L/m^2/min$).

A door located at the bottom of the stair shaft is assumed to be open for the duration of the simulation. A small amount of leakage is also assumed to the exterior over the height of the stair shaft. Similarly, leakage from the corridor to other apartments at the same level is simulated by assuming there is leakage directly to the outside.

The design fire in the apartment is one with a fast fire growth rate reaching a peak at 5.76 MW in 360 seconds in an unconstrained situation. This fire results in fully developed ventilation controlled burning (and flashover at ~150 seconds) in the apartment. In all cases, a window providing 4 m^2 of ventilation to the exterior is assumed to break at 120 sec. The upper layer temperature in the apartment at that time is in the order of 150°C. This is likely to be a reasonable assumption for float glass windows, and a conservative assumption for resistant glazing which would be expected to be present in a high-rise building. Toughened or laminated glass will be more difficult and take longer to break. Assuming early breakage in the modelling ensures the fire proceeds to a fully developed ventilated limited regime (i.e. is not starved of oxygen) and therefore is a conservative assumption.

In all the simulations, no account is taken of the reliability of any of the fire systems incorporated. They are assumed to be totally effective.

Fire Modelling Objectives

The main objective is to maintain tenable conditions in the common corridor and stairway for a period of 30 minutes given that a fire capable of becoming fully developed originates in one of the apartments located at the 3rd floor level. It is considered, for the purposes of this modelling, that 30 minutes is an adequate time to allow for complete evacuation of this building. A separate egress analysis has not been carried out.

The occurrence of untenable conditions may be due to a number of different factors. The following were considered in this analysis (Purser, 1988; Buchanan, 1994; Fire Code Reform Centre Limited, 1996):

- Radiant heat from a hot upper layer will cause pain to the occupants if the upper layer exceeds about 200°C.
- Convective heat will cause injury to occupants if they are required to breathe hot gases. The temperature criterion varies depending on the length of time occupants are exposed and the moisture content of the gases (e.g. 30 minutes at 60°C or 5 minutes at 130°C – for water vapour content < 10%). Conservatively, a criterion of 60°C is adopted here.
- Occupants are provided with a visibility of not less than 5 m while escaping.
- Occupants are exposed to safe levels of narcotic gases (carbon monoxide, carbon dioxide and oxygen, as represented by a fractional effective dose (FED) for incapacitation of less than 1).

For the purpose of this study, a reference height of 1.5 m above floor level was taken for evaluation of FED and visibility. For actual design purposes, a higher reference height may be appropriate.

Fire Modelling Software

This analysis has used the fire simulation software BRANZFIRE Version 99.002 developed by the Building Research Association of New Zealand (Wade, 1996; Wade, 1997; Wade et al, 1997; Wade, 1999). A three-compartment simulation was carried out comprising an apartment and corridor at third floor level and a stair shaft serving the entire building.

Simulation Results

Figures C3 to C8 show simulation results for each of the scenarios for the rate of heat release, smoke layer height, upper layer temperature, visibility, upper layer carbon monoxide, and fractional effective dose for the common corridor space.

Conclusions

The main conclusions from this analysis are:

1. Fire doors to each apartment are essential to provide the common corridor with any reasonable level of protection from smoke spreading from the apartment. Comparison between scenarios 4 and 8 show that even with sprinklers installed there may still be significant smoke spread prior to the operation of the sprinklers resulting in poor visibility (smoke-logging) of the corridor within a short period of time.
2. Pressurisation systems (in conjunction with fire doors to apartments) appear to be potentially the most effective method of maintaining tenability and good visibility in the building's escape routes. Scenario 5 shows pressurising the corridor in an unsprinklered building is effective, while scenario 6 shows using stairway pressurisation alone would not be. However scenario 7 shows stairway pressurisation in combination with sprinklers would be acceptable. However there could be greater variability in performance of pressurisation systems as the actual number of doors open to the stairway at any one time may be quite different from the number assumed in the design. In this analysis, the final exit door was assumed open for the simulation. Further investigation of this variability and the sensitivity of the modelling results to it, is warranted.
3. If pressurisation systems are to be used then smoke detectors in at least the corridors are essential for early activation of the system.
4. If sprinklers were not installed in the building, then a corridor pressurisation system (in conjunction with fire doors to apartments) would appear to be highly desirable for prevention of untenable conditions in the corridor adjacent to the apartment of fire origiu. Without pressurisation, untenable conditions in the corridor may occur within about 4 minutes (scenario 1) meaning an automatic warning system for building alert is required (e.g. heat detectors in apartments, smoke detectors in corridors). A building alert initiated directly from smoke detector activation within an apartment is not desirable due to the likelihood of a greater number of nuisance alarms.
5. Where sprinklers are installed, fast response sprinklers are preferable to standard response sprinklers for the additional time provided for evacuation (compare scenarios 2 and 3).
6. In the sprinklered cases, only a small delay (~30 seconds) in the time for the visibility criteria of 5 m in the corridor was achieved while a more significant delay for the FED resulted (~extra 6 minutes). Compare scenarios 1 and 2. This was mainly due to the amount of smoke produced prior to the operation of the sprinkler system. However, even though with sprinklers the corridor visibility was less than desirable it was still >2 m after a 30 minute period, compared with < 300 mm at the same time for the unsprinklered case.
7. To improve corridor visibility in the sprinklered case (with apartment fire doors and without pressurisation systems) illuminated exit signs are recommended in preference to reflective signs.
8. To ensure building evacuation is initiated within a reasonable time frame, it is essential for an automatic fire detection or suppression system to be installed within the building. As a minimum this would require a smoke detection system within corridors and stairways for building alert, and heat and/or smoke detectors within apartments. Smoke detectors within apartments are strongly recommended for early warning within the apartment.

Scenario	Fire Protection Features - Apartment Building						
	fire door to apartment	standard response sprinklers	fast response sprinklers	pressurise corridor	pressurise stair	reflective exit signs in corridor	illuminated exit signs in corridor
1	x					x	
2	x		x			x	
3	x	x				x	
4			x			x	
5	x			x		x	
6	x				x	x	
7	x		x		x	x	
8						x	
9	x		x				x

Table C1: Fire Protection Features - Apartment Building

Scenario	Tenability in Corridor - Apartment Building			
	upper layer temp > 200 C	visibility at 1.5 m above floor < 5 m	FED at 1.5 m above floor > 1.0	temperature at 1.5 m above floor > 60 C
1	NR	~220 s	~390 s	NR
2	NR	~250 s	~770 s	NR
3	NR	~220 s	~600 s	NR
4	NR	~90 s	~250 s	NR
5	NR	NR	NR	NR
6	NR	~290 s	~450 s	NR
7	NR	NR*	NR	NR
8	~600 s	~90 s	~230 s	~200 s
9	NR	~1260 s	~770 s	NR

Table C2: Tenability in Corridor - Apartment Building

NR = tenability criteria not reached

NR* = visibility tenability criteria briefly exceeded, but only for a short period.

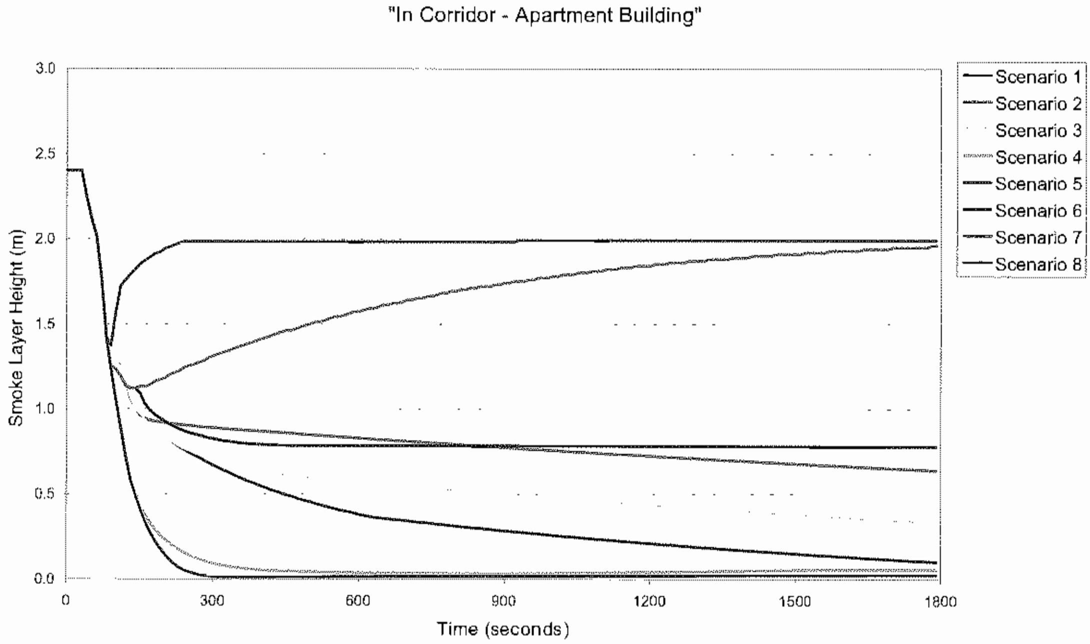

Figure C2: Smoke Layer Height

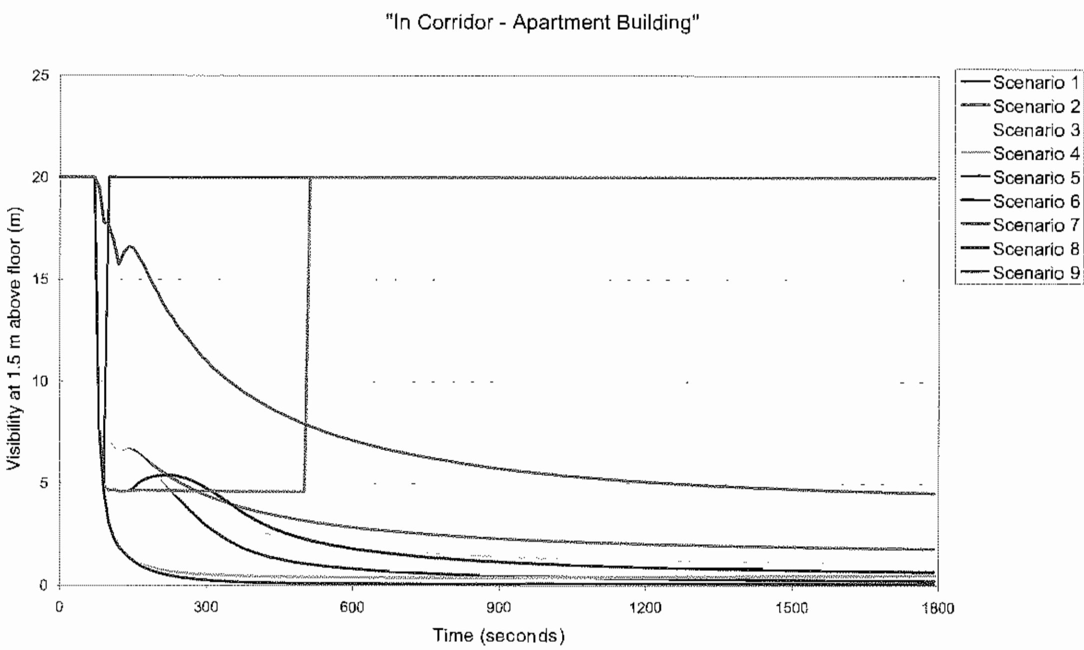

Figure C3: Visibility

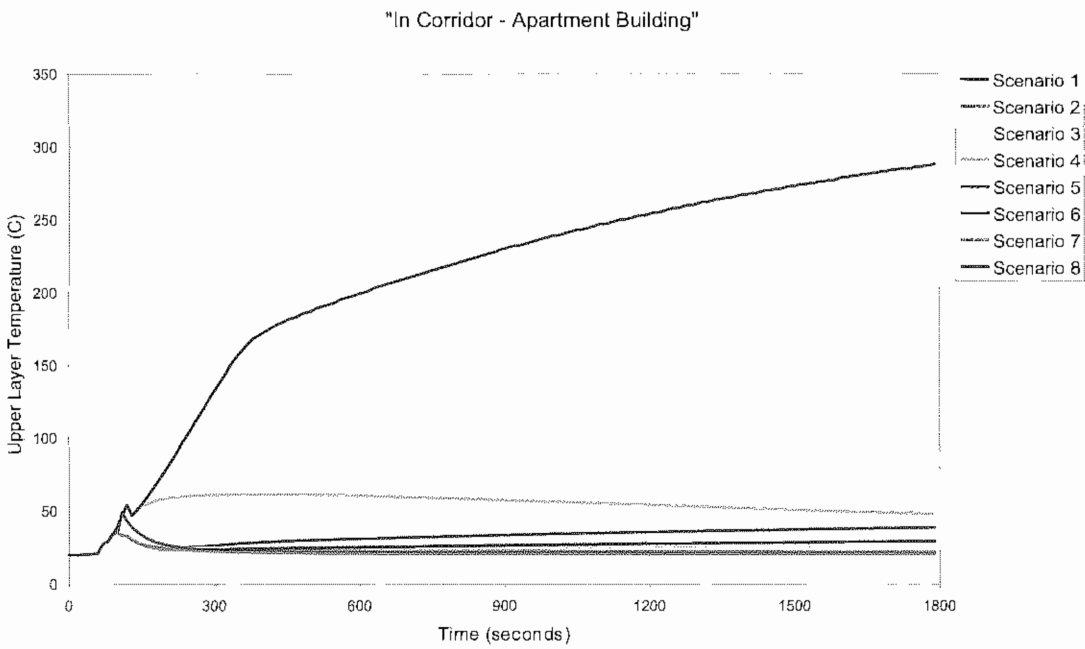

Figure C4: Upper Layer Temperature

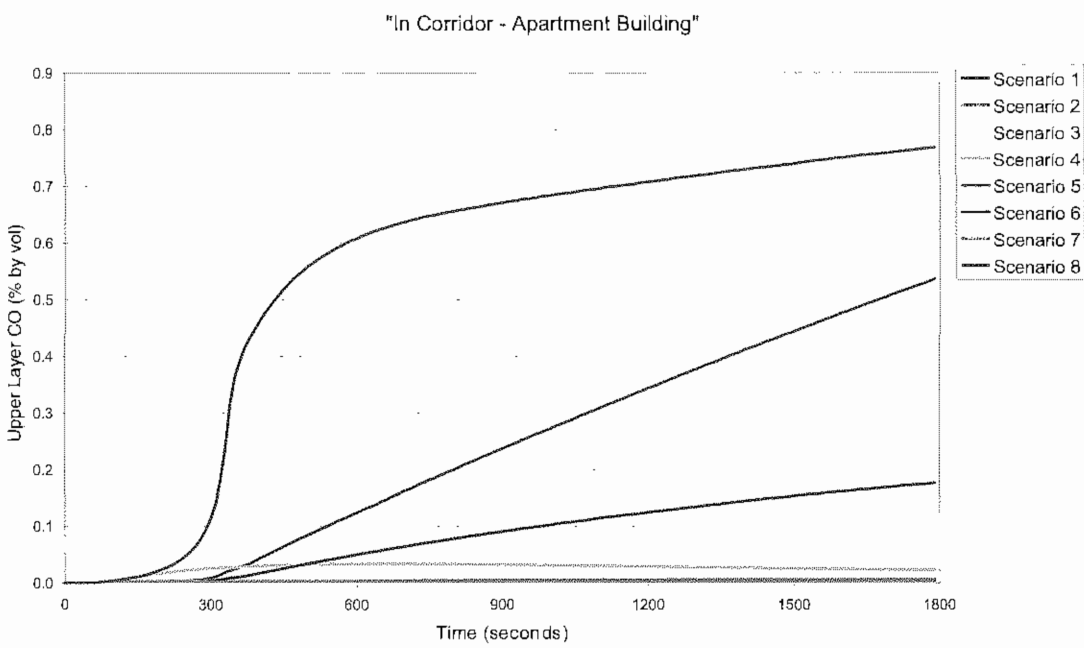

Figure C5: Upper Layer CO

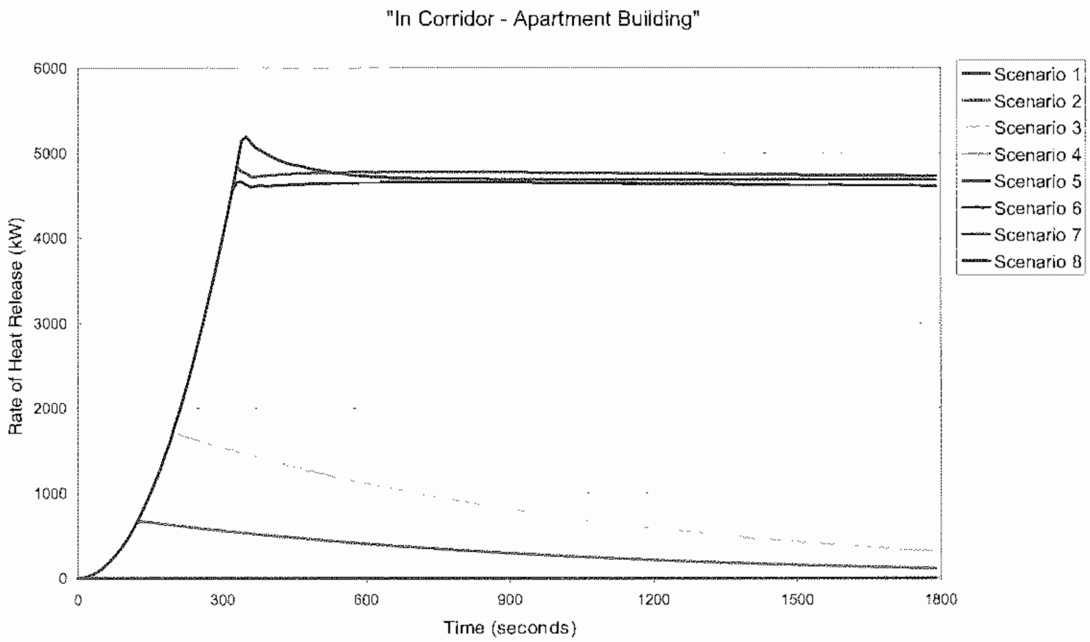

Figure C6: Heat Release Rate

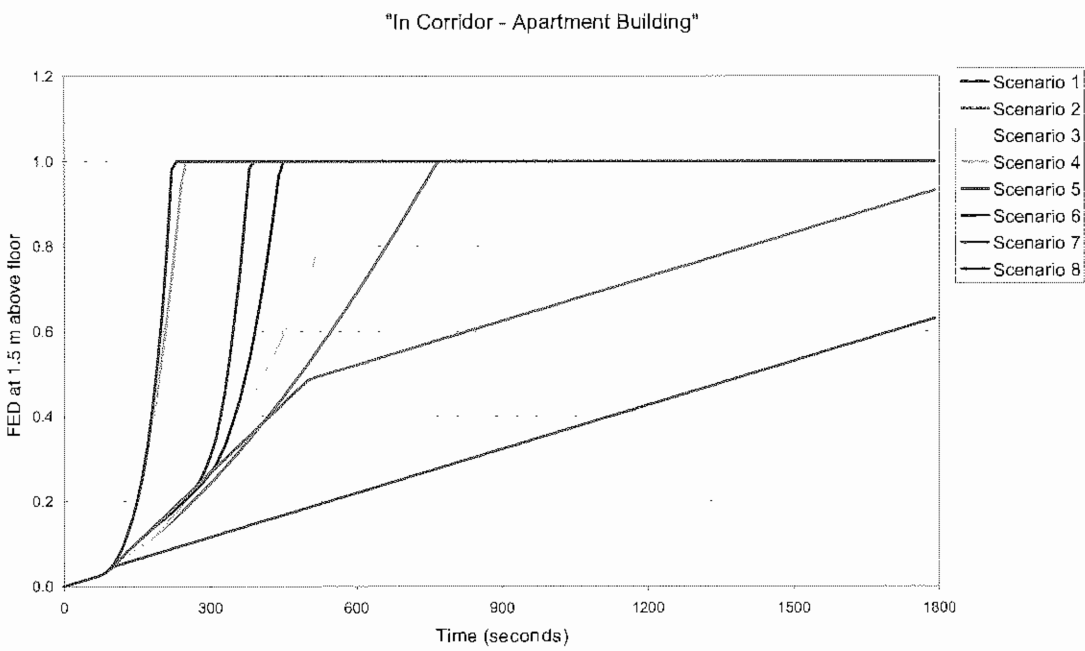

Figure C7: Fractional Effective Dose

Part 2 - Fire Safety in a High-Rise Office Building

Aim

The aim of this part of the study is to reconstruct the disastrous fire in the Joelma Office Building, Sao Paulo, Brazil of February 1974, and to also model the behaviour of the fire had sprinklers and protected lobbies been installed into the building. As for the previous analysis the fire safety is evaluated in terms of preventing the occurrence of untenable conditions in common escape routes and exitways. Computer simulations of smoke spread from an office to a common open stairway were carried out.

Building Characteristics

The building under consideration is a 25-storey office building. The first floor and basement were used for storage of office records. The second through tenth floor was used as an open air parking garage and floors 11 to 25 contained offices. Leakage of smoke from the lobby to the lift shaft has not been considered for the purposes of this analysis. This is a conservative assumption.

typical office floor – 585 m^2 floor area and 2.6 m ceiling height.

open stairway connecting levels – 11.5 m^2 floor area (7.2 m x 1.2 m x 5.3 m high).

The stair shaft and all floors are assumed to be of concrete construction with particleboard on the walls and insulating fibreboard on the ceilings.

The means of escape was by one open stairway located across the elevators. The building had no fire protection systems.

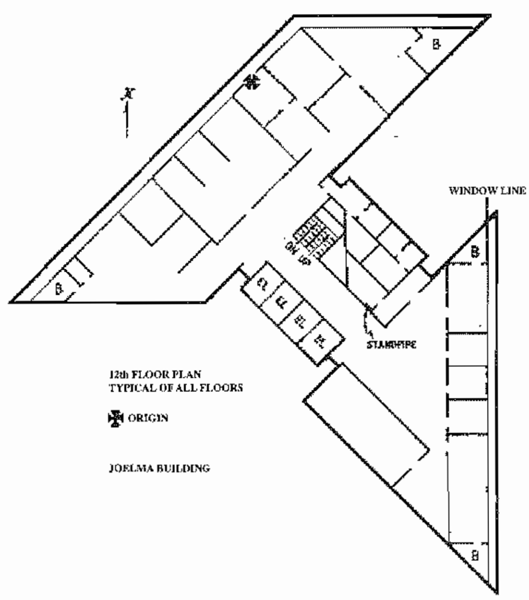

Figure C8: Typical Office Floor Plan – Joelma Building (from Sharry, 1974)

Fire Scenarios and Assumptions

The fire occurred in a window air conditioner on the twelfth floor of the building and caused 179 deaths, 300 injuries and total destruction of the office contents. Three alternative fire designs have been considered. The building as it was, with sprinklers and with both sprinklers and a protected lobby. A matrix describing the fire protection systems for each scenario is given in Table C3.

Where sprinklers are used (scenarios 2 and 3), it is assumed that the radial distance between the fire plume and the sprinkler head is 3.2 m. Conduction losses from the sprinkler head to the pipework are represented by c-factor = 1. A response time index of 200 $ms^{½}$ is taken for standard sprinklers. An activation temperature of 74°C was used. On activation of the sprinkler system, the design fire is modified using a suppression algorithm based on a water discharge rate of 2.7 mm/min ($L/m^2/min$).

In scenario 3, a lobby is created to fire separate the lift lobby and stairway from the office spaces. The double door is assumed to be closed. To allow for smoke leakage around the door, gaps of 3 mm at the top, meeting stile and each side of the leaf are assumed, with a 10 mm gap under the sill. These gaps are maintained for the 30 minute duration of the simulation. The fire resistance level of the door is taken to be at least -/30/30.

The design fire in the office of origin is one with a fast fire growth rate reaching a peak at 5.76 MW in 360 seconds in an unconstrained situation. In all cases, a window providing 3.75 m^2 of ventilation to the exterior is assumed to break at 90 sec. In these simulations, the fire growth beyond the initial room of origin is not modelled, only the smoke spread. Thus in the actual fire the damage and conditions on the rest of the floor and in the stairway was much more severe than modelled here. This modelling is concerned with the earlier stages of fire development which led to untenability in the escape route.

In all the simulations, no account is taken of the reliability of any of the fire systems incorporated. They are assumed to be totally effective.

Fire Modelling Objectives

The main objective is to maintain tenable conditions in the common escape route being the open stairway in scenario 1 and 2, and the new lobby in scenario 3, for a period of 30 minutes given that a fire capable of becoming fully developed originates in one of the office spaces located at the 12th floor level.

The occurrence of untenable conditions may be due to a number of different factors. The following were considered in this analysis (Purser, 1988; Buchanan, 1994; Fire Code Reform Centre Limited, 1996):

- Radiant heat from a hot upper layer will cause pain to the occupants if the upper layer exceeds about 200°C.
- Convective heat will cause injury to occupants if they are required to breathe hot gases. The temperature criterion varies depending on the length of time occupants are exposed and the moisture content of the gases (e.g. 30 minutes at 60°C or 5 minutes at 130°C – for water vapour content < 10%). Conservatively, a criterion of 60°C is adopted here.
- Occupants are provided with a visibility of not less than 5 m while escaping.
- Occupants are exposed to safe levels of narcotic gases (carbon monoxide, carbon dioxide and oxygen, as represented by a fractional effective dose (FED) for incapacitation of less than 1).

For the purpose of this study, a reference height of 1.5 m above floor level was taken for evaluation of FED and visibility. For actual design purposes, a higher reference height may be appropriate.

Fire Modelling Software

This analysis has used the fire simulation software BRANZFIRE Version 99.002 developed by the Building Research Association of New Zealand (Wade, 1996; Wade, 1997; Wade et al, 1997; Wade, 1999). A four (scenarios 1 and 2) and five-compartment (scenario 3) simulation was carried out comprising office spaces and stairway.

Simulation Results

Figures C9 to C14 show simulation results for each of the scenarios for the rate of heat release, smoke layer height, upper layer temperature, visibility, upper layer carbon monoxide, and fractional effective dose for the common escape route.

Conclusions

The main conclusions from this analysis are:

1. The reconstruction of the fire incident is consistent with the observed reports (Sharry, 1974), with untenable conditions predicted within the open stairway escape route within five minutes (poor visibility) and eight minutes (narcotic gases).
2. The effect of adding a sprinkler system to the building is predicted to have only a small effect on the time to exceed the visibility criteria within the stairway due to the amount of smoke produced prior to activation of the sprinkler. However, it is likely that the extent of fire spread beyond room of origin and between floors would have been dramatically decreased.
3. The effect of adding both sprinklers and lift/stairway lobby compartmentation would most likely have kept the escape routes tenable for more than 20 minutes.
4. For this type/configuration of building, sprinklers and fire isolation of the escape route/exitway are essential.
5. While not a direct conclusion of this analysis, smoke detectors, while desirable to initiate earlier evacuation, are probably not essential within the actual office space, but would be strongly recommended within fire isolated exitways.

Scenario	Fire Protection Features - Office Building		
	no fire protection	standard response sprinklers	protected lobby
1	X		
2		X	
3		X	X

Table C3 : Fire Protection Features – Office Building

Scenario	Tenability in Escape Route - Office Building			
	upper layer temp > 200 C	visibility at 1.5 m above floor < 5 m	FED at 1.5 m above floor > 1.0	temperature at 1.5 m above floor > 60 C
1	NR	~290 s	~470 s	~1060 s
2	NR	~300 s	~530 s	NR
3	NR	~1370 s	~1530 s	NR

Table C4 : Tenability in Stairway - Office Building

NR = tenability condition not reached

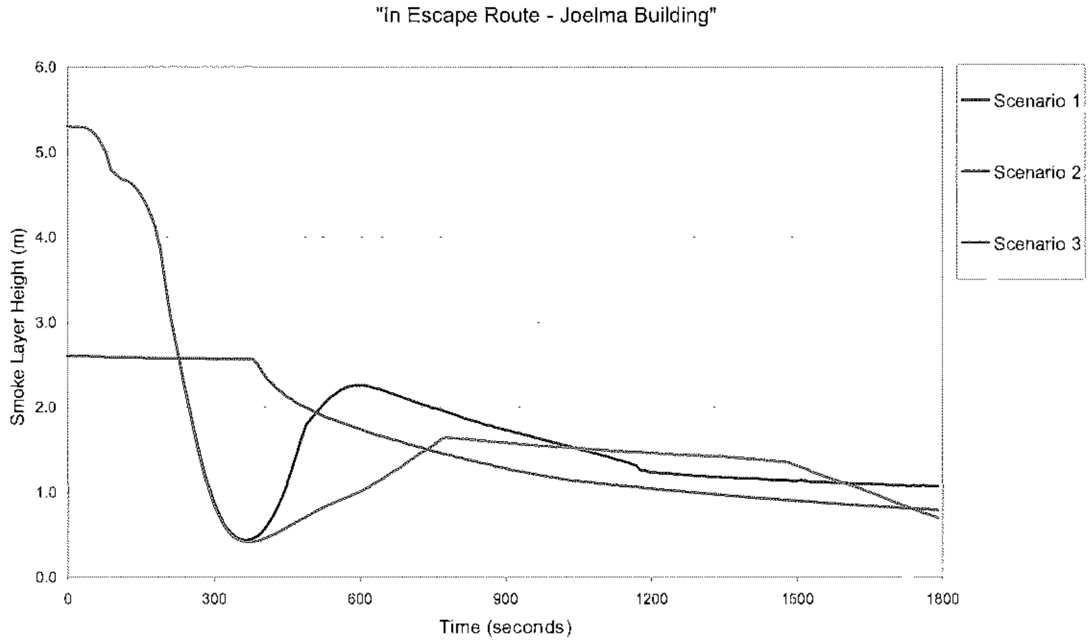

Figure C9 : Smoke Layer Height

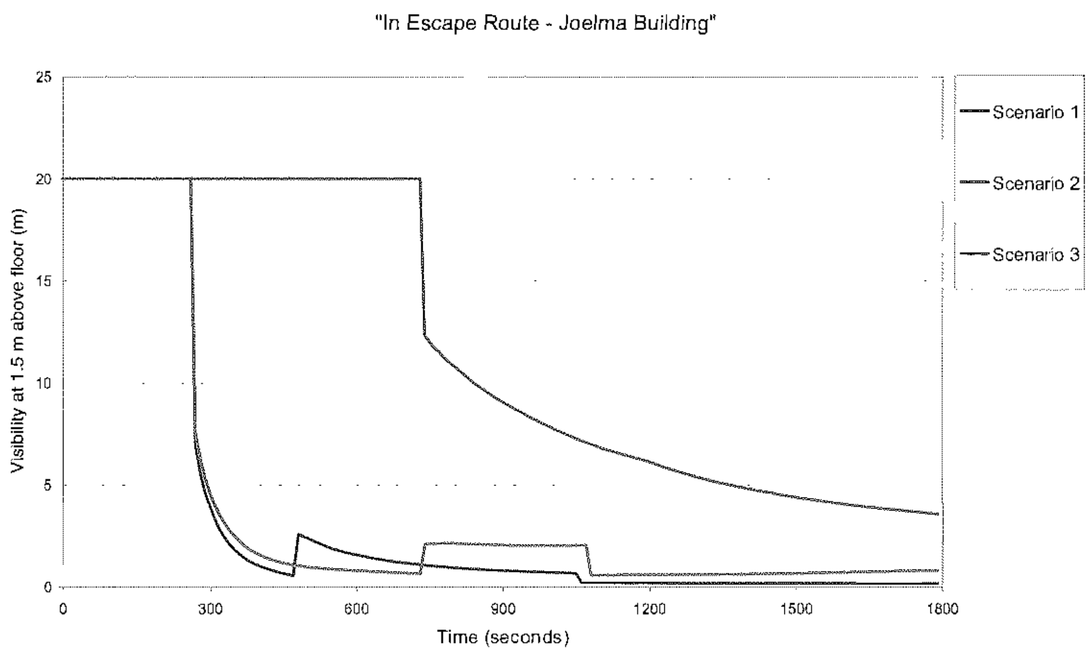

Figure C10 : Visibility

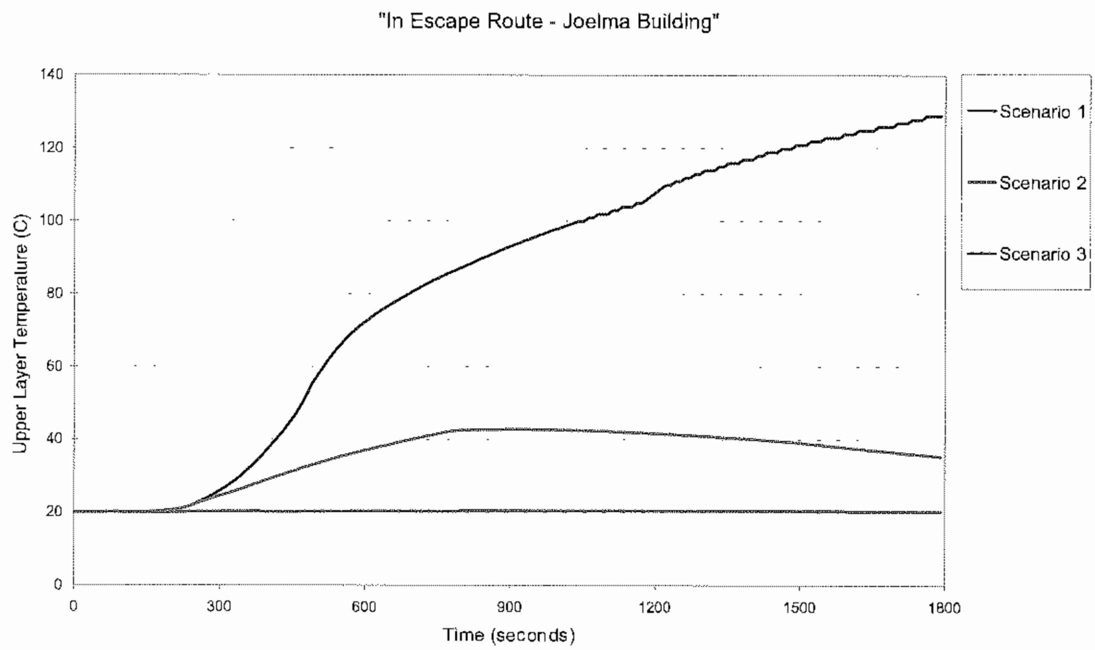

Figure C11 : Upper Layer Temperature

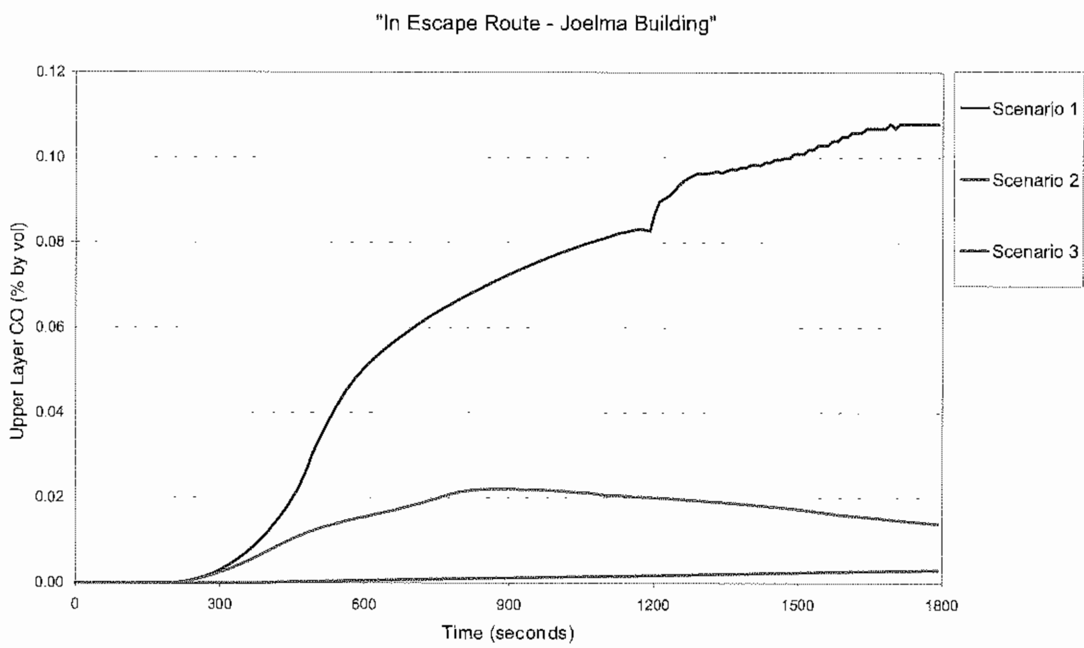

Figure C12 : Upper Layer CO

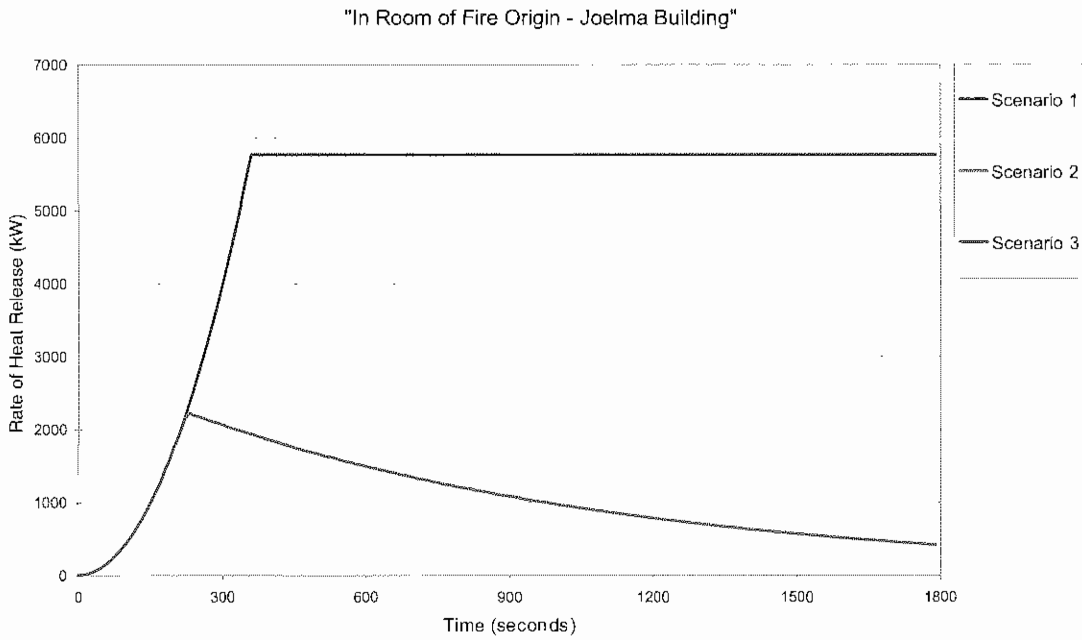

Figure C13 : Rate of Heat Release

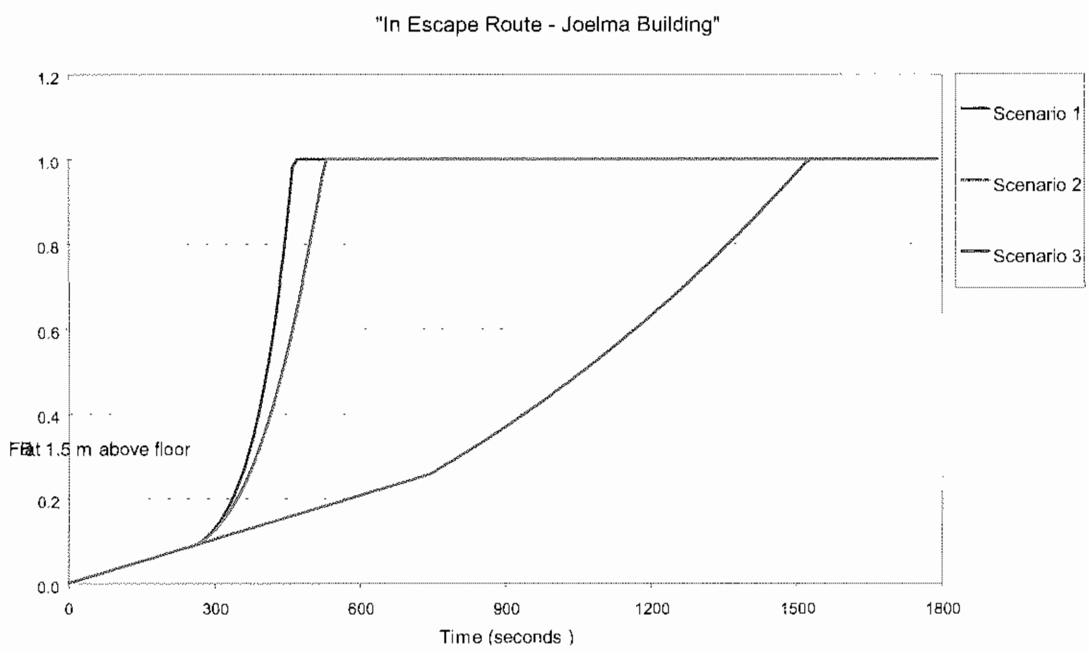

Figure C14 : Fractional Effective Dose

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